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AC Machines

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2.1 NEMA FRAME ASSIGNMENTS—THREE-PHASE MOTORS

OPEN MOTORS - GENERAL PURPOSE

	NEMA program	3600 rpm			1800 rpm			1200 rpm			900 rpm		
		Orig.	1952 rerate	1964 rerate	Orig.	1952 rerate	1964 rerate	Orig.	1952 rerate	1964 rerate	Orig.	1952 rerate	1964 rerate
	1	–	–	–	203	182	143T	204	184	145T	225	213	182T
	1.5	203	182	143T	204	184	145T	224	184	182T	254	213	184T
	2	204	184	145T	224	184	145T	225	213	184T	254	215	213T
	3	224	184	145T	225	213	182T	254	215	213T	284	254U	215T
	5	225	213	182T	254	215	184T	284	254U	215T	324	256U	254T
	7.5	254	215	184T	284	254U	213T	324	256U	254T	326	284U	256T
	10	284	254U	213T	324	256U	215T	326	284U	256T	364	286U	284T
	15	324	256U	215T	326	284U	254T	364	324U	284T	365	326U	286T
	20	326	284U	254T	364	286U	256T	365	326U	286T	404	364U	324T
hp	25	364S	286U	256T	364	324U	284T	404	364U	324T	405	365U	326T
	30	364S	324S	284TS	365	326U	286T	405	365U	326T	444	404U	364T
	40	365S	326S	286TS	404	364U	324T	444	404U	364T	445	405U	365T
	50	404S	364US	324TS	405S	365US	326T	445	405U	365T	504U	444U	404T
	60	405S	365US	326TS	444S	404US	364TS†	504U	444U	404T	505	445U	405T
	75	444S	404US	364TS	445S	405US	365TS†	505	445U	405T	–	–	444T
	100	445S	405US	365TS	504S	444US	404TS†	–	–	444T	–	–	445T
	125	504S	444US	404TS	505S	445US	405TS†	–	–	445T	–	–	–
	150	505S	445US	405TS	–	–	444TS†	–	–	–	–	–	–
	200	–	–	444TS	–	–	445TS†	–	–	–	–	–	–
	250	–	–	445TS	–	–	–	–	–	–	–	–	–

† When motors are to be used with V-belt or chain drives, the correct frame size is the frame size shown but with the suffix letter S omitted. For the corresponding shaft extension dimensions, see Page 2-8 of this manual.

TEFC MOTORS - GENERAL PURPOSE

	NEMA program	3600 rpm			1800 rpm			1200 rpm			900 rpm		
		Orig.	1952 rerate	1964 rerate	Orig.	1952 rerate	1964 rerate	Orig.	1952 rerate	1964 rerate	Orig.	1952 rerate	1964 rerate
	1	–	–	–	203	182	143T	204	184	145T	225	213	182T
	1.5	203	182	143T	204	184	145T	224	184	182T	254	213	184T
	2	204	184	145T	224	184	145T	225	213	184T	254	215	213T
	3	224	184	182T	225	213	182T	254	215	213T	284	254U	215T
	5	225	213	184T	254	215	184T	284	254U	215T	324	256U	254T
	7.5	254	215	213T	284	254U	213T	324	256U	254T	326	284U	256T
	10	284	254U	215T	324	256U	215T	326	284U	256T	364	286U	284T
	15	324	256U	254T	326	284U	254T	364	324U	284T	365	326U	286T
	20	326	286U	256T	364	286U	256T	365	326U	286T	404	364U	324T
hp	25	365S	324U	284TS	365	324U	284T	404	364U	324T	405	365U	326T
	30	404S	326S	286TS	404	326U	286T	405	365U	326T	444	404U	364T
	40	405S	364US	324TS	405	364U	324T	444	404U	364T	445	405U	365T
	50	444S	365US	326TS	444S	365US	326T	445	405U	365T	504U	444U	404T
	60	445S	405US	364TS	445S	405US	364TS†	504U	444U	404T	505	445U	405T
	75	504S	444US	365TS	504S	444US	365TS†	505	445U	405T	–	–	444T
	100	505S	445US	405TS	505S	445US	405TS†	–	–	444T	–	–	445T
	125	–	–	444TS	–	–	444TS†	–	–	445T	–	–	–
	150	–	–	445TS	–	–	445TS†	–	–	–	–	–	–

† When motors are to be used with V-belt or chain drives, the correct frame size is the frame size shown but with the suffix letter S omitted. For the corresponding shaft extension dimensions, see Page 2-8 of this manual.

2.2 SUFFIXES TO NEMA FRAMES

The following explanations of the various frame suffixes used on NEMA frame motors have been compiled for the benefit of EASA members. The suffixes for NEMA frame motors are the letters that immediately follow the frame numbers. Notice that more than one suffix may be used on any given motor.

Note: "D" dimension (shaft height) of a motor or generator in these frame sizes equals 1/4 the value of the first two digits in the frame number.

Example: 284 frame: 28/4 = 7, D = 7"

A — Industrial direct-current machine.

B — Carbonator pump motors. (See NEMA Stds. MG 1, 18.270 - 18.281.)

C — Type C face mounting on drive end.

CH — Face mounting dimensions are different from those for the frame designation having the suffix letter "C". (The letters "CH" are considered as one suffix and should not be separated.)

D — Type D flange mounting on drive end.

E — Shaft extension dimensions for elevator motors in frames larger than 326T frames.

FC — Face mounting on opposite drive end.

FD — Flange mounting on opposite drive end.

G — Gasoline pump motors. (See NEMA Stds. MG 1, 18.91.)

H — Indicates a small machine having an "F" dimension larger than that of the same frame without the suffix letter "H". (See NEMA Stds. MG 1, 4.4.1 and 4.5.1.)

HP or HPH — Type P flange-mounted, vertical solid-shaft motors having dimensions in accordance with NEMA Stds. MG 1, 18.252. (The letters "HP" and "HPH" are considered as one suffix and should not be separated.)

J — Jet pump motors. (See NEMA Stds. MG 1, 18.132.)

JM — Face-mounted, close-coupled pump motor having antifriction bearings and dimensions in accordance with Table 1 of NEMA Stds. MG 1, 18.250. (The letters "JM" are considered as one suffix and should not be separated.)

JP — Type C face-mounted, close-coupled pump motor having antifriction bearings and dimensions in accordance with Table 2 of NEMA Stds. MG 1, 18.250. (The letters "JP" are considered as one suffix and should not be separated.)

K — Sump pump motors. (See NEMA Stds. MG 1, 18.78.)

LP or LPH — Type P flange-mounted, vertical solid-shaft motors having dimensions in accordance with NEMA Stds. MG 1, 18.251. (The letters "LP" and "LPH" are considered as one suffix and should not be separated.)

M — Oil burner motors. (See NEMA Stds. MG 1, 18.106.)

N — Oil burner motors. (See NEMA Stds. MG 1, 18.106.)

P or PH — Type P flange-mounted, vertical hollow-shaft motors having dimensions in accordance with NEMA Stds. MG 1, 18.238.

R — Drive end tapered shaft extension having dimensions in accordance with NEMA Stds. MG 1, 4.4.2.

S — Standard short shaft for direct connection.

T — Included as part of a frame designation for which standard dimensions have been established.

U — Previously used as part of a frame designation for which standard dimensions had been established.

V — Vertical mounting only.

SUFFIXES TO NEMA FRAMES—CONTINUED

VP — Type P flange-mounted, vertical solid-shaft motors having dimensions in accordance with NEMA Stds. MG 1, 18.237. (The letters "VP" are considered as one suffix and should not be separated.)

X — Wound-rotor crane motors with double shaft extension. (See NEMA Stds. MG 1, 18.229 and 18.230.)

Y — Special mounting dimensions. (Dimensional diagram must be obtained from manufacturer.)

Z — All mounting dimensions are standard except the shaft extension(s). Also used to designate machines with double shaft extension.

Note: Manufacturers may use any letter preceding the frame number, but such a letter will have no reference to standard mounting dimensions.

Suffix letters shall be added to the frame number in the following sequences:

Suffix Letter	Sequence
A, H	1
G, J, M, N, T, U, HP, HPH, JM, JP, LP, LPH & VP	2
R, S	3
C, D, P, PH	4
FC, FD	5
V	6
E, X, Y, Z	7

Example: "T" frame motor with a "C" face mounted vertically with a nonstandard shaft extension; (Sequences 2, 4, 6 and 7) 184TCVZ.

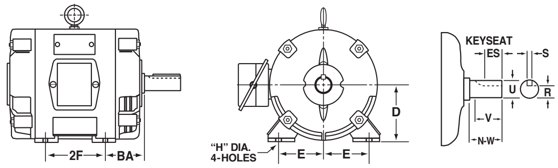
Note: This material is reproduced by permission of the National Electrical Manufacturers Association from NEMA Stds. MG 1, 4.2.2. It was originally published as *EASA Tech Note 7* (September 1985). It was reviewed and updated as necessary in August 2016.

2.3 DIMENSIONS FOR AC MACHINES—INCHES

NEMA FRAME DIMENSIONS—FOOT-MOUNTED AC MACHINES

DIMENSIONS IN INCHES

(Note: Above-NEMA frame dimensions are manufacturer-specific.)



Frame	A									Keyseat			AA
designations	max	D	E	2F	BA	H*	U	N-W	V min	R	ES min	S	min
42		2.62	1.75	1.69	2.06	0.28	0.3750	1.12		0.328		Flat	
48		3.00	2.12	2.75	2.50	0.34	0.5000	1.50		0.453		Flat	
48H		3.00	2.12	4.75	2.50	0.34	0.5000	1.50		0.453		Flat	
56		3.50	2.44	3.00	2.75	0.34	0.6250	1.88		0.517	1.41	0.188	
56H		3.50	2.44	5.00	2.75	0.34	0.6250	1.88		0.517	1.41	0.188	
66		4.12	2.94	5.00	3.12	0.41	0.7500	2.25		0.644	1.91	0.188	
143	7.0	3.50	2.75	4.00	2.25	0.34	0.7500	2.00	1.75	0.644	1.41	0.188	3/4
143T	7.0	3.50	2.75	4.00	2.25	0.34	0.8750	2.25	2.00	0.771	1.41	0.188	3/4
145	7.0	3.50	2.75	5.00	2.25	0.34	0.7500	2.00	1.75	0.644	1.41	0.188	3/4
145T	7.0	3.50	2.75	5.00	2.25	0.34	0.8750	2.25	2.00	0.771	1.41	0.188	3/4
182	9.0	4.50	3.75	4.50	2.75	0.41	0.8750	2.25	2.00	0.771	1.41	0.188	3/4
182T	9.0	4.50	3.75	4.50	2.75	0.41	1.1250	2.75	2.50	0.986	1.78	0.250	3/4
184	9.0	4.50	3.75	5.50	2.75	0.41	0.8750	2.25	2.00	0.771	1.41	0.188	3/4
184T	9.0	4.50	3.75	5.50	2.75	0.41	1.1250	2.75	2.50	0.986	1.78	0.250	3/4
203		5.00	4.00	5.50	3.12	0.41	0.7500	2.25	2.00	0.644	1.53	0.188	
204		5.00	4.00	6.50	3.12	0.41	0.7500	2.25	2.00	0.644	1.53	0.188	
213	10.5	5.25	4.25	5.50	3.50	0.41	1.1250	3.00	2.75	0.986	2.03	0.250	3/4
213T	10.5	5.25	4.25	5.50	3.50	0.41	1.3750	3.38	3.12	1.201	2.41	0.312	1
215	10.5	5.25	4.25	7.00	3.50	0.41	1.1250	3.00	2.75	0.986	2.03	0.250	3/4
215T	10.5	5.25	4.25	7.00	3.50	0.41	1.3750	3.38	3.12	1.201	2.41	0.312	1
224		5.50	4.50	6.75	3.50	0.41	1.0000	3.00	2.75	0.859	2.03	0.250	
225		5.50	4.50	7.50	3.50	0.41	1.0000	3.00	2.75	0.859	2.03	0.250	
254		6.25	5.00	8.25	4.25	0.53	1.1250	3.38	3.12	0.986	2.03	0.250	
254U	12.5	6.25	5.00	8.25	4.25	0.53	1.3750	3.75	3.50	1.201	2.78	0.312	1
254T	12.5	6.25	5.00	8.25	4.25	0.53	1.625	4.00	3.75	1.416	2.91	0.375	1-1/4
256U	12.5	6.25	5.00	10.00	4.25	0.53	1.3750	3.75	3.50	1.201	2.78	0.312	1
256T	12.5	6.25	5.00	10.00	4.25	0.53	1.625	4.00	3.75	1.416	2.91	0.375	1-1/4
284		7.00	5.50	9.50	4.75	0.53	1.2500	3.75	3.50	1.112	2.03	0.250	
284U	14.0	7.00	5.50	9.50	4.75	0.53	1.625	4.88	4.62	1.416	3.78	0.375	1-1/4
284T	14.0	7.00	5.50	9.50	4.75	0.53	1.875	4.62	4.38	1.591	3.28	0.500	1-1/2
284TS	14.0	7.00	5.50	9.50	4.75	0.53	1.625	3.25	3.00	1.416	1.91	0.375	1-1/2
286U	14.0	7.00	5.50	11.00	4.75	0.53	1.625	4.88	4.62	1.416	3.78	0.375	1-1/4
286T	14.0	7.00	5.50	11.00	4.75	0.53	1.875	4.62	4.38	1.591	3.28	0.500	1-1/2
286TS	14.0	7.00	5.50	11.00	4.75	0.53	1.625	3.25	3.00	1.416	1.91	0.375	1-1/2
324		8.00	6.25	10.50	5.25	0.66	1.625	4.88	4.62	1.416	3.78	0.375	
324U	16.0	8.00	6.25	10.50	5.25	0.66	1.875	5.62	5.38	1.591	4.28	0.500	1-1/2
324S	16.0	8.00	6.25	10.50	5.25	0.66	1.625	3.25	3.00	1.416	1.91	0.375	1-1/2
324T	16.0	8.00	6.25	10.50	5.25	0.66	2.125	5.25	5.00	1.845	3.91	0.500	2
324TS	16.0	8.00	6.25	10.50	5.25	0.66	1.875	3.75	3.50	1.591	2.03	0.500	2
326		8.00	6.25	12.00	5.25	0.66	1.625	4.88	4.62	1.416	3.78	0.375	
326U	16.0	8.00	6.25	12.00	5.25	0.66	1.875	5.62	5.38	1.591	4.28	0.500	1-1/2
326S	16.0	8.00	6.25	12.00	5.25	0.66	1.625	3.25	3.00	1.416	1.91	0.375	1-1/2
326T	16.0	8.00	6.25	12.00	5.25	0.66	2.125	5.25	5.00	1.845	3.91	0.500	2
326TS	16.0	8.00	6.25	12.00	5.25	0.66	1.875	3.75	3.50	1.591	2.03	0.500	2

NEMA FRAME DIMENSIONS—FOOT-MOUNTED AC MACHINES—CONTINUED

DIMENSIONS IN INCHES

Frame designations	A max	D	E	2F	BA	H*	U	N-W	V min	Keyseat			AA min
										R	ES min	S	
364		9.00	7.00	11.25	5.88	0.66	1.875	5.62	5.38	1.591	4.28	0.500	
364S		9.00	7.00	11.25	5.88	0.66	1.625	3.25	3.00	1.416	1.91	0.375	
364U	18.0	9.00	7.00	11.25	5.88	0.66	2.125	6.38	6.12	1.845	5.03	0.500	2
364US	18.0	9.00	7.00	11.25	5.88	0.66	1.875	3.75	3.50	1.591	2.03	0.500	2
364T	18.0	9.00	7.00	11.25	5.88	0.66	2.375	5.88	5.62	2.021	4.28	0.625	3
364TS	18.0	9.00	7.00	11.25	5.88	0.66	1.875	3.75	3.50	1.591	2.03	0.500	3
365		9.00	7.00	12.25	5.88	0.66	1.875	5.62	5.38	1.591	4.28	0.500	
365S		9.00	7.00	12.25	5.88	0.66	1.625	3.25	3.00	1.416	1.91	0.375	
365U	18.0	9.00	7.00	12.25	5.88	0.66	2.125	6.38	6.12	1.845	5.03	0.500	2
365US	18.0	9.00	7.00	12.25	5.88	0.66	1.875	3.75	3.50	1.591	2.03	0.500	2
365T	18.0	9.00	7.00	12.25	5.88	0.66	2.375	5.88	5.62	2.021	4.28	0.625	3
365TS	18.0	9.00	7.00	12.25	5.88	0.66	1.875	3.75	3.50	1.591	2.03	0.500	3
404		10.00	8.00	12.25	6.62	0.81	2.125	6.38	6.12	1.845	5.03	0.500	
404S		10.00	8.00	12.25	6.62	0.81	1.875	3.75	3.50	1.591	2.03	0.500	
404U	20.0	10.00	8.00	12.25	6.62	0.81	2.375	7.12	6.88	2.021	5.53	0.625	2
404US	20.0	10.00	8.00	12.25	6.62	0.81	2.125	4.25	4.00	1.845	2.78	0.500	2
404T	20.0	10.00	8.00	12.25	6.62	0.81	2.875	7.25	7.00	2.450	5.65	0.750	3
404TS	20.0	10.00	8.00	12.25	6.62	0.81	2.125	4.25	4.00	1.845	2.78	0.500	3
405		10.00	8.00	13.75	6.62	0.81	2.125	6.38	6.12	1.845	5.03	0.500	3/4
405S		10.00	8.00	13.75	6.62	0.81	1.875	3.75	3.50	1.591	2.03	0.500	
405U	20.0	10.00	8.00	13.75	6.62	0.81	2.375	7.12	6.88	2.021	5.53	0.625	2
405US	20.0	10.00	8.00	13.75	6.62	0.81	2.125	4.25	4.00	1.845	2.78	0.500	2
405T	20.0	10.00	8.00	13.75	6.62	0.81	2.875	7.25	7.00	2.450	5.65	0.750	3
405TS	20.0	10.00	8.00	13.75	6.62	0.81	2.125	4.25	4.00	1.845	2.78	0.500	3
444		11.00	9.00	14.50	7.50	0.81	2.375	7.12	6.88	2.021	5.53	0.625	
444S		11.00	9.00	14.50	7.50	0.81	2.125	4.25	4.00	1.845	2.78	0.500	
444U	22.0	11.00	9.00	14.50	7.50	0.81	2.875	8.62	8.38	2.450	7.03	0.750	2-1/2
444US	22.0	11.00	9.00	14.50	7.50	0.81	2.125	4.25	4.00	1.845	2.78	0.500	2-1/2
444T	22.0	11.00	9.00	14.50	7.50	0.81	3.375	8.50	8.25	2.880	6.91	0.875	3
444TS	22.0	11.00	9.00	14.50	7.50	0.81	2.375	4.75	4.50	2.021	3.03	0.625	3
445		11.00	9.00	16.50	7.50	0.81	2.375	7.12	6.88	2.021	5.53	0.625	
445S		11.00	9.00	16.50	7.50	0.81	2.125	4.25	4.00	1.845	2.78	0.500	
445U	22.0	11.00	9.00	16.50	7.50	0.81	2.875	8.62	8.38	2.450	7.03	0.750	2-1/2
445US	22.0	11.00	9.00	16.50	7.50	0.81	2.125	4.25	4.00	1.845	2.78	0.500	2-1/2
445T	22.0	11.00	9.00	16.50	7.50	0.81	3.375	8.50	8.25	2.880	6.91	0.875	3
445TS	22.0	11.00	9.00	16.50	7.50	0.81	2.375	4.75	4.50	2.021	3.03	0.625	3
447T	22.0	11.00	9.00	20.00	7.50	0.81	3.375	8.50	8.25	2.880	6.91	0.875	3
447TS	22.0	11.00	9.00	20.00	7.50	0.81	2.375	4.75	4.50	2.021	3.03	0.625	3
449T	22.0	11.00	9.00	25.00	7.50	0.81	3.375	8.50	8.25	2.880	6.91	0.875	3
449TS	22.0	11.00	9.00	25.00	7.50	0.81	2.375	4.75	4.50	2.021	3.03	0.625	3
504U	25.0	12.50	10.00	16.00	8.50	0.94	2.875	8.62	8.38	2.450	7.28	0.750	2-1/2
504S	25.0	12.50	10.00	16.00	8.50	0.94	2.125	4.25	4.00	1.845	2.78	0.500	2-1/2
505	25.0	12.50	10.00	18.00	8.50	0.94	2.875	8.62	8.38	2.450	7.28	0.750	2-1/2
505S	25.0	12.50	10.00	18.00	8.50	0.94	2.125	4.25	4.00	1.845	2.78	0.500	2-1/2

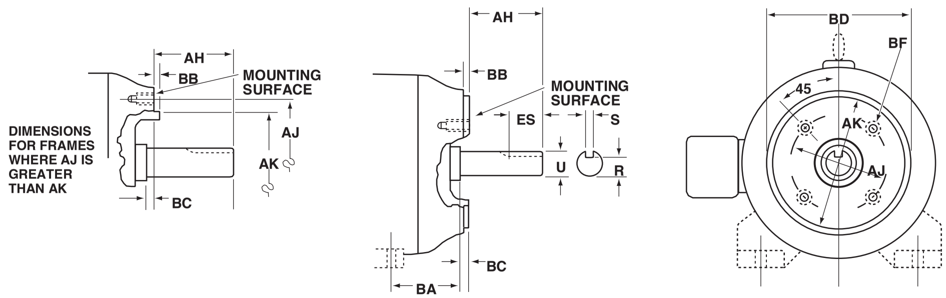
Reference: NEMA Stds. MG 1, 4.4.1.

*Frames 42 to 66, inclusive: the H dimension is *Width of Slot*.

*Frames 143 to 505S, inclusive: the H dimension is *Diameter of Hole*.

NEMA FRAME DIMENSIONS—TYPE C FACE-MOUNTING FOOT OR FOOTLESS AC MOTORS

DIMENSIONS IN INCHES



Frame designations†	AJ	AK	BA	BB min	BC	BD max	BF hole Number	BF hole Tap size	BF hole Bolt penetration allowance	U	AH	Keyseat R	Keyseat ES min	Keyseat S
42C	3.750	3.000	2.062	0.16	-0.19	5.00	4	1/4-20		0.3750	1.312	0.328		Flat
48C	3.750	3.000	2.50	0.16	-0.19	5.625	4	1/4-20		0.5000	1.69	0.453		Flat
56C	5.875	4.500	2.75	0.16	-0.19	6.50	4	3/8-16		0.6250	2.06	0.517	1.41	0.188
66C	5.875	4.500		0.16	-0.19	6.50	4	3/8-16		0.7500	2.44	0.644		0.188
143TC and 145TC	5.875	4.500	2.75	0.16	+0.12	6.50	4	3/8-16	0.56	0.8750	2.12	0.771	1.41	0.188
182C and 184C	5.875	4.500		0.16	+0.12	6.50	4	3/8-16	0.56	0.8750	2.12	0.771		0.188
182TC and 184TC	7.250	8.500	3.50	0.25	+0.12	9.00	4	1/2-13	0.75	1.1250	2.62	0.986	1.78	0.250
182TCH and 184TCH	5.875	4.500	3.50	0.16	+0.12	6.50	4	3/8-16	0.56	1.1250	2.62	0.986	1.78	0.250
213C and 215C	7.250	8.500		0.25	+0.25	9.00	4	1/2-13	0.75	1.1250	2.75	0.986		0.250
213TC and 215TC	7.250	8.500	4.25	0.25	+0.25	9.00	4	1/2-13	0.75	1.3750	3.12	1.201	2.41	0.312
254UC and 256UC	7.250	8.500		0.25	+0.25	10.00	4	1/2-13	0.75	1.3750	3.50	1.201		0.312
254TC and 256TC	7.250	8.500	4.75	0.25	+0.25	10.00	4	1/2-13	0.75	1.625	3.75	1.416	2.91	0.375
284UC and 286UC	9.000	10.500		0.25	+0.25	11.25	4	1/2-13	0.75	1.625	4.62	1.416		0.375
284TC and 286TC	9.000	10.500	4.75	0.25	+0.25	11.25	4	1/2-13	0.75	1.875	4.38	1.591	3.28	0.500
284TSC and 286TSC	9.000	10.500	4.75	0.25	+0.25	11.25	4	1/2-13	0.75	1.625	3.00	1.416	1.91	0.375
324UC and 326UC	11.000	12.500		0.25	+0.25	14.00	4	5/8-11	0.94	1.875	5.38	1.591		0.500
324SC and 326SC	11.000	12.500		0.25	+0.25	14.00	4	5/8-11	0.94	1.625	3.00	1.416		0.375
324TC and 326TC	11.000	12.500	5.25	0.25	+0.25	14.00	4	5/8-11	0.94	2.125	5.00	1.845	3.91	0.500
324TSC and 326TSC	11.000	12.500	5.25	0.25	+0.25	14.00	4	5/8-11	0.94	1.875	3.50	1.591	2.03	0.500
364UC and 365UC	11.000	12.500		0.25	+0.25	14.00	8	5/8-11	0.94	2.125	6.12	1.845		0.500

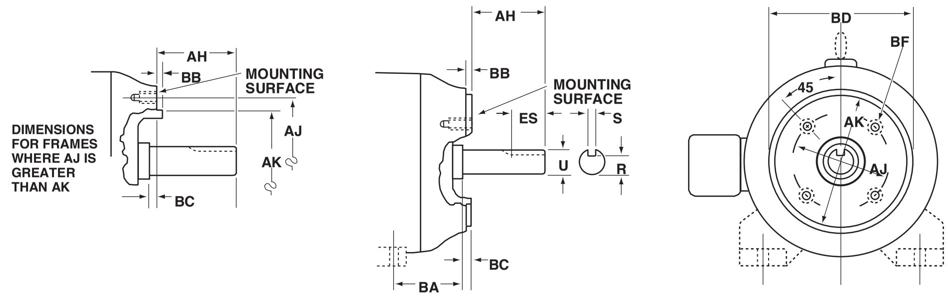
Reference: NEMA Stds. MG 1, 4.4.4.

† See Pages Page 2-8 of this manual for dimensions A, D, E, 2F and H.

For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.4, 4.11 and 4.12.

NEMA FRAME DIMENSIONS—TYPE C FACE-MOUNTING FOOT OR FOOTLESS AC MOTORS—CONTINUED

DIMENSIONS IN INCHES



Frame designations†	AJ	AK	BA	BB min	BC	BD max	BF hole Number	BF hole Tap size	BF hole Bolt penetration allowance	U	AH	Keyseat R	Keyseat ES min	Keyseat S
364USC and 365USC	11.000	12.500		0.25	+0.25	14.00	8	5/8-11	0.94	1.875	3.50	1.591		0.500
364TC and 365TC	11.000	12.500	5.88	0.25	+0.25	14.00	8	5/8-11	0.94	2.375	5.62	2.021	4.28	0.625
364TSC and 365TSC	11.000	12.500	5.88	0.25	+0.25	14.00	8	5/8-11	0.94	1.875	3.50	1.591	2.03	0.500
404UC and 405UC	11.000	12.500		0.25	+0.25	15.50	8	5/8-11	0.94	2.375	6.88	2.021		0.625
404USC and 405USC	11.000	12.500		0.25	+0.25	15.50	8	5/8-11	0.94	2.125	4.00	1.845		0.500
404TC and 405TC	11.000	12.500	6.62	0.25	+0.25	15.50	8	5/8-11	0.94	2.875	7.00	2.450	5.65	0.750
404TSC and 405TSC	11.000	12.500	6.62	0.25	+0.25	15.50	8	5/8-11	0.94	2.125	4.00	1.845	2.78	0.500
444UC and 445UC	14.000	16.000		0.25	+0.25	18.00	8	5/8-11	0.94	2.875	8.38	2.450		0.750
444USC and 445USC	14.000	16.000		0.25	+0.25	18.00	8	5/8-11	0.94	2.125	4.00	1.845		0.500
444TC and 445TC	14.000	16.000	7.50	0.25	+0.25'	18.00	8	5/8-11	0.94	3.375	8.25	2.880	6.91	0.875
444TSC and 445TSC	14.000	16.000	7.50	0.25	+0.25	18.00	8	5/8-11	0.94	2.375	4.50	2.021	3.03	0.625
447TC and 449TC	14.000	16.000	7.50	0.25	+0.25	18.00	8	5/8-11	0.94	3.375	8.25	2.880	6.91	0.875
447TSC and 449TSC	14.000	16.000	7.50	0.25	+0.25	18.00	8	5/8-11	0.94	2.375	4.50	2.021	3.03	0.625
504UC and 505C	14.500	16.500		0.25	+0.25	18.00	4	5/8-11	0.94	2.875	8.38	2.450		0.750
504SC and 505SC	14.500	16.500		0.25	+0.25	18.00	4	5/8-11	0.94	2.125	4.00	1.845		0.500

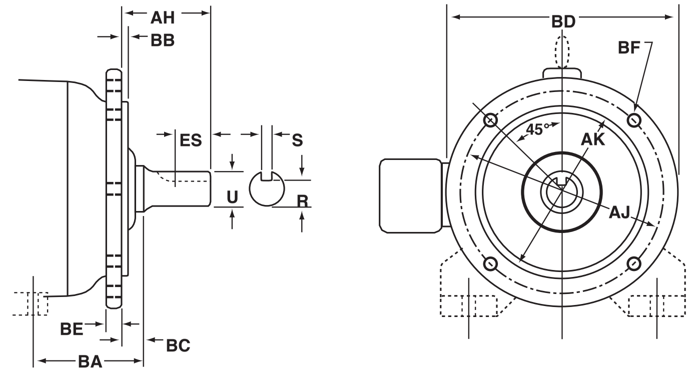
Reference: NEMA Stds. MG 1, 4.4.4.

† See Page Page 2-8 of this manual for dimensions A, D, E, 2F and H.

For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.4, 4.11 and 4.12.

NEMA FRAME DIMENSIONS—TYPE D FLANGE-MOUNTING FOOT OR FOOTLESS AC MOTORS

DIMENSIONS IN INCHES



Frame designations†	AJ	AK	BA	BB min	BC	BD max	BE nom	BF hole Number	BF hole Size	BF hole Recommended bolt length	U	AH	Keyseat R	Keyseat ES min	Keyseat S
143TD and 145TD	10.00	9.000	2.75	0.25	0.00	11.00	0.50	4	0.53	1.25	0.8750	2.25	0.771	1.41	0.188
182D and 184D	10.00	9.000		0.25	0.00	11.00	0.50	4	0.53	1.25	0.8750	2.25	0.771		0.188
182TD and 184TD	10.00	9.000	3.50	0.25	0.00	11.00	0.50	4	0.53	1.25	1.1250	2.75	0.986	1.78	0.250
213D and 215D	10.00	9.000		0.25	0.00	11.00	0.50	4	0.53	1.25	1.1250	3.00	0.986		0.250
213TD and 215TD	10.00	9.000	4.25	0.25	0.00	11.00	0.50	4	0.53	1.25	1.3750	3.38	1.201	2.41	0.312
254UD and 256UD	12.50	11.000		0.25	0.00	14.00	0.75	4	0.81	2.00	1.3750	3.75	1.201		0.312
254TD and 256TD	12.50	11.000	4.75	0.25	0.00	14.00	0.75	4	0.81	2.00	1.625	4.00	1.416	2.91	0.375
284UD and 286UD	12.50	11.000		0.25	0.00	14.00	0.75	4	0.81	2.00	1.625	4.88	1.416		0.375
284TD and 286TD	12.50	11.000	4.75	0.25	0.00	14.00	0.75	4	0.81	2.00	1.875	4.62	1.591	3.28	0.500
284TSD and 286TSD	12.50	11.000	4.75	0.25	0.00	14.00	0.75	4	0.81	2.00	1.625	3.25	1.416	1.91	0.375
324UD and 326UD	16.00	14.000		0.25	0.00	18.00	0.75	4	0.81	2.00	1.875	5.62	1.591		0.500
324SD and 326SD	16.00	14.000		0.25	0.00	18.00	0.75	4	0.81	2.00	1.625	3.25	1.416		0.375
324TD and 326TD	16.00	14.000	5.25	0.25	0.00	18.00	0.75	4	0.81	2.00	2.125	5.25	1.845	3.91	0.500
324TSD and 326TSD	16.00	14.000	5.25	0.25	0.00	18.00	0.75	4	0.81	2.00	1.875	3.75	1.591	2.03	0.500
364UD and 365UD	16.00	14.000		0.25	0.00	18.00	0.75	4	0.81	2.00	2.125	6.38	1.845		0.500
364USD and 365USD	16.00	14.000		0.25	0.00	18.00	0.75	4	0.81	2.00	1.875	3.75	1.591		0.500

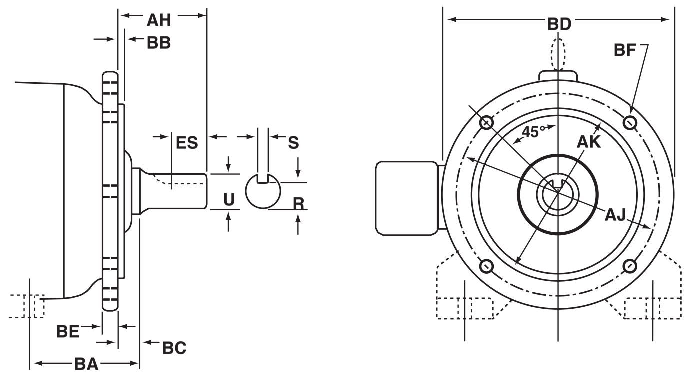
Reference: NEMA Stds. MG 1, 4.4.6.

†See Page Page 2-8 of this manual for dimensions A, D, E, 2F and H.

For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.6, 4.11 and 4.12.

NEMA FRAME DIMENSIONS—TYPE D FLANGE-MOUNTING FOOT OR FOOTLESS AC MOTORS—CONTINUED

DIMENSIONS IN INCHES



Frame designations†	AJ	AK	BA	BB min	BC	BD max	BE nom	BF hole			U	AH	Keyseat		
								Number	Size	Recommended bolt length			R	ES min	S
364TD and 365TD	16.00	14.000	5.88	0.25	0.00	18.00	0.75	4	0.81	2.00	2.375	5.88	2.021	4.28	0.625
364TSD and 365TSD	16.00	14.000	5.88	0.25	0.00	18.00	0.75	4	0.81	2.00	1.875	3.75	1.591	2.03	0.500
404UD and 405UD	20.00	18.000		0.25	0.00	22.00	1.00	8	0.81	2.25	2.375	7.12	2.021		0.625
404USD and 405USD	20.00	18.000		0.25	0.00	22.00	1.00	8	0.81	2.25	2.125	4.25	1.845		0.500
404TD and 405TD	20.00	18.000	6.62	0.25	0.00	22.00	1.00	8	0.81	2.25	2.875	7.25	2.450	5.65	0.750
404TSD and 405TSD	20.00	18.000	6.62	0.25	0.00	22.00	1.00	8	0.81	2.25	2.125	4.25	1.845	2.78	0.500
444UD and 445UD	20.00	18.000		0.25	0.00	22.00	1.00	8	0.81	2.25	2.875	8.62	2.450		0.750
444USD and 445USD	20.00	18.000		0.25	0.00	22.00	1.00	8	0.81	2.25	2.125	4.25	1.845		0.500
444TD and 445TD	20.00	18.000	7.50	0.25	0.00	22.00	1.00	8	0.81	2.25	3.375	8.50	2.880	6.91	0.875
444TSD and 445TSD	20.00	18.000	7.50	0.25	0.00	22.00	1.00	8	0.81	2.25	2.375	4.75	2.021	3.03	0.625
447TD and 449TD	20.00	18.000	7.50	0.25	0.00	22.00	1.00	8	0.81	2.25	3.375	8.50	2.880	6.91	0.875
447TSD and 449TSD	20.00	18.000	7.50	0.25	0.00	22.00	1.00	8	0.81	2.25	2.375	4.75	2.021	3.03	0.625
504UD and 505D	22.00	18.000		0.25	0.00	25.00		8	0.81		2.875	8.62	2.450		0.750
504SD and 505SD	22.00	18.000		0.25	0.00	25.00		8	0.81		2.125	4.25	1.845		0.500

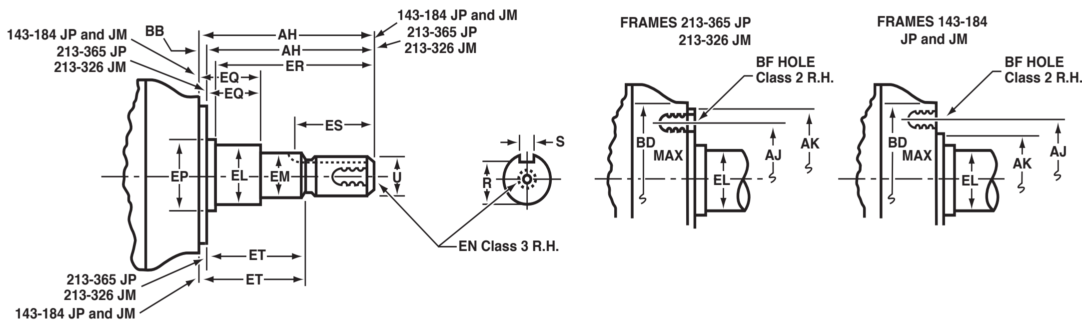
Reference: NEMA Stds. MG 1, 4.4.6.

†See Page Page 2-8 of this manual for dimensions A, D, E, 2F and H.

For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.6, 4.11 and 4.12.

NEMA FRAME DIMENSIONS—TYPE JM FACE-MOUNTING, CLOSED-COUPLED, AC PUMP MOTORS

DIMENSIONS IN INCHES



Frame designations	U	AH†	AJ	AK	BB	BD max	BF Number	BF Tap size	BF Bolt penetration allowance
143JM and 145JM	0.8745 0.8740	4.281 4.219	5.875	4.500 4.497	0.156 0.125	6.62	4	3/8-16	0.56
182JM and 184JM	0.8745 0.8740	4.281 4.219	5.875	4.500 4.497	0.156 0.125	6.62	4	3/8-16	0.56
213JM and 215JM	0.8745 0.8740	4.281 4.219	7.250	8.500 8.497	0.312 0.250	9.00	4	1/2-13	0.75
254JM and 256JM	1.2495 1.2490	5.281 5.219	7.250	8.500 8.497	0.312 0.250	10.00	4	1/2-13	0.75
284JM and 286JM	1.2495 1.2490	5.281 5.219	11.000	12.500 12.495	0.312 0.250	14.00	4	5/8-11	0.94
324JM and 326JM	1.2495 1.2490	5.281 5.219	11.000	12.500 12.495	0.312 0.250	14.00	4	5/8-11	0.94

Frame designations	EL	EM	EN Tap size	EN Tap drill depth max	EN Bolt penetration allowance	EP min	EQ†	ER min	Keyseat R	Keyseat ES min	Keyseat S	ET†
143JM and 145JM	1.156 1.154	1.0000 0.9995	3/8-16	1.12	0.75	1.156	0.640 0.610	4.25	0.771-0.756	1.65	0.190-0.188	2.890 2.860
182JM and 184JM	1.250 1.248	1.0000 0.9995	3/8-16	1.12	0.75	1.250	0.640 0.610	4.25	0.771-0.756	1.65	0.190-0.188	2.890 2.860
213JM and 215JM	1.250 1.248	1.0000 0.9995	3/8-16	1.12	0.75	1.750	0.640 0.610	4.25	0.771-0.756	1.65	0.190-0.188	2.890 2.860
254JM and 256JM	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	1.750	0.640 0.610	5.25	1.112-1.097	2.53	0.252-0.250	3.015 2.985
284JM and 286JM	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	2.125	0.645 0.605	5.25	1.112-1.097	2.53	0.252-0.250	3.020 2.980
324JM and 326JM	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	2.125	0.645 0.605	5.25	1.112-1.097	2.53	0.252-0.250	3.020 2.980

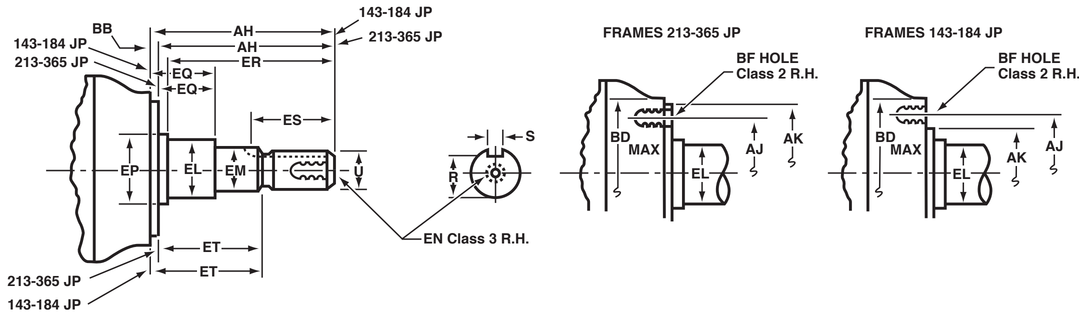
Reference: NEMA Stds. MG 1, 18.250.

†AH, EQ, and ET dimensions measured with the shaft pulled by hand away from the motor to the limit of end play.

For tolerances on face runout, permissible eccentricity of mounting rabbet and permissible shaft runout, see NEMA Stds. MG 1, 18.250, Tables 1 and 2.

NEMA FRAME DIMENSIONS—TYPE JP FACE-MOUNTING, CLOSED-COUPLED, AC PUMP MOTORS

DIMENSIONS IN INCHES



Frame designations	U	AH†	AJ	AK	BB	BD max	BF Number	BF Tap size	BF Bolt penetration allowance
143JP and 145JP	0.8745 0.8740	7.343 7.281	5.875	4.500 4.497	0.156 0.125	6.62	4	3/8-16	0.56
182JP and 184JP	0.8745 0.8740	7.343 7.281	5.875	4.500 4.497	0.156 0.125	6.62	4	3/8-16	0.56
213JP and 215JP	1.2495 1.2490	8.156 8.094	7.250	8.500 8.497	0.312 0.250	9.00	4	1/2-13	0.75
254JP and 256JP	1.2495 1.2490	8.156 8.094	7.250	8.500 8.497	0.312 0.250	10.00	4	1/2-13	0.75
284JP and 286JP	1.2495 1.2490	8.156 8.094	11.000	12.500 12.495	0.312 0.250	14.00	4	5/8-11	0.94
324JP and 326JP	1.2495 1.2490	8.156 8.094	11.000	12.500 12.495	0.312 0.250	14.00	4	5/8-11	0.94
364JP and 365JP	1.6245 1.6240	8.156 8.094	11.000	12.500 12.495	0.312 0.250	14.00	4	5/8-11	0.94

Frame designations	EL	EM	EN Tap size	EN Tap drill depth max	EN Bolt penetration allowance	EP min	EQ†	ER min	Keyseat R	Keyseat ES min	Keyseat S	ET†
143JP and 145JP	1.156 1.154	1.0000 0.9995	3/8-16	1.12	0.75	1.156	1.578 1.548	7.312	0.771-0.756	1.65	0.190-0.188	5.952 5.922
182JP and 184JP	1.250 1.248	1.0000 0.9995	3/8-16	1.12	0.75	1.250	1.578 1.548	7.312	0.771-0.756	1.65	0.190-0.188	5.952 5.922
213JP and 215JP	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	1.750	2.390 2.360	8.125	1.112-1.097	2.53	0.252-0.250	5.890 5.860
254JP and 256JP	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	1.750	2.390 2.360	8.125	1.112-1.097	2.53	0.252-0.250	5.890 5.860
284JP and 286JP	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	2.125	2.390 2.360	8.125	1.112-1.097	2.53	0.252-0.250	5.895 5.855
324JP and 326JP	1.750 1.748	1.3750 1.3745	1/2-13	1.50	1.00	2.125	2.395 2.355	8.125	1.112-1.097	2.53	0.252-0.250	5.895 5.855
364JP and 365JP	2.125 2.123	1.7500 1.7495	1/2-13	1.50	1.00	2.500	2.395 2.355	8.125	1.416-1.401	2.53	0.377-0.375	5.895 5.855

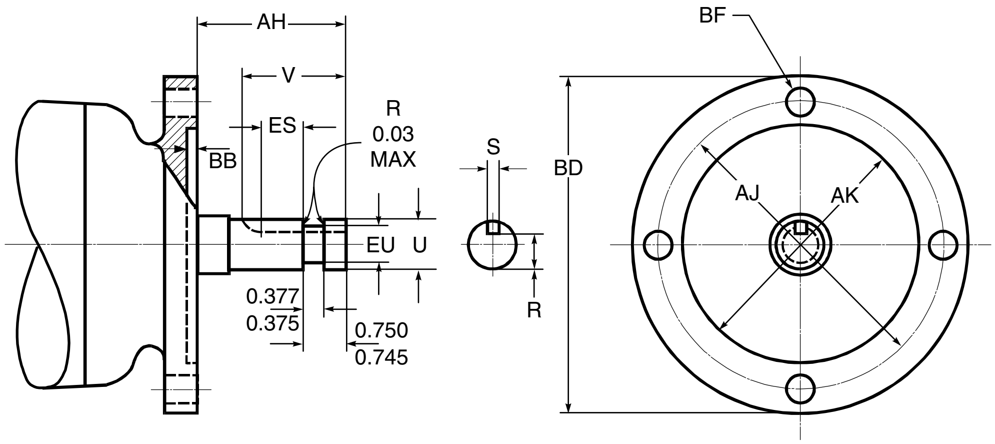
Reference: NEMA Stds. MG 1, 18.250.

†AH, EQ, and ET dimensions measured with the shaft pulled by hand away from the motor to the limit of end play.

For tolerances on face runout, permissible eccentricity of mounting rabbet and permissible shaft runout, see NEMA Stds. MG 1, 18.250, Tables 1 and 2.

NEMA FRAME DIMENSIONS—TYPE VP MEDIUM AC MOTORS FOR VERTICAL TURBINE PUMP APPLICATIONS

DIMENSIONS IN INCHES



Frame designations*	AJ**	AK	BB min	BD max	BF clearance hole	
					Number	Size
143VP and 145VP	9.125	8.250	0.19	10.00	4	0.44
182VP and 184VP	9.125	8.250	0.19	10.00	4	0.44
213VP and 215VP	9.125	8.250	0.19	10.00	4	0.44
254VP and 256VP	9.125	8.250	0.19	10.00	4	0.44
284VP and 286VP	9.125	8.250	0.19	10.00	4	0.44
324VP and 326VP	14.750	13.500	0.25	16.50	4	0.69
364VP and 365VP	14.750	13.500	0.25	16.50	4	0.69
404VP and 405VP	14.750	13.500	0.25	16.50	4	0.69
444VP and 445VP	14.750	13.500	0.25	16.50	4	0.69

Frame designations**	U	V min	AH***	EU	Keyseat		
					R	ES min	S
143VP and 145VP	0.8750	2.75	2.75	0.6875	0.771 - 0.756	1.28	0.190 - 0.188
182VP and 184VP	1.1250	2.75	2.75	0.8750	0.986 - 0.971	1.28	0.252 - 0.250
213VP and 215VP	1.1250	2.75	2.75	0.8750	0.986 - 0.971	1.28	0.252 - 0.250
254VP and 256VP	1.1250	2.75	2.75	0.8750	0.986 - 0.971	1.28	0.252 - 0.250
284VP and 286VP	1.1250	2.75	2.75	0.8750	0.986 - 0.971	1.28	0.252 - 0.250
324VP and 326VP	1.625	4.50	4.50	1.2500	1.416 - 1.401	3.03	0.377 - 0.375
364VP and 365VP	1.625	4.50	4.50	1.2500	1.416 - 1.401	3.03	0.377 - 0.375
404VP and 405VP	1.625	4.50	4.50	1.2500	1.416 - 1.401	3.03	0.377 - 0.375
444VP and 445VP	2.125	4.50	4.50	1.7500	1.416 - 1.401	3.03	0.502 - 0.500

Reference: NEMA Stds. MG 1, 18.237.

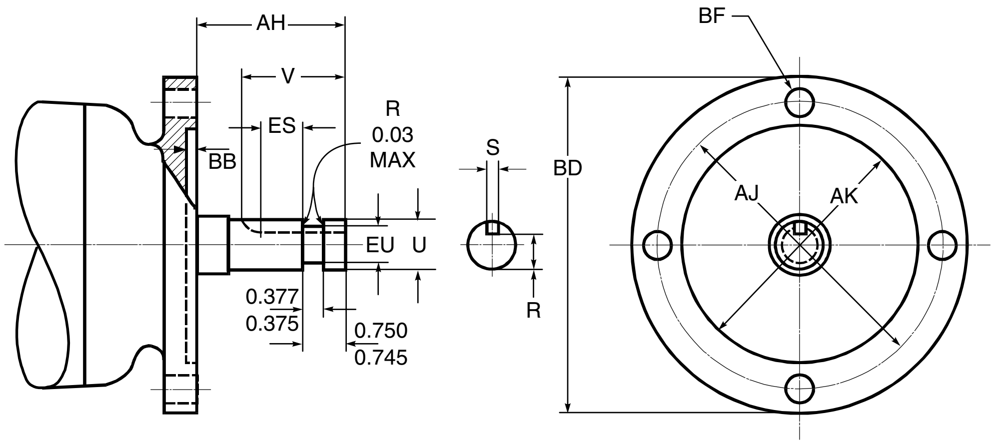
* The assignment of horsepower and speed ratings to these frames shall be in accordance with NEMA Stds. MG 1, Part 13, except for the inclusion of the suffix letters VP in place of the suffix letters T and TS.

** AJ dimension—centerline of bolt holes shall be within 0.025 inch of true location. True location is defined as angular and diametrical location with reference to the centerline of AK dimension.

*** The tolerance on the AH dimension shall be ± 0.06. inch. Dimension AH shall be measured with motor in vertical position, shaft down.

NEMA FRAME DIMENSIONS—TYPE LP SOLID SHAFT DIRECT-CONNECTED, CHEMICAL PROCESS IN-LINE PUMP MOTORS

DIMENSIONS IN INCHES



Frame designations	AJ*	AK	BB min	BD max	BF clearance hole		U
					Number	Size	
143LP and 145LP	9.125	8.253 - 8.250	0.19	10.00	4	0.44	1.1250 - 1.1245
182LP and 184LP	9.125	8.253 - 8.250	0.19	10.00	4	0.44	1.1250 - 1.1245
213LP and 215LP	9.125	8.253 - 8.250	0.19	10.00	4	0.44	1.6250 - 1.6245
254LP and 256LP	9.125	8.253 - 8.250	0.19	10.00	4	0.44	1.6250 - 1.6245
284LP and 286LP	9.125	8.253 - 8.250	0.19	10.00	4	0.44	2.1250 - 2.1240
284LPH and 286LPH	14.750	13.505 - 13.500	0.25	16.50	4	0.69	2.1250 - 2.1240
324LP and 326LP	14.750	13.505 - 13.500	0.25	16.50	4	0.69	2.1250 - 2.1240
364LP and 365LP	14.750	13.505 - 13.500	0.25	16.50	4	0.69	2.1250 - 2.1240
404LP and 405LP	14.750	13.505 - 13.500	0.25	16.50	4	0.69	2.1250 - 2.1240
444LP and 445LP	14.750	13.505 - 13.500	0.25	16.50	4	0.69	2.1250 - 2.1240

Frame designations	V in	AH**	EP min	EU	Keyseat		
					R	ES min	S
143LP and 145LP	2.75	2.781 - 2.719	1.156	0.875 - 0.870	0.986 - 0.971	1.28	0.252 - 0.250
182LP and 184LP	2.75	2.781 - 2.719	1.156	0.875 - 0.870	0.986 - 0.971	1.28	0.252 - 0.250
213LP and 215LP	2.75	2.781 - 2.719	1.750	1.250 - 1.245	1.416 - 1.401	1.28	0.377 - 0.375
254LP and 256LP	2.75	2.781 - 2.719	1.750	1.250 - 1.245	1.416 - 1.401	1.28	0.377 - 0.375
284LP and 286LP	4	4.531 - 4.469	2.250	1.750 - 1.745	1.845 - 1.830	3.03	0.502 - 0.500
284LPH and 286LPH	4	4.531 - 4.469	2.250	1.750 - 1.745	1.845 - 1.830	3.03	0.502 - 0.500
324LP and 326LP	4	4.531 - 4.469	2.250	1.750 - 1.745	1.845 - 1.830	3.03	0.502 - 0.500
364LP and 365LP	4	4.531 - 4.469	2.250	1.750 - 1.745	1.845 - 1.830	3.03	0.502 - 0.500
404LP and 405LP	4	4.531 - 4.469	2.250	1.750 - 1.745	1.845 - 1.830	3.03	0.502 - 0.500
444LP and 445LP	4	4.531 - 4.469	2.250	1.750 - 1.745	1.845 - 1.830	3.03	0.502 - 0.500

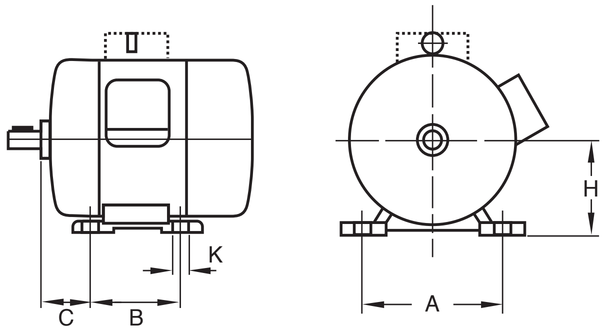
Reference: NEMA Stds. MG 1, 18.251.

* AJ centerline of bolt holes shall be within 0.025 inch of true location for all frames. True location is defined as angular and diametrical location with reference to the centerline of AK.

** Dimension measured with motor in vertical position shaft down.

IEC MOUNTING DIMENSIONS—FOOT-MOUNTED AC AND DC MACHINES

DIMENSIONS IN INCHES

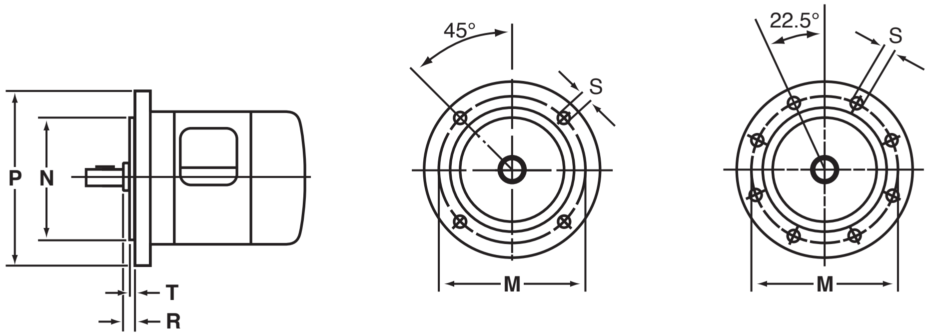


Frame number	H	A	B	C	K	Bolt or screw
56M	2.20	3.55	2.80	1.40	0.23	M5
63M	2.48	3.95	3.15	1.55	0.28	M6
71M	2.79	4.40	3.55	1.75	0.28	M6
80M	3.14	4.90	3.95	1.95	0.40	M8
90S	3.54	5.50	3.95	2.20	0.40	M8
90L	3.54	5.50	4.90	2.20	0.40	M8
100S	3.93	6.30	4.40	2.50	0.48	M10
100L	3.93	6.30	5.50	2.50	0.48	M10
112S	4.40	7.50	4.50	2.75	0.48	M10
112M	4.40	7.50	5.50	2.75	0.48	M10
132S	5.19	8.50	5.50	3.50	0.48	M10
132M	5.19	8.50	7.00	3.50	0.48	M10
160S	6.29	10.00	7.00	4.25	0.58	M12
160M	6.29	10.00	8.25	4.25	0.58	M12
160L	6.29	10.00	10.00	4.25	0.58	M12
180S	7.08	11.00	8.00	4.75	0.58	M12
180M	7.08	11.00	9.50	4.75	0.58	M12
180L	7.08	11.00	11.00	4.75	0.58	M12
200S	7.87	12.50	9.00	5.25	0.73	M16
200M	7.87	12.50	10.50	5.25	0.73	M16
200L	7.87	12.50	12.00	5.25	0.73	M16
225S	8.85	14.00	11.25	5.85	0.73	M16
225M	8.85	14.00	12.25	5.85	0.73	M16
250S	9.84	16.00	12.25	6.60	0.95	M20
250M	9.84	16.00	13.75	6.60	0.95	M20
280S	11.02	18.00	14.50	7.50	0.95	M20
280M	11.02	18.00	16.50	7.50	0.95	M20
315S	12.40	20.00	16.00	8.50	1.11	M24
315M	12.40	20.00	18.00	8.50	1.11	M24
355S	13.97	24.00	19.70	10.00	1.11	M24
355M	13.97	24.00	22.05	10.00	1.11	M24
355L	13.97	24.00	24.80	10.00	1.11	M24
400S	15.74	27.00	22.05	11.00	1.38	M30
400M	15.74	27.00	24.80	11.00	1.38	M30
400L	15.74	27.00	27.95	11.00	1.38	M30

Reference: IEC 60072-1 Stds. Dimensions, except for bolt and screw sizes, are shown in inches (rounded off). Bolt and screw sizes are shown in millimeters. For tolerances on dimensions, see IEC Stds. 60072-1, 6.1, Foot-Mounted Machines, Table 1. (Note: Data in IEC tables is shown in millimeters.)

IEC FLANGE-MOUNTED AC AND DC MACHINES–DIMENSIONS FOR FLANGES

DIMENSIONS IN INCHES



Flange number (FF-FT)[1]	M	N	P[2]	R	Number of holes	S Free holes (FF)	Tapped holes (FT)[3] thread	T max
55	2.165	1.575	2.75	0	4	0.23	M5	0.09
65	2.560	1.969	3.14	0	4	0.23	M5	0.09
75	2.955	2.362	3.54	0	4	0.23	M5	0.09
85	3.345	2.756	4.13	0	4	0.28	M6	0.09
100	3.935	3.150	4.72	0	4	0.28	M6	0.11
115	4.530	3.740	5.51	0	4	0.40	M8	0.11
130	5.120	4.331	6.29	0	4	0.40	M8	0.13
165	6.495	5.118	7.87	0	4	0.48	M10	0.13
215	8.465	7.087	9.84	0	4	0.58	M12	0.15
265	10.435	9.055	11.81	0	4	0.58	M12	0.15
300	11.810	9.843	13.77	0	4	0.73	M16	0.19
350	13.780	11.811	15.74	0	4	0.73	M16	0.19
400	15.750	13.780	17.71	0	8	0.73	M16	0.19
500	19.685	17.717	21.65	0	8	0.73	M16	0.19
600	23.620	21.654	25.98	0	8	0.95	M20	0.23
740	29.135	26.772	31.49	0	8	0.95	M20	0.23
940	37.010	34.646	39.37	0	8	1.11	M24	0.23
1080	42.520	39.370	45.27	0	8	1.11	M24	0.23

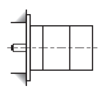
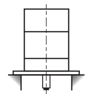
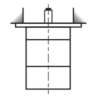
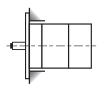
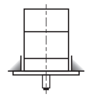
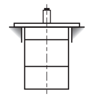
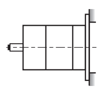
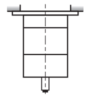
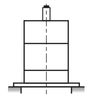
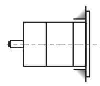
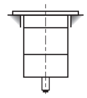
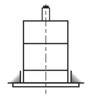
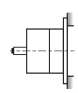
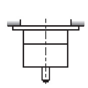
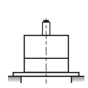
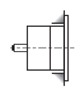
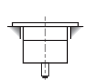
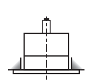
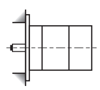
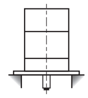
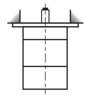
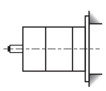
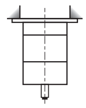
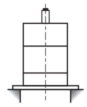
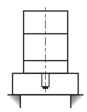
[1] This table does not apply to FI flange.
[2] The external outline of mounting flanges up to and including FF300 and FT300 may be other than circular. Dimension P may deviate from that given in the table only on the minus side.
[3] For FT flange-mounted machines, it is recommended that the free holes in the mounting part should be as shown in Column S for the corresponding size of FF flange.

DESIGNATION OF FLANGE-MOUNTED MACHINES
FF flange—Flange with free holes (clearance holes).
FT flange—Flange with tapped holes and with diameter N smaller than the diameter M.
FI flange—Flange with tapped holes and with diameter N greater than the diameter M.

Reference: IEC 60072-1 Stds. Dimensions, except for thread sizes of tapped holes, are shown in inches (rounded off). Thread sizes of tapped holes are shown in millimeters. For tolerances on dimensions, see IEC Stds. 60072-1, 6.2, Flange-Mounted Machines, Table 3. (Note: Data in IEC tables is shown in millimeters.)

IEC FLANGE-MOUNTED MACHINES WITH ENSHIELD BEARING(S) ONLY WITH FLANGE PART OF AN ENDSHIELD

SIGNIFICANCE OF SECOND AND THIRD NUMERALS FOR FIRST NUMERAL 3

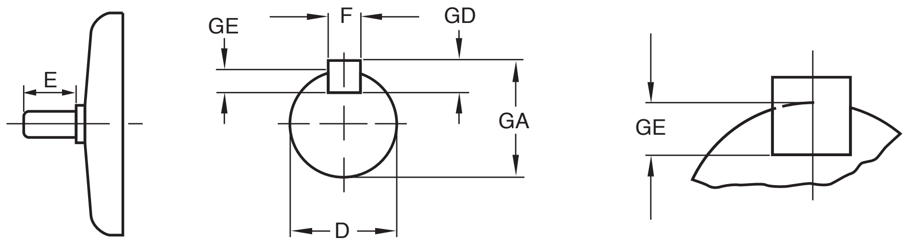
Machine construction				Second numeral	Designation and sketch						
					Third numeral						
Number of bearings	Flange position	Access to back of flange	Face of flange faces toward		0 (shaft horizontal)	1 (D-end down)	2	3 (D-up down)	4	5 to 8 (not allocated)	9
2	D-end	Yes	D-end	0	IM 3001 	IM 3011 	Suitable for operation in accordance with third numerals 0 and 1	IM 3031 	Suitable for operation in accordance with third numerals 0, 1 and 3		Not covered by third numerals 0 to 4–inclination of shaft not specified
2	D-end	Yes	N-end	1	IM 3101 	IM 3111 		IM 3131 			
2	N-end	Yes	N-end	2	IM 3201 	IM 3211 		IM 3231 			
2	N-end	Yes	D-end	3	IM 3301 	IM 3311 		IM 3331 			
1	N-end	Yes	N-end	4	IM 3401 	IM 3411 		IM 3431 			
1	N-end	Yes	D-end	5	IM 3501 	IM 3511 		IM 3531 			
2	D-end	No	D-end	6	IM 3601 	IM 3611 		IM 3631 			
2	N-end	No	N-end	7	IM 3701 	IM 3711 		IM 3731 			
2	D-end skirt part of endshield[1]	Yes	D-end	8		IM 3811 					

[1] Second numeral 8 is the same as second numeral 0 except for the skirt.

Reference: IEC Std. 60034-7, Table 7.

IEC SHAFT EXTENSION, KEY AND KEYSEAT DIMENSIONS FOR CONTINUOUS DUTY AC MOTORS

DIMENSIONS IN INCHES



Frame	D		E	Key		Keyseat		GA
	2 pole	4, 6, 8 pole		F	GD	F	GE	
56M	0.354	0.354	0.79	0.118	0.118	0.118	0.071	0.401
63M	0.433	0.433	0.91	0.157	0.157	0.157	0.099	0.492
71M	0.551	0.551	1.18	0.196	0.196	0.196	0.119	0.629
80M	0.748	0.748	1.57	0.263	0.236	0.236	0.138	0.846
90S	0.945	0.945	1.97	0.314	0.275	0.314	0.160	1.062
90L	0.945	0.945	1.97	0.314	0.275	0.314	0.160	1.062
100L	1.102	1.102	2.36	0.314	0.275	0.314	0.160	1.220
112M	1.102	1.102	2.36	0.314	0.275	0.314	0.160	1.220
132S	1.496	1.496	3.15	0.393	0.314	0.393	0.200	1.614
132M	1.496	1.496	3.15	0.393	0.314	0.393	0.200	1.614
160M	1.654	1.654	4.33	0.472	0.314	0.472	0.200	1.771
160L	1.654	1.654	4.33	0.472	0.314	0.472	0.200	1.771
180M	1.890	1.890	4.33	0.551	0.354	0.551	0.220	2.027
180L	1.890	1.890	4.33	0.551	0.354	0.551	0.220	2.027
200L	2.165	2.165	4.33	0.629	0.393	0.629	0.240	2.322
225S	2.165	—	4.33	0.629	0.393	0.629	0.240	2.322
225M	2.165	—	4.33	0.629	0.393	0.629	0.240	2.322
225S	—	2.362	5.51	0.708	0.433	0.708	0.280	2.519
225M	—	2.362	5.51	0.708	0.433	0.708	0.280	2.519
250M	2.362	—	5.51	0.708	0.433	0.708	0.280	2.519
250M	—	2.559	5.51	0.708	0.433	0.708	0.280	2.716
280S	2.559	—	5.51	0.708	0.433	0.708	0.280	2.716
280M	2.559	—	5.51	0.708	0.433	0.708	0.280	2.716
280S	—	2.953	5.51	0.787	0.472	0.787	0.300	3.129
280M	—	2.953	5.51	0.787	0.472	0.787	0.300	3.129
315S	2.559	—	5.51	0.708	0.433	0.708	0.275	2.716
315M	2.559	—	5.51	0.708	0.433	0.708	0.275	2.716
315S	—	3.150	6.69	0.866	0.551	0.866	0.354	3.346
315M	—	3.150	6.69	0.866	0.551	0.866	0.354	3.346

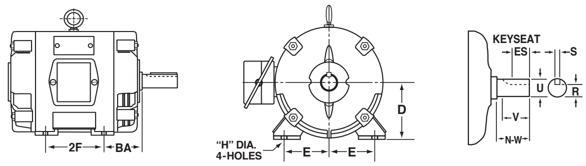
Reference: IEC Stds. 60072-1 and 60034-7. All dimensions are rounded off. For tolerances on dimensions, see IEC Stds. 60072-1, 7, Shaft Extension, Keys and Keyways Dimensions, Table 4. Alternative shaft sizes are available; check with the manufacturer. (Note: Data in IEC tables is shown in millimeters.)

2.4 DIMENSIONS FOR AC MACHINES—MILLIMETERS

NEMA FRAME DIMENSIONS—FOOT-MOUNTED AC MACHINES

DIMENSIONS IN MILLIMETERS

(Note: Above-NEMA frame dimensions are manufacturer-specific.)



Frame designations	A max	D	E	2F	BA	H*	U	N-W	V min	Keyseat R	Keyseat ES min	Keyseat S	AA min†
42		66	44.5	43	52	7.5	9.52	28		8.3		Flat	
48		76	54.0	70	64	9.0	12.70	38		11.5		Flat	
48H		76	54.0	121	64	9.0	12.70	38		11.5		Flat	
56		88	62.0	76	70	9.0	15.87	48		13.1	36	4.80	
56H		88	62.0	127	70	9.0	15.87	48		13.1	36	4.80	
66		104	74.5	127	79	11	19.05	57		16.3	49	4.80	
143	177	88	70.0	102	57	9	19.05	51	45	16.3	36	4.80	3/4
143T	177	88	70.0	102	57	9	22.22	57	51	19.5	36	4.80	3/4
145	177	88	70.0	127	57	9	19.05	51	45	16.3	36	4.80	3/4
145T	177	88	70.0	127	57	9	22.22	57	51	19.5	36	4.80	3/4
182	228	114	95.5	114	70	11	22.22	57	51	19.5	36	4.80	3/4
182T	228	114	95.5	114	70	11	28.57	70	64	25.0	46	6.35	3/4
184	228	114	95.5	140	70	11	22.22	57	51	19.5	36	4.80	3/4
184T	228	114	95.5	140	70	11	28.57	70	64	25.0	46	6.35	3/4
203		127	101.5	140	79	11	19.05	57	51	16.3	39	4.80	
204		127	101.5	165	79	11	19.05	57	51	16.3	39	4.80	
213	266	133	108.0	140	89	11	28.57	76	70	25.0	52	6.35	3/4
213T	266	133	108.0	140	89	11	34.92	86	80	30.5	62	7.95	1
215	266	133	108.0	178	89	11	28.57	76	70	25.0	52	6.35	3/4
215T	266	133	108.0	178	89	11	34.92	86	80	30.5	62	7.95	1
224		139	114.5	171	89	11	25.40	76	70	21.8	52	6.35	
225		139	114.5	191	89	11	25.40	76	70	21.8	52	6.35	
254		158	127.0	210	108	14	28.57	86	80	25.0	52	6.35	
254U	317	158	127.0	210	108	14	34.92	95	89	30.5	71	7.95	1
254T	317	158	127.0	210	108	14	41.27	102	96	35.9	74	9.55	1-1/4
256U	317	158	127.0	254	108	14	34.92	95	89	30.5	71	7.95	1
256T	317	158	127.0	254	108	14	41.27	102	96	35.9	74	9.55	1-1/4
284		177	139.5	241	121	14	31.75	95	89	28.2	52	6.35	
284U	355	177	139.5	241	121	14	41.27	124	118	35.9	97	9.55	1-1/4
284T	355	177	139.5	241	121	14	47.62	117	112	40.4	84	12.70	1-1/2
284TS	355	177	139.5	241	121	14	41.27	83	77	35.9	49	9.55	1-1/2
286U	355	177	139.5	279	121	14	41.27	124	118	35.9	97	9.55	1-1/4
286T	355	177	139.5	279	121	14	47.62	117	112	40.4	84	12.70	1-1/2
286TS	355	177	139.5	279	121	14	41.27	83	77	35.9	49	9.55	1-1/2
324		203	159.0	267	133	17	41.27	124	118	35.9	97	9.55	
324U	406	203	159.0	267	133	17	47.62	143	137	40.4	109	12.70	1-1/2
324S	406	203	159.0	267	133	17	41.27	83	77	35.9	49	9.55	1-1/2
324T	406	203	159.0	267	133	17	53.97	133	127	46.8	100	12.70	2
324TS	406	203	159.0	267	133	17	47.62	95	89	40.4	52	12.70	2
326		203	159.0	305	133	17	41.27	124	118	35.9	97	9.55	
326U	406	203	159.0	305	133	17	47.62	143	137	40.4	109	12.70	1-1/2
326S	406	203	159.0	305	133	17	41.27	83	77	35.9	49	9.55	1-1/2
326T	406	203	159.0	305	133	17	53.97	133	127	46.8	100	12.70	2
326TS	406	203	159.0	305	133	17	47.62	95	89	40.4	52	12.70	2

NEMA FRAME DIMENSIONS—FOOT-MOUNTED AC MACHINES—CONTINUED

DIMENSIONS IN MILLIMETERS

Frame designations	A max	D	E	2F	BA	H*	U	N-W	V min	Keyseat			AA min†
										R	ES min	S	
364		228	178.0	286	149	17	47.62	143	137	40.4	109	12.70	
364S		228	178.0	286	149	17	41.27	83	77	35.9	49	9.55	
364U	457	228	178.0	286	149	17	53.97	162	156	46.8	128	12.70	2
364US	457	228	178.0	286	149	17	47.62	95	89	40.4	52	12.70	2
364T	457	228	178.0	286	149	17	60.32	149	143	51.3	109	15.90	3
364TS	457	228	178.0	286	149	17	47.62	95	89	40.4	52	12.70	3
365		228	178.0	311	149	17	47.62	143	137	40.4	109	12.70	
365S		228	178.0	311	149	17	41.27	83	77	35.9	49	9.55	
365U	457	228	178.0	311	149	17	53.97	162	156	46.8	128	12.70	2
365US	457	228	178.0	311	149	17	47.62	95	89	40.4	52	12.70	2
365T	457	228	178.0	311	149	17	60.32	149	143	51.3	109	15.90	3
365TS	457	228	178.0	311	149	17	47.62	95	89	40.4	52	12.70	3
404		254	203.0	311	168	21	53.97	162	156	46.8	128	12.70	
404S		254	203.0	311	168	21	47.62	95	89	40.4	52	12.70	
404U	508	254	203.0	311	168	21	60.32	181	175	51.3	141	15.90	2
404US	508	254	203.0	311	168	21	53.97	108	102	46.8	71	12.70	2
404T	508	254	203.0	311	168	21	73.02	184	178	62.2	144	19.05	3
404TS	508	254	203.0	311	168	21	53.97	108	102	46.8	71	12.70	3
405		254	203.0	349	168	21	53.97	162	156	46.8	128	12.70	
405S		254	203.0	349	168	21	47.62	95	89	40.4	52	12.70	
405U	508	254	203.0	349	168	21	60.32	181	175	51.3	141	15.90	2
405US	508	254	203.0	349	168	21	53.97	108	102	46.8	71	12.70	2
405T	508	254	203.0	349	168	21	73.02	184	178	62.2	144	19.05	3
405TS	508	254	203.0	349	168	21	53.97	108	102	46.8	71	12.70	3
444		279	228.5	368	191	21	60.32	181	175	51.3	141	15.90	
444S		279	228.5	368	191	21	53.97	108	102	46.8	71	12.70	
444U	558	279	228.5	368	191	21	73.02	219	213	62.2	179	19.05	2-1/2
444US	558	279	228.5	368	191	21	53.97	108	102	46.8	71	12.70	2-1/2
444T	558	279	228.5	368	191	21	85.72	216	210	73.1	176	22.25	3
444TS	558	279	228.5	368	191	21	60.32	121	115	51.3	77	15.90	3
445		279	228.5	419	191	21	60.32	181	175	51.3	141	15.90	
445S		279	228.5	419	191	21	53.97	108	102	46.8	71	12.70	
445U	558	279	228.5	419	191	21	73.02	219	213	62.2	179	19.05	2-1/2
445US	558	279	228.5	419	191	21	53.97	108	102	46.8	71	12.70	2-1/2
445T	558	279	228.5	419	191	21	85.72	216	210	73.1	176	22.25	3
445TS	558	279	228.5	419	191	21	60.32	121	115	51.3	77	15.90	3
447T	558	279	228.5	508	191	21	85.72	216	210	73.1	176	22.25	3
447TS	558	279	228.5	508	191	21	60.32	121	115	51.3	77	15.90	3
449T	558	279	228.5	635	191	21	85.72	216	210	73.1	176	22.25	3
449TS	558	279	228.5	635	191	21	60.32	121	115	51.3	77	15.90	3
504U	635	317	254.0	635	216	24	73.02	219	213	62.2	185	19.05	2-1/2
504S	635	317	254.0	635	216	24	53.97	108	102	46.8	71	12.70	2-1/2
505	635	317	254.0	457	216	24	73.02	219	213	62.2	185	19.05	2-1/2
505S	635	317	254.0	457	216	24	53.97	108	102	46.8	71	12.70	2-1/2

Reference: NEMA Stds. MG 1, 4.4.1.

† Dimensions, except for AA Min., are shown in millimeters (rounded off). The AA Min. dimension is conduit size in inches. For dimensions of clearance holes, see NEMA Stds. MG 1, 6, 4.4.1.

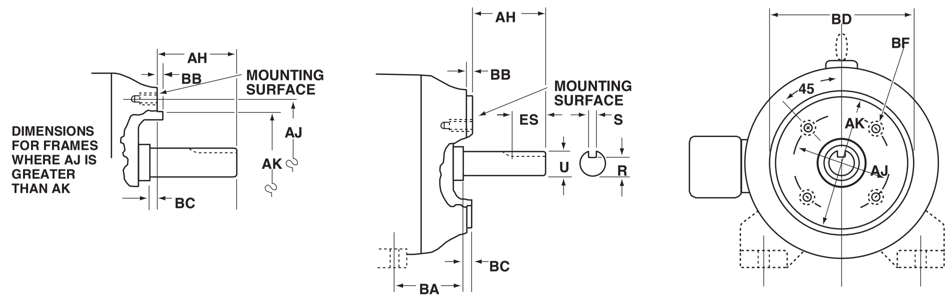
* Frames 42 to 66, inclusive: the H dimension is *Width of Slot.*

* Frames 143 to 505S, inclusive: the H dimension is *Diameter of Hole.*

(Note: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE C FACE-MOUNTING FOOT OR FOOTLESS AC MOTORS

DIMENSIONS IN MILLIMETERS



Frame designations†	AJ	AK	BA	BB min	BC	BD max	BF hole Number	BF hole Tap size*	BF hole Bolt penetration allowance	U	AH	Keyseat R	Keyseat ES min	Keyseat S
42C	95.25	76.20	52.4	4	-5	127	4	1/4-20		9.52	33	8.3		Flat
48C	95.25	76.20	64	4	-5	142	4	1/4-20		12.70	43	11.5		Flat
56C	149.25	114.30	70	4	-5	165	4	3/8-16		15.87	52	13.1	36	4.80
66C	149.25	114.30		4	-5	165	4	3/8-16		19.05	62	16.3		4.80
143TC and 145TC	149.25	114.30	70	4	+3	165	4	3/8-16	14	22.22	54	19.5	36	4.80
182C and 184C	149.25	114.30		4	+3	165	4	3/8-16	14	22.22	54	19.5		4.80
182TC and 184TC	184.15	215.90	89	7	+3	228	4	1/2-13	19	28.57	67	25.0	46	6.35
182TCH and 184TCH	149.25	114.30	89	4	+3	165	4	3/8-16	14	28.57	67	25.0	46	6.35
213C and 215C	184.15	215.90		7	+6	228	4	1/2-13	19	28.57	70	25.0		6.35
213TC and 215TC	184.15	215.90	108	7	+6	228	4	1/2-13	19	34.92	79	30.5	62	7.95
254UC and 256UC	184.15	215.90		7	+6	254	4	1/2-13	19	34.92	89	30.5		7.95
254TC and 256TC	184.15	215.90	121	7	+6	254	4	1/2-13	19	41.27	95	35.9	74	9.55
284UC and 286UC	228.60	266.70		7	+6	285	4	1/2-13	19	41.27	117	35.9		9.55
284TC and 286TC	228.60	266.70	121	7	+6	285	4	1/2-13	19	47.62	111	40.4	84	12.70
284TSC and 286TSC	228.60	266.70	121	7	+6	285	4	1/2-13	19	41.27	76	35.9	49	9.55
324UC and 326UC	279.40	317.5		7	+6	355	4	5/8-11	24	47.62	137	40.4		12.70
324SC and 326SC	279.40	317.5		7	+6	355	4	5/8-11	24	41.27	76	35.9		9.55
324TC and 326TC	279.40	317.5	133	7	+6	355	4	5/8-11	24	53.97	127	46.8	100	12.70
324TSC and 326TSC	279.40	317.5	133	7	+6	355	4	5/8-11	24	47.62	89	40.4	52	12.70
364UC and 365UC	279.40	317.5		7	+6	355	8	5/8-11	24	53.97	155	46.8		12.70

Reference: NEMA Stds. MG 1, 4.4.4.

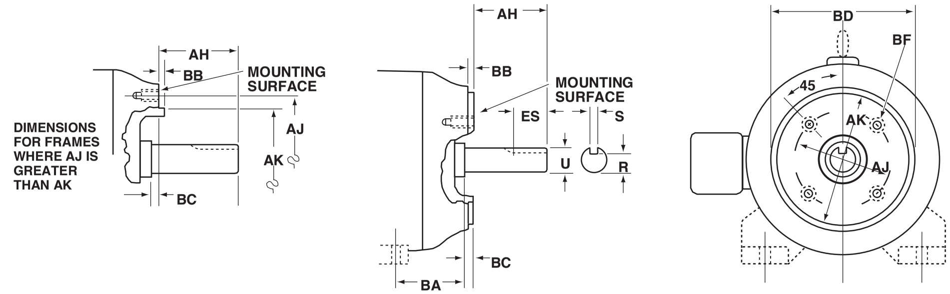
* Dimensions, except for tap sizes, are shown in millimeters (rounded off). Tap sizes are in inches.

† See Page 2-22 of this manual for dimensions A, D, E, 2F and H.

For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.4, 4.11 and 4.12. (Note: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE C FACE-MOUNTING FOOT OR FOOTLESS AC MOTORS—CONTINUED

DIMENSIONS IN MILLIMETERS



Frame designations†	AJ	AK	BA	BB min	BC	BD max	BF hole Number	BF hole Tap size*	BF hole Bolt penetration allowance	U	AH	Keyseat R	Keyseat ES min	Keyseat S
364USC and 365USC	279.40	317.5		7	+6	355	8	5/8-11	24	47.62	89	40.4		12.70
364TC and 365TC	279.40	317.5	149	7	+6	355	8	5/8-11	24	60.32	143	51.3	109	15.90
364TSC and 365TSC	279.40	317.5	149	7	+6	355	8	5/8-11	24	47.62	89	40.4	52	12.70
404UC and 405UC	279.40	317.5		7	+6	393	8	5/8-11	24	60.32	175	51.3		15.90
404USC and 405USC	279.40	317.5		7	+6	393	8	5/8-11	24	53.97	102	46.8		12.70
404TC and 405TC	279.40	317.5	168	7	+6	393	8	5/8-11	24	73.02	178	62.2	144	19.05
404TSC and 405TSC	279.40	317.5	168	7	+6	393	8	5/8-11	24	53.97	102	46.8	71	12.70
444UC and 445UC	355.60	406.4		7	+6	457	8	5/8-11	24	73.02	213	62.2		19.05
444USC and 445USC	355.60	406.4		7	+6	457	8	5/8-11	24	53.97	102	46.8		12.70
444TC and 445TC	355.60	406.4	191	7	+6	457	8	5/8-11	24	85.72	210	73.1	176	22.25
444TSC and 445TSC	355.60	406.4	191	7	+6	457	8	5/8-11	24	60.32	114	51.3	77	15.90
447TC and 449TC	355.60	406.4	191	7	+6	457	8	5/8-11	24	85.72	210	73.1	176	22.25
447TSC and 449TSC	355.60	406.4	191	7	+6	457	8	5/8-11	24	60.32	114	51.3	77	15.90
504UC and 505C	368.30	419.1		7	+6	457	4	5/8-11	24	73.02	213	62.2		19.05
504SC and 505SC	368.30	419.1		7	+6	457	4	5/8-11	24	53.97	102	46.8		12.70

Reference: NEMA Stds. MG 1, 4.4.4.

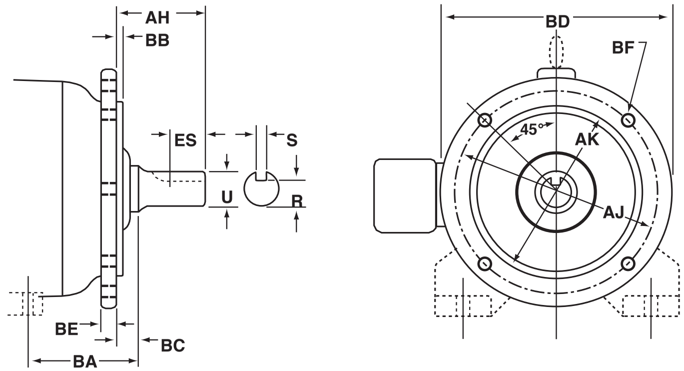
* Dimensions, except for tap sizes, are shown in millimeters (rounded off). Tap sizes are in inches.

† See Page 2-22 of this manual for dimensions A, D, E, 2F and H.

For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.4, 4.11 and 4.12. (Note: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE D FLANGE-MOUNTING FOOT OR FOOTLESS AC MOTORS

DIMENSIONS IN MILLIMETERS

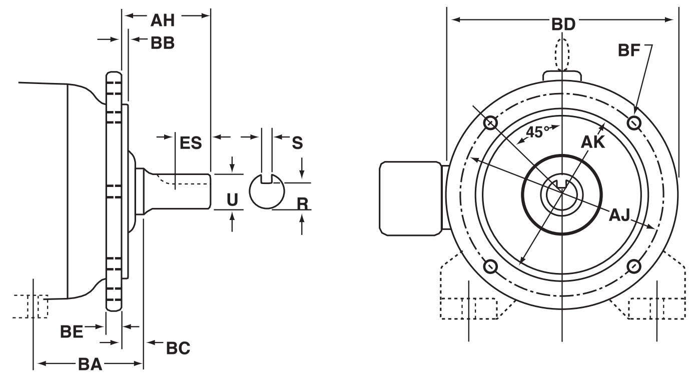


Frame designations†	AJ	AK	BA	BB min	BC	BD max	BE nom	BF hole Number	BF hole Size	BF hole Recommended bolt length	U	AH	Keyseat R	Keyseat ES min	Keyseat S
143TD and 145TD	254.0	228.60	70	6	0	279	13	4	13	32	22.22	57	19.5	36	4.80
182D and 184D	254.0	228.60		6	0	279	13	4	13	32	22.22	57	19.5		4.80
182TD and 184TD	254.0	228.60	90	6	0	279	13	4	13	32	28.57	70	25.0	46	6.35
213D and 215D	254.0	228.60		6	0	279	13	4	13	32	28.57	76	25.0		6.35
213TD and 215TD	254.0	228.60	108	6	0	279	13	4	13	32	34.92	86	30.5	62	7.95
254UD and 256UD	317.5	279.40		6	0	355	19	4	21	51	34.92	95	30.5		7.95
254TD and 256TD	317.5	279.40	121	6	0	355	19	4	21	51	41.27	102	35.9	74	9.55
284UD and 286UD	317.5	279.40		6	0	355	19	4	21	51	41.27	124	35.9		9.55
284TD and 286TD	317.5	279.40	121	6	0	355	19	4	21	51	47.62	117	40.4	84	12.70
284TSD and 286TSD	317.5	279.40	121	6	0	355	19	4	21	51	41.27	83	35.9	49	9.55
324UD and 326UD	406.5	355.6		6	0	457	19	4	21	51	47.62	143	40.4		12.70
324SD and 326SD	406.5	355.6		6	0	457	19	4	21	51	41.27	83	35.9		9.55
324TD and 326TD	406.5	355.6	133	6	0	457	19	4	21	51	53.97	133	46.8	100	12.70
324TSD and 326TSD	406.5	355.6	133	6	0	457	19	4	21	51	47.62	95	40.4	52	12.70
364UD and 365UD	406.5	355.6		6	0	457	19	4	21	51	53.97	162	46.8		12.70
364USD and 365USD	406.5	355.6		6	0	457	19	4	21	51	47.62	95	40.4		12.70

Reference: NEMA Stds. MG 1, 4.4.6.
All dimensions are rounded off.
† See Page 2-22 of this manual for dimensions A, D, E, 2F and H.
For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1-2009, Rev. 1-2010, 4.4.6, 4.11 and 4.12. (NOTE: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE D FLANGE-MOUNTING FOOT OR FOOTLESS AC MOTORS—CONTINUED

DIMENSIONS IN MILLIMETERS

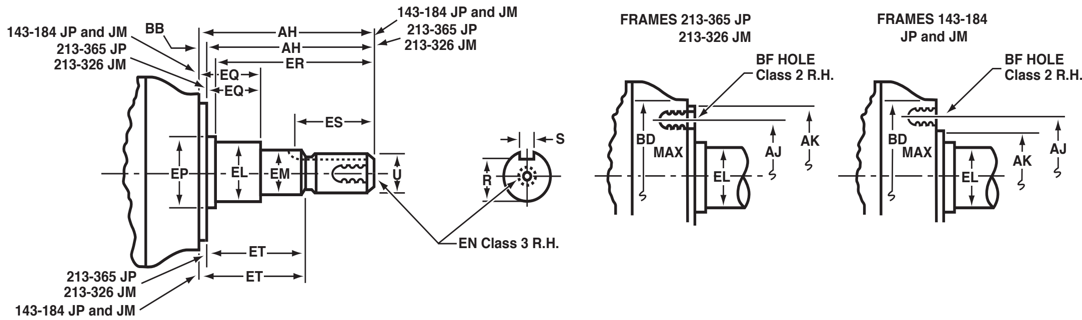


Frame designations†	AJ	AK	BA	BB min	BC	BD max	BE nom	BF hole Number	BF hole Size	BF hole Recommended bolt length	U	AH	Keyseat R	Keyseat ES min	Keyseat S
364TD and 365TD	406.5	355.6	149	6	0	457	19	4	21	51	60.32	149	51.3	109	15.90
364TSD and 365TSD	406.5	355.6	149	6	0	457	19	4	21	51	47.62	95	40.4	52	12.70
404UD and 405UD	508.0	457.2		6	0	558	25	8	21	57	60.32	181	51.3		15.90
404USD and 405USD	508.0	457.2		6	0	558	25	8	21	57	53.97	108	46.8		12.70
404TD and 405TD	508.0	457.2	168	6	0	558	25	8	21	57	73.02	184	62.2	144	19.05
404TSD and 405TSD	508.0	457.2	168	6	0	558	25	8	21	57	53.97	108	46.8	71	12.70
444UD and 445UD	508.0	457.2		6	0	558	25	8	21	57	73.02	219	62.2		19.05
444USD and 445USD	508.0	457.2		6	0	558	25	8	21	57	53.97	108	46.8		12.70
444TD and 445TD	508.0	457.2	191	6	0	558	25	8	21	57	85.72	216	73.1	176	22.25
444TSD and 445TSD	508.0	457.2	191	6	0	558	25	8	21	57	60.32	121	51.3	77	15.90
447TD and 449TD	508.0	457.2	191	6	0	558	25	8	21	57	85.72	216	73.1	176	22.25
447TSD and 449TSD	508.0	457.2	191	6	0	558	25	8	21	57	60.32	121	51.3	77	15.90
504UD and 505D	559.0	457.2		6	0	635		8	21		73.02	219	62.2		19.05
504SD and 505SD	559.0	457.2		6	0	635		8	21		53.97	108	46.8		12.70

Reference: NEMA Stds. MG 1, 4.4.6.
All dimensions are rounded off.
† See Page 2-22 of this manual for dimensions A, D, E, 2F and H.
For tolerances on dimensions, face runout and permissible eccentricity of mounting rabbet, see NEMA Stds. MG 1, 4.4.6, 4.11 and 4.12. (NOTE: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE JM FACE-MOUNTING, CLOSED-COUPLED, AC PUMP MOTORS

DIMENSIONS IN MILLIMETERS



Frame designations	U	AH†	AJ	AK	BB	BD max	BF		
							Number	Tap size	Bolt penetration allowance
143JM and 145JM	22.21	108	149.25	114.30	3.5	168	4	3/8-16	14
182JM and 184JM	22.21	108	149.25	114.30	3.5	168	4	3/8-16	14
213JM and 215JM	22.21	108	184.15	215.90	7	228	4	1/2-13	19
254JM and 256JM	31.73	134	184.15	215.90	7	254	4	1/2-13	19
284JM and 286JM	31.73	134	279.40	317.5	7	355	4	5/8-11	24
324JM and 326JM	31.73	134	279.40	317.5	7	355	4	5/8-11	24

Frame designations	EL	EM	EN			EP min	EQ†	ER min	Keyseat			ET†
			Tap size	Tap drill depth max	Bolt penetration allowance				R	ES min	S	
143JM and 145JM	29.35	25.40	3/8-16	28	19	30	16.0	108	19.5	42	4.80	73.0
182JM and 184JM	31.75	25.40	3/8-16	28	19	32	16.0	108	19.5	42	4.80	73.0
213JM and 215JM	31.75	25.40	3/8-16	28	19	45	16.0	108	19.5	42	4.80	73.0
254JM and 256JM	44.45	34.92	1/2-13	38	25	45	16.0	134	28.2	65	6.40	76.5
284JM and 286JM	44.45	34.92	1/2-13	38	25	54	16.0	134	28.2	65	6.40	76.5
324JM and 326JM	44.45	34.92	1/2-13	38	25	54	16.0	134	28.2	65	6.40	76.5

Reference: NEMA Stds. MG 1, 18.250.

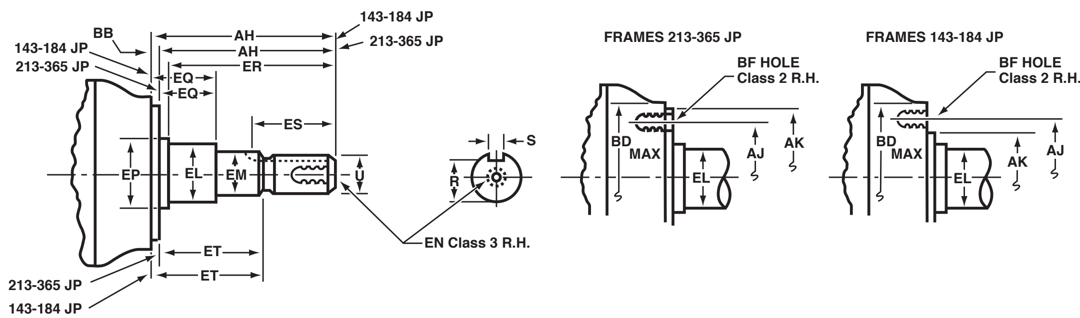
Dimensions, except for tap sizes, are shown in millimeters (rounded off). Tap sizes are in inches. For tolerances on dimensions, refer to equivalent dimension in inches on Page 2-14 of this manual.

† AH, EQ, and ET dimensions measured with the shaft pulled by hand away from the motor to the limit of end play.

For tolerances on face runout, permissible eccentricity of mounting rabbet and permissible shaft runout, see NEMA Stds. MG 1, 18.250, Table 1. (Note: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE JP FACE-MOUNTING, CLOSED-COUPLED, AC PUMP MOTORS

DIMENSIONS IN MILLIMETERS



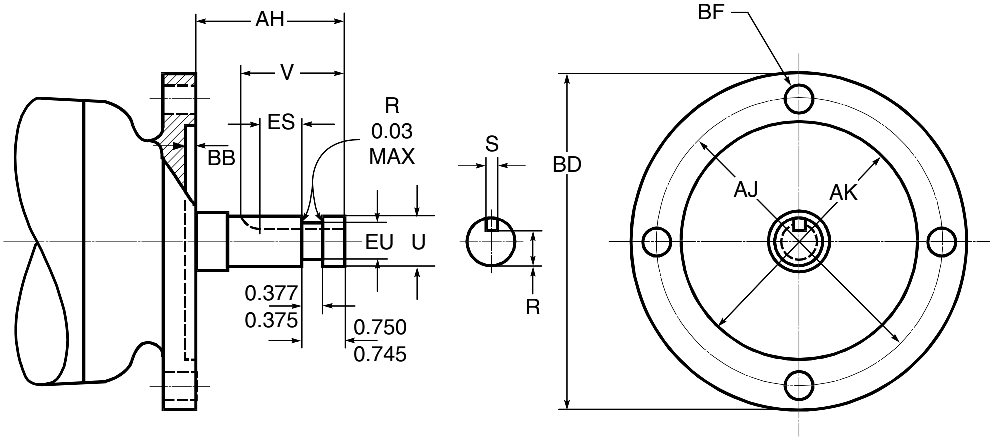
Frame designations	U	AH†	AJ	AK	BB	BD max	BF Number	BF Tap size	BF Bolt penetration allowance
143JP and 145JP	22.21	186	149.25	114.30	3.5	168	4	3/8-16	14
182JP and 184JP	22.21	186	149.25	114.30	3.5	168	4	3/8-16	14
213JP and 215JP	31.73	207	184.15	215.90	7	228	4	1/2-13	19
254JP and 256JP	31.73	207	184.15	215.90	7	254	4	1/2-13	19
284JP and 286JP	31.73	207	279.40	317.5	7	355	4	5/8-11	24
324JP and 326JP	31.73	207	279.40	317.5	7	355	4	5/8-11	24
364JP and 365JP	41.26	207	279.40	317.5	7	355	4	5/8-11	24

Frame designations	EL	EM	EN Tap size	EN Tap drill depth max	EN Bolt penetration allowance	EP min	EQ†	ER min	Keyseat R	Keyseat ES min	Keyseat S	ET†
143JP and 145JP	29.35	25.40	3/8-16	28	19	30	40.0	186	19.5	42	4.80	151.0
182JP and 184JP	31.75	25.40	3/8-16	28	19	32	40.0	186	19.5	42	4.80	151.0
213JP and 215JP	44.45	34.92	1/2-13	38	25	45	60.5	207	28.2	65	6.40	149.5
254JP and 256JP	44.45	34.92	1/2-13	38	25	45	60.5	207	28.2	65	6.40	149.5
284JP and 286JP	44.45	34.92	1/2-13	38	25	54	60.5	207	28.2	65	6.40	149.5
324JP and 326JP	44.45	34.92	1/2-13	38	25	54	60.5	207	28.2	65	6.40	149.5
364JP and 365JP	53.95	44.45	1/2-13	38	25	64	60.5	207	35.9	65	9.55	149.5

Reference: NEMA Stds. MG 1, 18.250.
Dimensions, except for tap sizes, are shown in millimeters (rounded off). Tap sizes are in inches. For tolerances on dimensions, refer to equivalent dimension in inches on Page Page 2-15 of this manual.
† AH, EQ, and ET dimensions measured with the shaft pulled by hand away from the motor to the limit of end play.
For tolerances on face runout, permissible eccentricity of mounting rabbet and permissible shaft runout, see NEMA Stds. MG 1, 18.250, Table 2. (Note: Data in NEMA tables is shown in inches.)

NEMA FRAME DIMENSIONS—TYPE VP MEDIUM AC MOTORS FOR VERTICAL TURBINE PUMP APPLICATIONS

DIMENSIONS IN MILLIMETERS



Frame designations*	AJ**	AK	BB min	BD max	BF clearance hole	
					Number	Size
143VP and 145VP	231.78	209.60	4.83	254	4	11.18
182VP and 184VP	231.78	209.60	4.83	254	4	11.18
213VP and 215VP	231.78	209.60	4.83	254	4	11.18
254VP and 256VP	231.78	209.60	4.83	254	4	11.18
284VP and 286VP	231.78	209.60	4.83	254	4	11.18
324VP and 326VP	374.65	342.90	6.35	419	4	17.53
364VP and 365VP	374.65	342.90	6.35	419	4	17.53
404VP and 405VP	374.65	342.90	6.35	419	4	17.53
444VP and 445VP	374.65	342.90	6.35	419	4	17.53

Frame designations*	U	V min	AH***	EU	Keyseat		
					R	ES min	S
143VP and 145VP	22.23	69.85	69.85	17.46	19.58 - 19.20	32.51	4.83 - 4.78
182VP and 184VP	28.58	69.85	69.85	22.23	25.05 - 24.66	32.51	6.40 - 6.35
213VP and 215VP	28.58	69.85	69.85	22.23	25.05 - 24.66	32.51	6.40 - 6.35
254VP and 256VP	28.58	69.85	69.85	22.23	25.05 - 24.66	32.51	6.40 - 6.35
284VP and 286VP	28.58	114.30	69.85	22.23	25.05 - 24.66	32.51	6.40 - 6.35
324VP and 326VP	41.28	114.30	114.30	31.75	35.97 - 35.59	76.96	9.58 - 9.53
364VP and 365VP	41.28	114.30	114.30	31.75	35.97 - 35.59	76.96	9.58 - 9.53
404VP and 405VP	41.28	114.30	114.30	31.75	35.97 - 35.59	76.96	9.58 - 9.53
444VP and 445VP	53.98	114.30	114.30	44.45	35.97 - 35.59	76.96	12.75 - 12.70

Reference: NEMA Stds. MG 1, 18.237 (Note: Data in NEMA tables is shown in inches.)

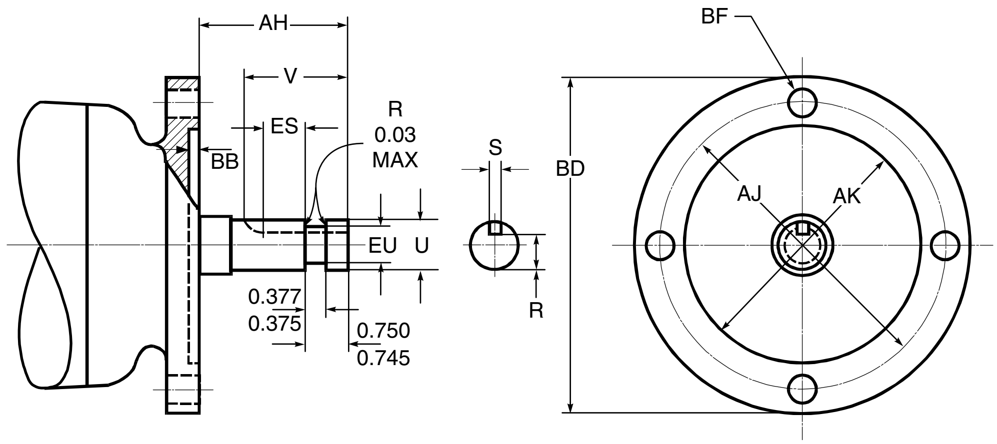
* The assignment of horsepower and speed ratings to these frames shall be in accordance with NEMA Stds. MG 1, Part 13, except for the inclusion of the suffix letters VP in place of the suffix letters T and TS.

** AJ dimension—centerline of bolt holes shall be within 0.64 mm of true location. True location is defined as angular and diametrical location with reference to the centerline of AK dimension.

*** The tolerance on the AH dimension shall be ± 0.06 inch. Dimension AH shall be measured with motor in vertical position, shaft down.

NEMA FRAME DIMENSIONS—TYPE LP SOLID SHAFT DIRECT-CONNECTED, CHEMICAL PROCESS IN-LINE PUMP MOTORS

DIMENSIONS IN MILLIMETERS



Frame designations	AJ*	AK	BB min	BD max	BF clearance hole Number	Size	U
143LP and 145LP	231.78	209.55 - 209.63	4.83	254	4	11.18	28.58 - 28.56
182LP and 184LP	231.78	209.55 - 209.63	4.83	254	4	11.18	28.58 - 28.56
213LP and 215LP	231.78	209.55 - 209.63	4.83	254	4	11.18	41.28 - 41.26
254LP and 256LP	231.78	209.55 - 209.63	4.83	254	4	11.18	41.28 - 41.26
284LP and 286LP	231.78	209.55 - 209.63	4.83	254	4	11.18	53.98 - 53.95
284LPH and 286LPH	374.65	343.00 - 342.90	6.35	419	4	17.53	53.98 - 53.95
324LP and 326LP	374.65	343.00 - 342.90	6.35	419	4	17.53	53.98 - 53.95
364LP and 365LP	374.65	343.00 - 342.90	6.35	419	4	17.53	53.98 - 53.95
404LP and 405LP	374.65	343.00 - 342.90	6.35	419	4	17.53	53.98 - 53.95
444LP and 445LP	374.65	343.00 - 342.90	6.35	419	4	17.53	53.98 - 53.95

Frame designations	V in	AH**	EP min	EU	Keyseat R	ES min	S
143LP and 145LP	69.85	70.64 - 69.06	29.36	22.23 - 22.10	25.05 - 24.66	32.51	6.4 - 6.35
182LP and 184LP	69.85	70.64 - 69.06	29.36	22.23 - 22.10	25.05 - 24.66	32.51	6.4 - 6.35
213LP and 215LP	69.85	70.64 - 69.06	44.45	28.58 - 28.56	35.97 - 35.59	32.51	9.58 - 9.53
254LP and 256LP	69.85	70.64 - 69.06	44.45	28.58 - 28.56	35.97 - 35.59	32.51	9.58 - 9.53
284LP and 286LP	101.60	115.09 - 113.51	57.15	44.45 - 44.32	46.86 - 46.48	76.96	12.80 - 12.70
284LPH and 286LPH	101.60	115.09 - 113.51	57.15	44.45 - 44.32	46.86 - 46.48	76.96	12.80 - 12.70
324LP and 326LP	101.60	115.09 - 113.51	57.15	44.45 - 44.32	46.86 - 46.48	76.96	12.80 - 12.70
364LP and 365LP	101.60	115.09 - 113.51	57.15	44.45 - 44.32	46.86 - 46.48	76.96	12.80 - 12.70
404LP and 405LP	101.60	115.09 - 113.51	57.15	44.45 - 44.32	46.86 - 46.48	76.96	12.80 - 12.70
444LP and 445LP	101.60	115.09 - 113.51	57.15	44.45 - 44.32	46.86 - 46.48	76.96	12.80 - 12.70

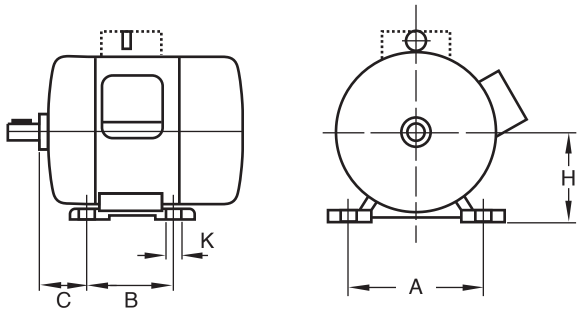
Reference: NEMA Stds. MG 1, 18.251 (Note: Data in NEMA tables is shown in inches.)

* AJ centerline of bolt holes shall be within 0.64 mm of true location for all frames. True location is defined as angular and diametrical location with reference to the centerline of AK.

** Dimension measured with motor in vertical position shaft down.

IEC MOUNTING DIMENSIONS—FOOT-MOUNTED AC AND DC MACHINES

DIMENSIONS IN MILLIMETERS

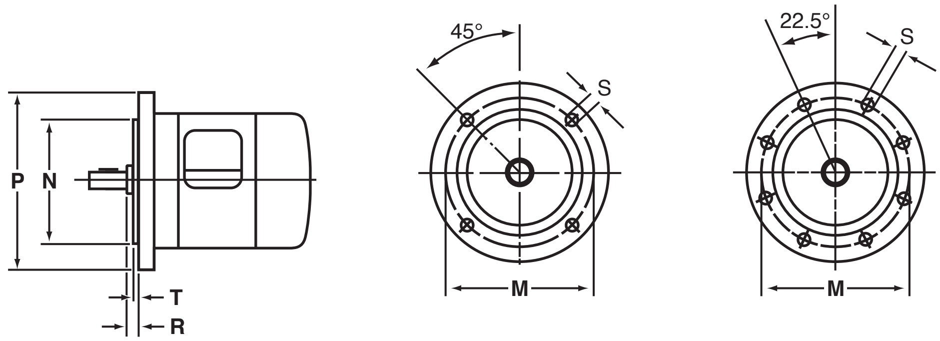


Frame number	H	A	B	C	K	Bolt or screw
56M	56	90	71	36	5.8	M5
63M	63	100	80	40	7	M6
71M	71	112	90	45	7	M6
80M	80	125	100	50	10	M8
90S	90	140	100	56	10	M8
90L	90	140	125	56	10	M8
100S	100	160	112	63	12	M10
100L	100	160	140	63	12	M10
112S	112	190	114	70	12	M10
112M	112	190	140	70	12	M10
132S	132	216	140	89	12	M10
132M	132	216	178	89	12	M10
160S	160	254	178	108	14.5	M12
160M	160	254	210	108	14.5	M12
160L	160	254	254	108	14.5	M12
180S	180	279	203	121	14.5	M12
180M	180	279	241	121	14.5	M12
180L	180	279	279	121	14.5	M12
200S	200	318	228	133	18.5	M16
200M	200	318	267	133	18.5	M16
200L	200	318	305	133	18.5	M16
225S	225	356	286	149	18.5	M16
225M	225	356	311	149	18.5	M16
250S	250	406	311	168	24	M20
250M	250	406	349	168	24	M20
280S	280	457	368	190	24	M20
280M	280	457	419	190	24	M20
315S	315	508	406	216	28	M24
315M	315	508	457	216	28	M24
355S	355	610	500	254	28	M24
355M	355	610	560	254	28	M24
355L	355	610	630	254	28	M24
400S	400	686	560	280	35	M30
400M	400	686	630	280	35	M30
400L	400	686	710	280	35	M30

Reference: IEC Stds. 60072-1 Standards. For tolerances on dimensions, see IEC Stds. 60072-1, 6.1, Foot-Mounted Machines, Table 1.

IEC FLANGE-MOUNTED AC AND DC MACHINES DIMENSIONS FOR FLANGES

DIMENSIONS IN MILLIMETERS



Flange number (FF-FT)[1]	M	N	P[2]	R	Number of holes	S Free holes (FF)	Tapped holes (FT)[3] thread	T maximum
55	55	40	70	0	4	5.8	M5	2.5
65	65	50	80	0	4	5.8	M5	2.5
75	75	60	90	0	4	5.8	M5	2.5
85	85	70	105	0	4	7	M6	2.5
100	100	80	120	0	4	7	M6	3
115	115	95	140	0	4	10	M8	3
130	130	110	160	0	4	10	M8	3.5
165	165	130	200	0	4	12	M10	3.5
215	215	180	250	0	4	14.5	M12	4
265	265	230	300	0	4	14.5	M12	4
300	300	250	350	0	4	18.5	M16	5
350	350	300	400	0	4	18.5	M16	5
400	400	350	450	0	8	18.5	M16	5
500	500	450	550	0	8	18.5	M16	5
600	600	550	660	0	8	24	M20	6
740	740	680	800	0	8	24	M20	6
940	940	880	1000	0	8	28	M24	6
1080	1080	1000	1150	0	8	28	M24	6

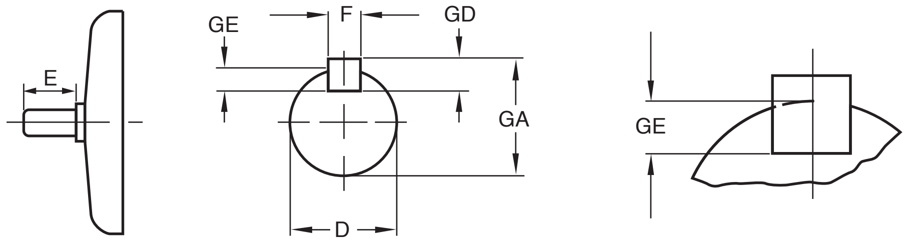
[1] This table does not apply to FI flange.
[2] The external outline of mounting flanges up to and including FF300 and FT300 may be other than circular. Dimension P may deviate from that given in the table only on the minus side.
[3] For FT flange-mounted machines, it is recommended that the free holes in the mounting part should be as shown in Column S for the corresponding size of FF flange.

DESIGNATION OF FLANGE-MOUNTED MACHINES
FF flange—Flange with free holes (clearance holes).
FT flange—Flange with tapped holes and with diameter N smaller than the diameter M.
FI flange—Flange with tapped holes and with diameter N greater than the diameter M.

Reference: IEC 60072-1 Stds. For tolerances on dimensions, see IEC Stds. 60072-1, 6.2, Flange-Mounted Machines, Table 3.

IEC SHAFT EXTENSION, KEY AND KEYSEAT DIMENSIONS FOR CONTINUOUS DUTY AC MOTORS

DIMENSIONS IN MILLIMETERS



	D			Key		Keyseat		
Frame	2 pole	4, 6, 8 pole	E	F	GD	F	GE	GA
56M	9	9	20	3	3	3	1.8	10.2
63M	11	11	23	4	4	4	2.5	12.5
71M	14	14	30	5	5	5	3	16
80M	19	19	40	6	6	6	3.5	21.5
90S	24	24	50	8	7	8	4	27
90L	24	24	50	8	7	8	4	27
100L	28	28	60	8	7	8	4	31
112M	28	28	60	8	7	8	4	31
132S	38	38	80	10	8	10	5	41
132M	38	38	80	10	8	10	5	41
160M	42	42	110	12	8	12	5	45
160L	42	42	110	12	8	12	5	45
180M	48	48	110	14	9	14	5.5	51.5
180L	48	48	110	14	9	14	5.5	51.5
200L	55	55	110	16	10	16	6	59
225S	55	—	110	16	10	16	6	59
225M	55	—	110	16	10	16	6	59
225S	—	60	140	18	11	18	7	64
225M	—	60	140	18	11	18	7	64
250M	60	—	140	18	11	18	7	64
250M	—	65	140	18	11	18	7	69
280S	65	—	140	18	11	18	7	69
280M	65	—	140	18	11	18	7	69
280S	—	75	140	20	12	20	7.5	79.5
280M	—	75	140	20	12	20	7.5	79.5
315S	65	—	140	18	11	18	7	69
315M	65	—	140	18	11	18	7	69
315S	—	80	170	22	14	22	9	85
315M	—	80	170	22	14	22	9	85

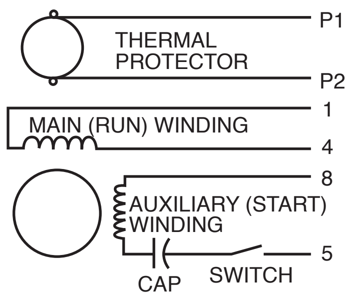
Reference: IEC Stds. 60072-1 and 60034-7. For tolerances on dimensions, see IEC Stds. 60072-1, 7, Shaft Extension, Keys and Keyways Dimensions, Table 4. Alternative shaft sizes are available; check with the manufacturer.

2.5 STANDARD TERMINAL MARKINGS AND CONNECTIONS

(**Note:** All terminal markings and connections in this section are based on NEMA Stds. MG 1, 2.41 or IEC Stds. 60034-8.)

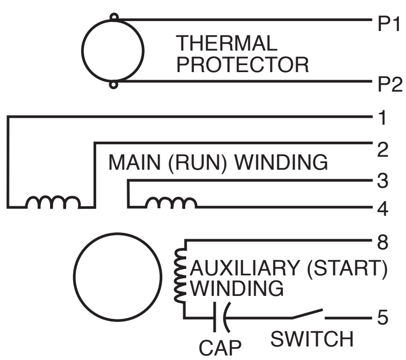
SINGLE-PHASE MOTORS–CAPACITOR-START
NEMA NOMENCLATURE

SINGLE VOLTAGE



ROTATION	L1	L2
CCW	1,8	4,5
CW	1,5	4,8

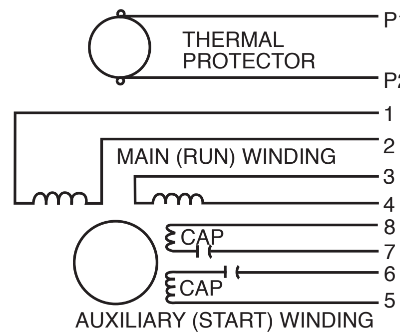
DUAL VOLTAGE
(MAIN WINDING ONLY)



Auxiliary winding is always at low-voltage rating; capacitor should be rated accordingly.

Voltage	Rotation	L1	L2	Join
High	CCW	1	4,5	2&3&8
	CW	1	4,8	2&3&5
Low	CCW	1,3,8	2,4,5	—
	CW	1,3,5	2,4,8	—

DUAL VOLTAGE
(MAIN AND AUXILIARY WINDING)



Capacitors in auxiliary windings are rated for lower voltage.

Voltage	Rotation	L1	L2	Join
High	CCW	1,8	4,5	2&3,6&7
	CW	1,5	4,8	2&3,6&7
Low	CCW	1,3,6,8	2,4,5,7	—
	CW	1,3,5,7	2,4,6,8	—

The switch in the auxiliary winding circuit has been omitted from this diagram. The connections to the switch must be made so that *both* auxiliary windings become de-energized when the switch is open.

Rotation: CCW – Counterclockwise
CW – Clockwise

The direction of shaft rotation can be determined by facing the end of the motor opposite the drive.

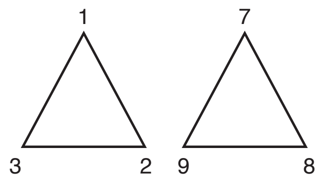
TERMINAL MARKINGS IDENTIFIED BY COLOR

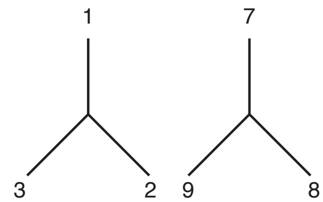
1-Blue	5-Black	P1-No color assigned
2-White	6-No color assigned	P2-Brown
3-Orange	7-No color assigned	
4-Yellow	8-Red	

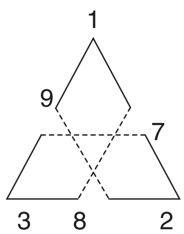
Reference: NEMA Stds. MG 1, 2.41.
Note: May not apply for some definite-purpose motors.

STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—PART-WINDING START

NEMA NOMENCLATURE—6 LEADS







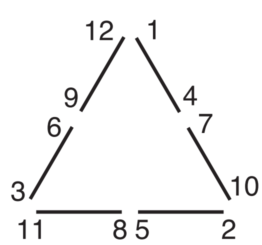
Double Delta
(Extended Delta)

Operating mode	L1	L2	L3	Open
Start	1	2	3	7,8,9
Run	1,7	2,8	3,9	—

NEMA NOMENCLATURE—9 LEADS
WYE-CONNECTED (LOW VOLTAGE ONLY)

	T1	T2	T3	T7	T8	T9	Together
Motor leads	1	2	3	7	8	9	4&5&6

NEMA NOMENCLATURE—12 LEADS



Delta

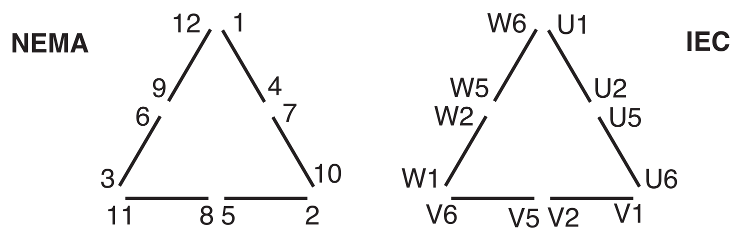
Voltage	T1	T2	T3	T7	T8	T9	Open
High*	1	2	3	12	10	11	4-7, 5-8, 6-9
Low	1,12	2,10	3,11	6,7	4,8	5,9	—

*Not suitable for one-circuit internal connections.

STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—PART-WINDING START (CONTINUED)

NEMA AND IEC NOMENCLATURE—12 LEADS

SINGLE VOLTAGE OR LOW VOLTAGE OF DUAL-VOLTAGE MOTORS

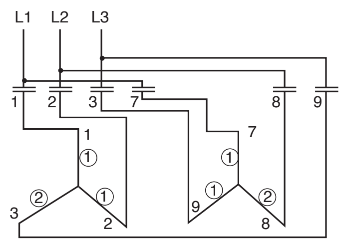


	T1	T2	T3	T7	T8	T9
NEMA	1,6	2,4	3,5	7,12	8,10	9,11
IEC	U1,W1	V1,U2	W1,V2	U5,W6	V5,U6	W5,V6

STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—REDUCED-CURRENT STARTING

NEMA NOMENCLATURE—6 LEADS

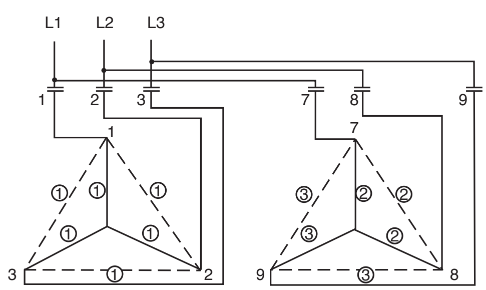
WYE-CONNECTED



2-step starting (2/3—1/3)
4- and 2-pole contactors

Operating mode	L1	L2	L3	Open
Start	1,7	2	3	8&9
Run	1,7	2,8	3,9	—

WYE- OR DELTA-CONNECTED

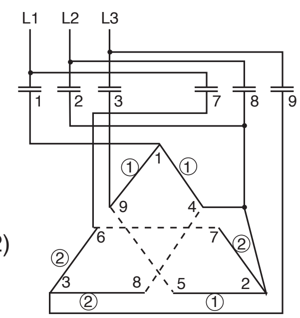


3-step starting
(1/2—1/3—1/6)—wye connected
(1/2—1/6—1/3)—delta connected
3-, 2- and 1-pole contactors

Operating mode	L1	L2	L3	Open
Start	1	2	3	8&9
Mid-step	1,7	2,8	3	9
Run	1,7	2,8	3,9	—

NEMA NOMENCLATURE—9 LEADS

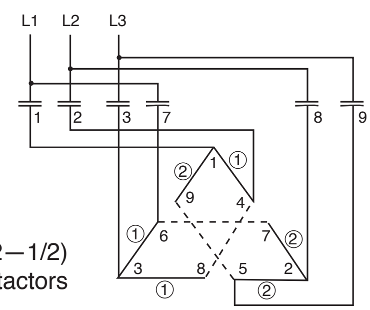
DELTA-CONNECTED



2-step starting (1/2—1/2)
Two 3-pole contactors

Operating mode	L1	L2	L3	Open
Start	1,7	2	3	8&9
Run	1,7	2,8	3,9	—

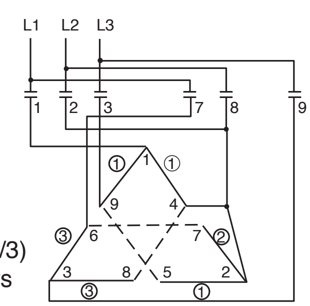
DELTA-CONNECTED



2-step starting (1/2—1/2)
4- and 2-pole contactors

Operating mode	L1	L2	L3	Open
Start	1,7	2	3	8&9
Run	1,7	2,8	3,9	—

DELTA-CONNECTED



3-step starting (1/2—1/6—1/3)
3-, 2- and 1-pole contactors

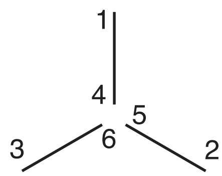
Operating mode	L1	L2	L3	Open
Start	1	2,8	3	7&9
Mid-step	1,7	2,8	3	9
Run	1,7	2,8	3,9	—

STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—SINGLE-SPEED

NEMA NOMENCLATURE—6 LEADS

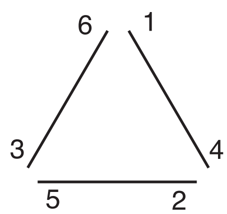
SINGLE VOLTAGE
EXTERNAL
WYE CONNECTION

L1	L2	L3	Join
1	2	3	4&5&6

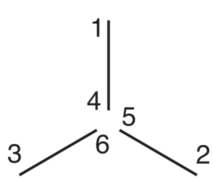


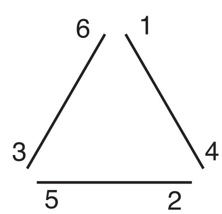
SINGLE VOLTAGE
EXTERNAL
DELTA CONNECTION

L1	L2	L3
1,6	2,4	3,5



SINGLE AND DUAL VOLTAGE
WYE-DELTA CONNECTIONS





Single voltage

Operating mode	Connection	L1	L2	L3	Join
Start	Wye	1	2	3	4&5&6
Run	Delta	1,6	2,4	3,5	—

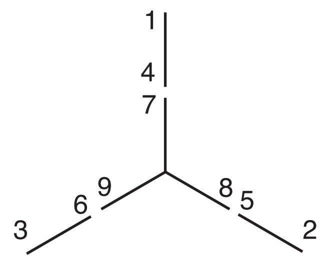
Dual voltage*

Voltage	Connection	L1	L2	L3	Join
High	Wye	1	2	3	4&5&6
Low	Delta	1,6	2,4	3,5	—

*Voltage ratio: 1.732 to 1.

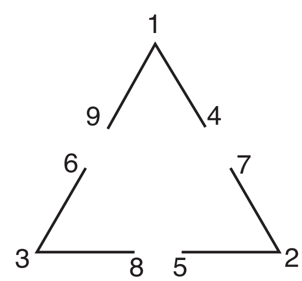
NEMA NOMENCLATURE—9 LEADS

DUAL VOLTAGE
WYE-CONNECTED



Voltage	L1	L2	L3	Join
High	1	2	3	4&7,5&8,6&9
Low	1,7	2,8	3,9	4&5&6

DUAL VOLTAGE
WYE-CONNECTED



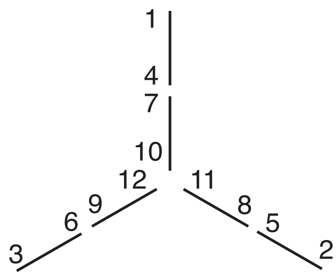
Voltage	L1	L2	L3	Join
High	1	2	3	4&7,5&8,6&9
Low	1,6,7	2,4,8	3,5,9	—

STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—SINGLE-SPEED

(**Caution:** Historically not all manufacturers comply with IEC terminal designations. See the next two pages for examples.)

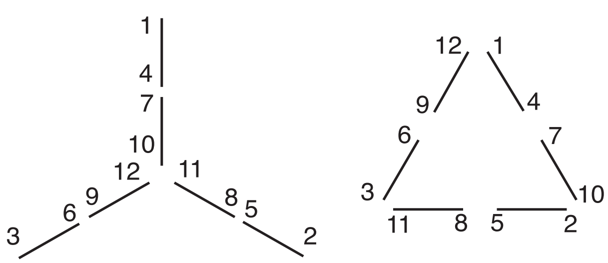
NEMA NOMENCLATURE—12 LEADS

DUAL VOLTAGE
EXTERNAL WYE CONNECTION



Voltage	L1	L2	L3	Join
High	1	2	3	4&7,5&8,6&9, 10&11&12
Low	1,7	2,8	3,9	4&5&6, 10&11&12

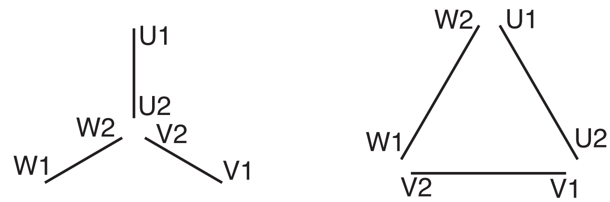
DUAL VOLTAGE
WYE-CONNECTED START
DELTA-CONNECTED RUN



Volt.	Conn.	L1	L2	L3	Join
High	Wye	1	2	3	4&7,5&8,6&9, 10&11&12
	Delta	1,12	2,10	3,11	4&7,5&8,6&9
Low	Wye	1,7	2,8	3,9	4&5&6, 10&11&12
	Delta	1,6,7,12	2,4,8,10	3,5,9,11	—

IEC NOMENCLATURE—6 LEADS

SINGLE AND DUAL VOLTAGE
WYE-DELTA CONNECTIONS



Single voltage

Operating mode	Conn.	L1	L2	L3	Join
Start	Wye	U1	V1	W1	U2&V2&W2
Run	Delta	U1,W1	V1,U2	W1,V2	—

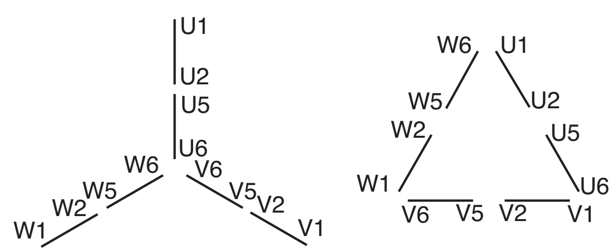
Dual voltage*

Voltage	Conn.	L1	L2	L3	Join
High	Wye	U1	V1	W1	U2&V2&W2
Low	Delta	U1,W2	V1,U2	W1,V2	—

*Voltage ratio: 1.732 to 1.

IEC NOMENCLATURE—12 LEADS

DUAL VOLTAGE WYE-CONNECTED START
DELTA-CONNECTED RUN



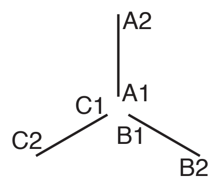
Volt.	Conn.	L1	L2	L3	Join
High	Wye	U1	V1	W1	U2&U5,V2&V5, W2&W5,U6&V6&W6
	Delta	U1,W6	V1,U6	W1,V6	U2&U5,V2&V5, W2&W5
Low	Wye	U1,U5	V1,V5	W1,W5	U2&V2&W2, U6&V6&W6
	Delta	U1,U5, W2,W6	V1,V5, U2,U6	W1,W5, V2,V6	—

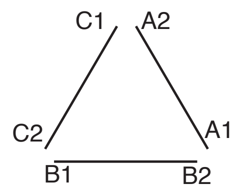
NON-STANDARD TERMINAL MARKINGS AND CONNECTIONS

THREE-PHASE MOTORS—SINGLE-SPEED

NOMENCLATURE FORMERLY USED IN GREAT BRITAIN—6 LEADS

SINGLE AND DUAL VOLTAGE
WYE-DELTA CONNECTIONS





Single voltage

Operating mode	Connection	L1	L2	L3	Join
Start	Wye	A2	B2	C2	A1&B1&C1
Run	Delta	A2,C1	B2,A1	C2,B1	—

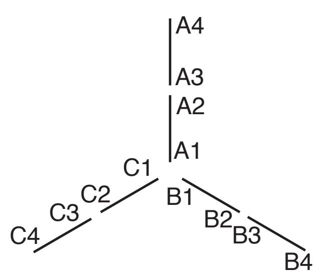
Dual voltage*

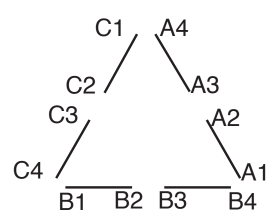
Voltage	Connection	L1	L2	L3	Join
High	Wye	A2	B2	C2	A1&B1&C1
Low	Delta	A2,C1	B2,A1	C2,B1	—

*Voltage ratio: 1.732 to 1.

NOMENCLATURE FORMERLY USED IN GREAT BRITIAN—12 LEADS

DUAL VOLTAGE
WYE-CONNECTED START, DELTA-CONNECTED RUN



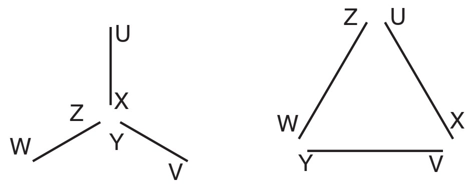


Voltage	Connection	L1	L2	L3	Join
High	Wye	A4	B4	C4	A3&A2,B3&B2,C3&C2,A1&B1&C1
	Delta	A4,C1	B4,A1	C4,B1	A3&A2,B3&B2,C3&C2
Low	Wye	A4,A2	B4,B2	C4,C2	A3&B3&C3, A1&B1&C1
	Delta	A4,A2,C1,C3	B4,B2,A1,A3	C4,C2,B1,B3	—

NON-STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—SINGLE-SPEED

NOMENCLATURE FORMERLY USED IN EUROPE—6 LEADS

SINGLE AND DUAL VOLTAGE
WYE-DELTA CONNECTIONS



Single voltage

Operating mode	Connection	L1	L2	L3	Join
Start	Wye	U	V	W	X&Y&Z
Run	Delta	U,Z	V,X	W,Y	—

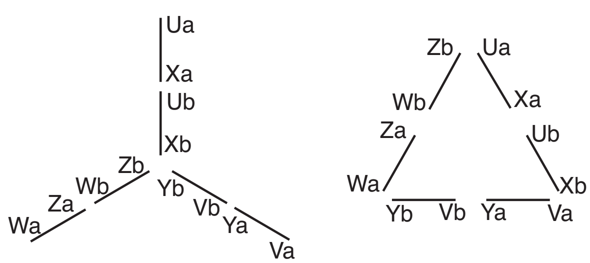
Dual voltage*

Voltage	Connection	L1	L2	L3	Join
High	Wye	U	V	W	X&Y&Z
Low	Delta	U,Z	V,X	W,Y	—

*Voltage ratio: 1.732 to 1.

NOMENCLATURE FORMERLY USED IN GERMANY—12 LEADS

DUAL VOLTAGE
WYE-CONNECTED START, DELTA-CONNECTED RUN

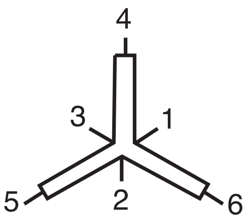


Voltage	Connection	L1	L2	L3	Join
High	Wye	Ua	Va	Wa	Xa&Ub,Ya&Yb,Za&Wb,Xb&Yb&Zb
	Delta	Ua,Zb	Va,Xb	Wa,Yb	Xa&Ub,Ya&Vb,Za&Wb
Low	Wye	Ua,Ub	Va,Vb	Wa,Wb	Xa&Ya&Za,Xb&Yb&Zb
	Delta	Ua,Ub,Za,Zb	Va,Vb,Xa,Xb	Wa,Wb,Ya,Yb	—

STANDARD TERMINAL MARKINGS AND CONNECTIONS
THREE-PHASE MOTORS—TWO-SPEED, SINGLE WINDING

NEMA NOMENCLATURE—6 LEADS

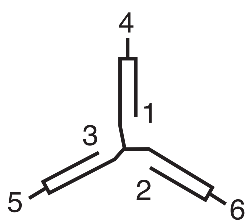
CONSTANT TORQUE CONNECTION



Low-speed horsepower is half of high speed horsepower.*

Speed	L1	L2	L3		Typical connection
High	6	4	5	1&2&3 Join	2 wye
Low	1	2	3	4-5-6 Open	1 delta

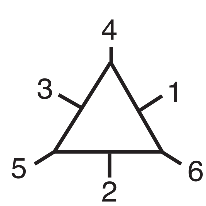
VARIABLE TORQUE CONNECTION



Low-speed horsepower is one-fourth of high speed horsepower.*

Speed	L1	L2	L3		Typical connection
High	6	4	5	1&2&3 Join	2 wye
Low	1	2	3	4-5-6 Open	1 wye

CONSTANT HORSEPOWER CONNECTION



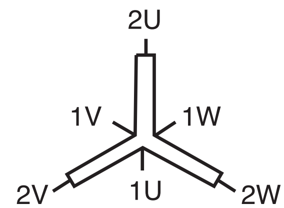
Low-speed horsepower is one-fourth of high speed horsepower.*

Speed	L1	L2	L3		Typical connection
High	6	4	5	1-2-3 Open	1 delta
Low	1	2	3	4&5&6 Join	2 wye

* CAUTION: On European motors, horsepower variance with speed may not be the same as shown above.

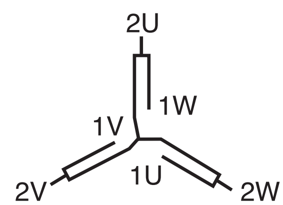
IEC NOMENCLATURE—6 LEADS

CONSTANT TORQUE CONNECTION



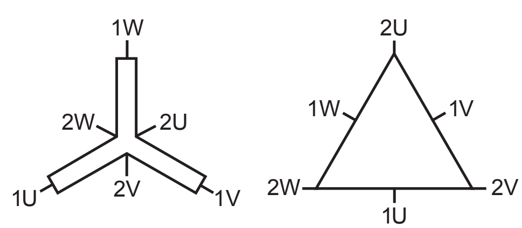
Speed	L1	L2	L3		Typical connection
High	2W	2U	2V	1U&1V&1W Join	2 wye
Low	1U	1V	1W	2U-2V-2W Open	1 delta

VARIABLE TORQUE CONNECTION



Speed	L1	L2	L3		Typical connection
High	2W	2U	2V	1U&1V&1W Join	2 wye
Low	1U	1V	1W	2U-2V-2W Open	1 wye

CONSTANT POWER, SIX TERMINALS



Speed	L1	L2	L3		Typical connection
High	2U	2V	2W	1U&1V&1W Open	Series delta
Low	1U	1V	1W	2U&2V&2W Join	Parallel wye

2.6 BRUSHLESS SERVO MOTORS: HOW ARE THEY DIFFERENT?

By Luther (Red) Norris
Quality Solutions Co., LLC
Greenwood, Indiana

Brushless servo motors are used in industry for many different applications. Primarily, though, they are used in automated machinery for the accurate positioning of the work piece or work tool.

Although brushless servo motors usually have stator windings with three power leads, they also have many features not found on standard AC induction motors or brush-type DC motors with commutators. For example, rather than an induction squirrel cage rotor or a wound rotor, they will have a rotor with permanent magnets that matches the number of poles in the stator winding.

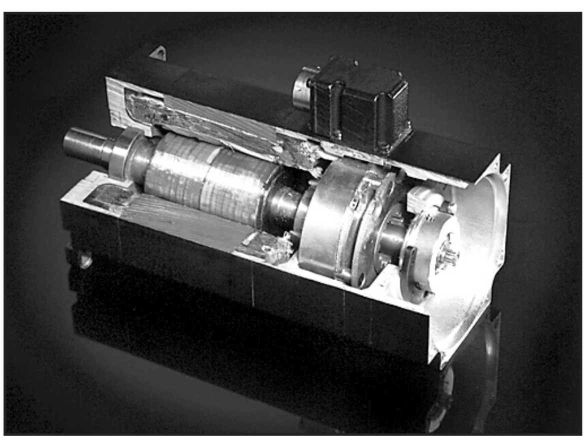
Since they do not have an induction or squirrel cage rotor, brushless servo motors will not run directly from three-phase AC power. Instead, they must be powered by a control or drive unit (commonly called an amplifier).

Brushless servo motors also will have a feedback device that communicates the position of the rotor to the amplifier. Based upon this information, the control will furnish power of the correct polarity and in the right sequence to the motor leads, causing the motor to rotate and develop maximum torque.

The stators and rotors of brushless servo motors are very similar, but feedback devices vary greatly, depending upon the design requirements of the drive. Once these requirements are met, the drive will cause the motor to rotate in the right direction and at the correct speed.

The devices that communicate the rotor position to the control are called commutation feedback devices. The switching of the current through the stator windings is similar to what occurs in the armature winding of a DC motor as the current is turned on and off at the commutator and brushes.

FIGURE 2-1



Baldor Electric servo motor.

The feedback devices used on brushless servo motors may also send information to the drive about other parameters–e.g., speed, acceleration, direction of rotation, and number of turns. They may include resolvers, encoders, Hall Effect sensors, or tachometer generators.

SOME OF THE DIFFERENCES

1. There are very few standards that all servo motor manufacturers follow. Service centers must know the differences peculiar to each manufacturer for the motors they repair. One manufacturer's motor usually will not be interchangeable with that of another manufacturer.
2. Operating speeds of brushless servo motors may be higher than those of other motors. They often run at up to 6000 rpm or higher.
3. Brushless servo motors cannot be test run on the service center test panel.
4. Auxiliary feedback devices will be attached to the motor that must be tested and adjusted.
5. A brushless servo motor will act as an AC alternator if its rotor is rotated. AC voltage is produced as the magnetic flux from the rotor's permanent magnets passes the stationary coils of the stator winding.
6. If a DC voltage is applied to the stator windings, the resultant magnetic poles in the stator winding will cause the rotor to "lock" in position where the poles in the stator align with poles of opposite polarity on the rotor.

USING THESE DIFFERENCES

The differences identified in Items 5 and 6 (above) are unique to brushless servo motors because they have permanent magnet rotors. These differences, when understood and utilized, will be powerful tools for repairing these motors.

Driving the permanent magnet rotor of a servo motor with a variable-speed motor will make the stator winding act as the armature winding in an alternator, producing an AC voltage. If the windings are physically laid out with three circuits that are displaced 120 electrical degrees apart, the voltages produced by the rotating permanent magnet field will also be 120 electrical degrees apart.

This counter-generated voltage will be similar to the three-phase AC voltages with which we are familiar. The phase sequence will be determined by the direction of rotation. The voltage and frequency of the generated voltage will vary with the speed of rotation. Higher speed will result in higher voltage and higher frequency.

In other words, if the rotor of a servo motor is driven from an external source such as a variable-speed motor, the counter voltage generated in the stator windings will be similar in voltage level, frequency, and phase sequence to the voltage required to cause it to run in the direction and speed that it is being driven.

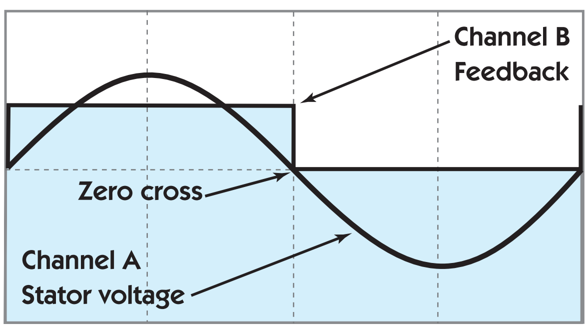
ELECTROMOTIVE FORCE

The counter EMF (electromotive force) or voltages that are generated when the motor is driven externally are nearly equivalent to the voltages that would be applied to cause the motor to rotate at the driven direction and speed. These counter-generated voltages may be used to compare the relative stator voltages to the feedback devices that the drive will use to determine when the stator (or armature) winding should be electronically commutated.

The signals from the feedback device (e.g., a resolver or encoder) that is also mounted on the motor rotating shaft may then be compared to the counter EMF of the stator winding for setting the timing relationship between these signals. This comparison may be accomplished by connecting one channel of a dual-channel oscilloscope to the counter EMF, and the other to the feedback device signal. Display both signals on the oscilloscope screen to compare the relationship of the two voltages and adjust as needed.

The counter EMF mentioned above may be used for checking alignment with a commutation feedback device.

FIGURE 2-2



Oscilloscope traces.

Alignment of the commutation is electrical, however, not mechanical. For this reason, manufacturers rarely use any physical markings.

Usually the alignment will be an electrical alignment of the zero cross points. That is, the point where the counter EMF crosses zero will align with a point where the commutation feedback signal also crosses zero.

The oscilloscope traces in Figure 2-2 show that, while back-driving the motor, the zero cross points of the counter EMF (channel A) align with the zero cross points of the commutation signal (channel B). If the commutation feedback device were physically moved or rotated with respect to the shaft, these zero cross points would move away from each other. This is an example of 120-degree pulse-alignment, which is similar to the way Hall sensors determine rotor position. It is also an example of back-driving and using the counter EMF to obtain alignment.

Another important use for counter-generated voltages is for determining the condition of the rotor magnets on brushless servo motors. Using a variable-frequency drive motor to drive a servo motor with a permanent magnet rotor makes it possible to vary the counter-generated voltage level. The voltage level is determined by the speed of rotation and the strength of the magnets.

COUNTER-GENERATED EMF

The condition of the magnets is reflected in the magnitude and shape of the counter-generated EMF produced when the motor is driven as a generator.

If the counter EMF of one of these motors is measured at a fixed rpm (usually 1000 rpm), this voltage may be compared to the rated Ke specified by the manufacturer. If the manufacturer's specification is not available, comparison may be made between similar motors.

The counter EMF level is directly related to the strength of the magnets; hence, it is an excellent gauge for judging the condition of the magnets.

For example, by regularly checking the voltage level (e.g., at 1000 rpm) and saving the waveform, it is possible to make meaningful comparisons between similar units. Comparison of the voltage level and waveform will indicate the condition of the magnets.

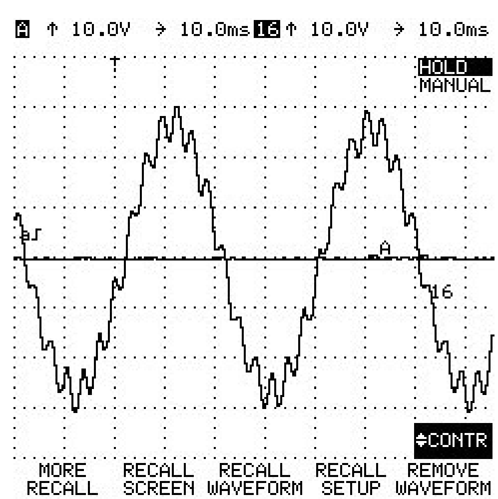
Defective magnets in a brushless servo motor will have three symptoms:

1. Lower counter-generated voltage (Ke).
2. Lower than rated torque (Kt) at rated current.
3. May have distorted counter-generated voltage waveform.

Figure 2-3 and Figure 2-4 are oscilloscope waveforms of counter-generated voltages taken from two similar servo motors. The motors were of the same type from the same manufacturer.

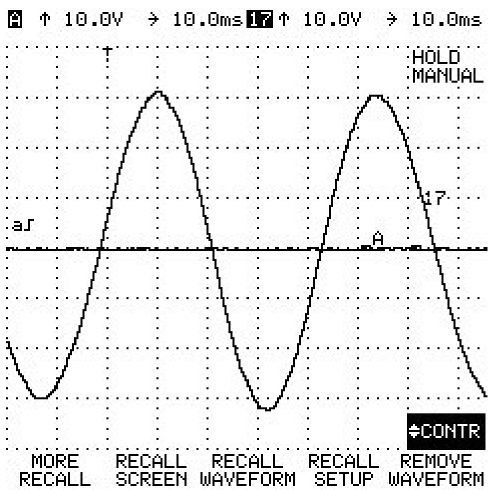
Figure 2-3 shows a waveform from a motor that had

FIGURE 2-3



Motor with damaged rotor magnets.

FIGURE 2-4



Motor with good rotor magnets.

damaged rotor magnets. The waveform is distorted, and the output voltage is low.

Figure 2-4 shows a waveform from a similar motor that had good rotor magnets. The counter EMF is of proper voltage, and the waveform is not distorted.

If a DC voltage is applied to the stator windings, alternate north and south poles will be set up by the DC current through the windings that will have the same number of poles and polarities as the permanent magnets on the rotor. This will cause poles on the rotor to align with opposite poles in the stator winding, since they will be magnetically attracted to each other. The rotor will lock in this position magnetically so long as the DC voltage is applied to the stator.

NUMBER OF LOCKUP POSITIONS

For each possible combination of lead polarities, there will be as many different lockup positions within the full 360 degrees of mechanical rotation of the shaft as there are pole pairs in the motor.

- Two-pole rotor would have one lockup position.
- Four-pole rotor would have two lockup positions.
- Six-pole rotor would have three lockup positions.
- Eight-pole motor would have four lockup positions.
- Etc.

There is only one set of lockup positions for each pair of leads for each polarity combination. In table form:

A	+	-			+	-
B	-	+	+	-		
C			-	+	-	+

Note: Line-to-neutral lockup is accomplished by applying a DC polarity to a phase lead and then applying the other polarity to the remaining two leads tied together. This will cause the rotor to align to the line-to-neutral counter EMF voltage. This would allow for an additional six lockup positions.

Understanding the relationship of these static lockup points to the dynamic counter EMF waveform of the servo motor when the rotor is being back-driven is the technology that is important for setting the feedback devices on these motors. The commutation feedback device may be set by using this method of locking the rotor and then aligning the device with that lockup point.

If a DC voltage is applied to the stator winding, the rotor will lock at one of the zero cross points of the counter EMF. By understanding which polarity to apply, and to which leads, you can identify the zero cross point that you want to align with the commutation signal. This is the static lockup method for setting the commutation feedback device.

To set the commutation feedback device, lock the rotor by applying a DC voltage to the leads and move the feedback device to the point where it toggles from high to low at that rotor position (see Figure 2-2). Then secure it in place. If the feedback device is a resolver, lock the rotor as described above and set the resolver on an angular position of zero degrees to align it for commutation of the motor.

This is a short description of how to set up these commutation devices. Knowing how all of the variables affect the setup is the secret to understanding how these motors work.

Although there are many similarities among servo motor manufacturers, each one chooses how the feedback device will be set and designs the control for that setup.

TESTING OF MAGNETS

To test the rotor magnets, apply DC stall amps to two of the stator leads and measure the maximum stall torque of the motor. When the DC voltage is applied, the rotor will lock up at the zero torque position. To measure peak torque, force the shaft to turn with a torque wrench and compare the force required with the manufacturer's specifications.

If the magnets have the proper strength, the peak torque will be within ten percent of the rated continuous stall torque when rated continuous stall amps are applied.

SUMMARY

A thorough understanding of the unique differences found in brushless servo motors will give you the ability and confidence to inspect, test, and repair these high-tech motors. Make use of these differences when servicing and repairing this equipment by: back-driving the motor and analyzing the counter EMF that is produced; and applying DC to the stator winding to lock up the rotor. These methods may be used for:

- Aligning commutation feedback devices.
- Checking the condition of the rotor magnets.
- Testing the peak torque at rated current.

Note: This article was first published in *EASA Currents* (March 2005); it was reviewed and updated as necessary in August 2016.

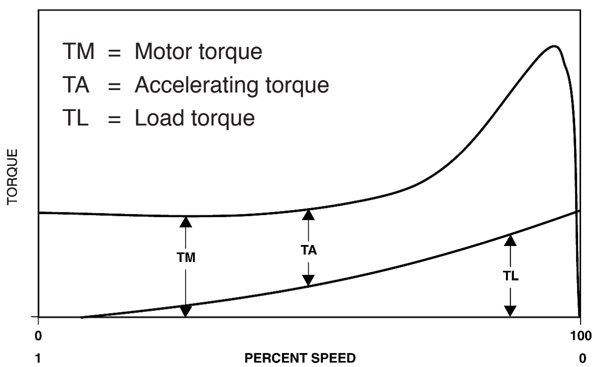
2.7 APPLICATION OF AC MACHINES AND THEIR ACCESSORIES

Motor starting capabilities and considerations

By Thomas H. Bishop, P.E.
EASA Senior Technical Support Specialist

Do not assume that because a motor can drive a running load, it also has the capability to accelerate the load up to rated speed. During starting, a motor must deliver the energy required to accelerate the load. To do this, the motor torque must exceed that needed to accelerate the load. The motor torque value in excess of the load torque requirement is termed the "torque available for acceleration," as shown in Figure 2-5.

FIGURE 2-5



Motor speed-torque curve with motor torque exceeding load torque.

Though this explanation appears to be relatively simple and straightforward, there are some complex conditions: namely, that the motor torque during starting is not constant. Unless the load is a pure inertia load (very rare), it does not have a constant speed-torque relationship. Therefore, the torque available for acceleration is the difference between the speed-torque curves for the motor and the load.

The acceleration time for the motor and load system can be determined from the following formula:

Acceleration time = (Wk^2 x rpm) / (308 x Tacc)

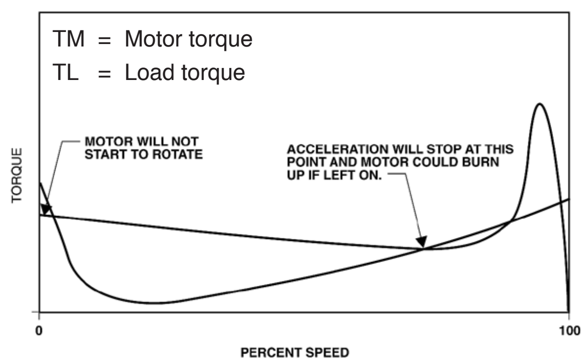
The inertia of the load is the Wk^2 factor in pound-feet squared; the rpm is the speed change of the load; and Tacc is the average accelerating torque of the motor in pound-feet. The result is acceleration time in seconds. In metric units Wk^2 is inertia in kilogram-meters squared, and Tacc is average accelerating torque in Newton-meters. The formula using metric units is:

Acceleration time = (Wk^2 x rpm) / (9.55 x Tacc)

However, as mentioned earlier, the torque available for acceleration is not constant. Calculating acceleration time would require determining the torque available at every point in the motor and load speed-torque curves. The practical method of accomplishing this is to break the curves into parts, or increments, and average the results.

Motor torque ratings are normally based on full rated voltage being available at the motor terminals. In many applications the voltage at the motor is less than rated, due to such conditions as voltage drop in the feeder circuit or reduced voltage starting. The result is a reduction in motor torque, varying approximately as the square of the ratio of applied voltage versus rated voltage. The effects of saturation reduce the motor torque even more. For example, if the voltage at the motor were 80% of rated, the expected torque reduction would be $(0.8/1.0)^2 = 0.64$, or 64%. Due to the reduced flux, however, the torque would probably be closer to 57% of rated.

FIGURE 2-6



Motor speed-torque curve with motor torque not always exceeding load torque.

Although the motor torque available has been reduced, the load torque remains unchanged. The result is a longer acceleration time. If the reduced motor torque is equal to that of the load, leaving none available for acceleration, the motor and load will not accelerate beyond that speed point. Further, if the motor torque is less than that of the load at initial startup, the rotor will not rotate. That is, it will remain in a locked-rotor condition. Figure 2-6 illustrates both of these conditions.

A major limiting factor for the starting capability of a motor is heating of the stator and rotor. During acceleration, some of the electrical energy is used to drive the load, and the remainder is absorbed by the stator and rotor in the form of heat. The primary source of this heating is I^2R losses in the stator and rotor, which are much greater during acceleration than during normal operating conditions. The starting current of a motor is frequently between 6 and 8 times rated current. If we take the average value of this range, 7 times rated current, the ratio of I^2R at starting compared to running would be 7^2 or 49, assuming the resistance remains unchanged. Since the heating also increases winding resistance, it would be reasonable to expect at least 50 times normal heating during starting conditions.

Fortunately, under normal starting conditions, the heating period is relatively short. For example, NEMA Stds. MG 1, 12.49 allows an acceleration time of up to 12 seconds for motors rated to 500 hp (375 kW) and rated 1 kV or less. During this period parts of the stator and rotor may exceed their rated temperatures. Conservative motor designers assume that all of the heat generated during starting is absorbed in the components that produce the heating–e.g., the stator and the rotor. Therefore these components heat very rapidly, and to relatively high temperatures.

However, since the duration of acceleration time is very short, it does not normally have a negative impact on motor life. Upon attaining rated speed, the current and temperature drop to normal levels for the load conditions. For motors larger than 500 hp (375 kW), or with loads with greater than normal inertia (see NEMA Stds. MG 1, Table 12-7), consult the motor manufacturer to determine the time limit for accelerating the load.

Motor starting capabilities are thermally limited by either the stator or the rotor. If the stator is the limiting factor, the motor is termed "stator-limited"; and if the rotor is the limiting factor, the motor is said to be "rotor-limited." In general, smaller motors, such as in NEMA frames, tend to be stator-limited; and larger motors, well above NEMA frame sizes, tend to be rotor-limited.

The limits of load inertia for motors rated from 1 to 500 hp (0.75 to 375 kW) are given in NEMA Stds. MG 1, Table 12-7; those for motors rated 100 to 15,000 hp (75 to 11000 kW) are listed in Table 20-1. The overlap in power ratings is due to different speed ratings, with higher speeds (for the same hp rating) appearing in Table 12-7 and lower speed ratings in Table 20-1. According to the NEMA standards, there are three conditions that apply to the maximum inertia ratings given in these tables. The first is that the applied voltage and frequency are at rated values. Thus, if voltage is reduced at starting, the inertia limits given in the tables may not apply.

The second condition is that the load torque is equal to or less than a torque that varies as the square of the speed and attains 100% full-load torque at rated speed. Further, the motor must develop a torque that exceeds these values by at least 10%, up to the speed at which breakdown torque occurs. Essentially this means that the motor should be able to accelerate a load with a variable or constant torque speed-torque characteristic.

The third condition is the number of starts allowed. There are three subsets of conditions that apply. The first is that the motor is allowed "two starts in succession, coasting to rest between starts, with the motor initially at ambient temperature." The second is that the motor is allowed "one start with the motor initially at a temperature not exceeding its rated load operating temperature." A potential difficulty with adhering to this condition is determining the rated load operating temperature. That would require temperature sensing in the windings, such as from resistance temperature detectors (RTDs). Without such devices, the operating temperature will not be known.

The third subset of the third condition applies to additional starts and states: "If additional starts are required, it is recommended that none be made until all conditions affecting operation have been thoroughly investigated and the apparatus has been examined for evidence of excessive heating. It should be recognized that the number of starts should be kept to a minimum since the life of the motor is affected by the number of starts."

Among the difficulties posed by this last requirement is how to determine if "all" conditions affecting operation have been "thoroughly" investigated. Further, examining the motor for evidence of excessive heating would necessitate an internal inspection. While these constraints are not very practical, they are the standard that applies.

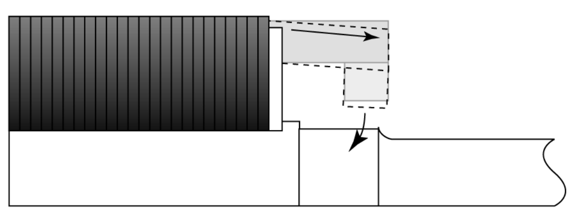
CONTACT MOTOR MANUFACTURER

Although it does not fulfill the necessary requirements to be considered an alternative, at the very least the motor should be allowed to cool to room temperature (ambient) prior to restarting. A better alternative, which may not always be practical, is to contact the manufacturer for restarting and additional start requirements for the specific motor and load application.

The disadvantages of exceeding the limits of motor starting capability can range from overheating of components to failure to accelerate the load, and on to failure of the motor itself. Overheating of components during starting often has a long-term, cumulative effect that reduces the life of the component (e.g., the stator or rotor). The consequences of failure to start the load are obvious; the motor is unsuitable and unusable for the application.

Failure of motor components may be due to a number of stresses associated with acceleration. In the rotor, the bars and end rings that make up the rotor cage are subject to high and cyclic (alternating) magnetic forces. Heating of the rotor cage results in axial expansion of the bars and radial expansion of the end rings, creating stress in various sections of the bars and

FIGURE 2-7



During starting, the upper portion of the bar carries the current. This current heats and expands the top portion of the bar forcing it to bend inward toward the shaft.

end rings. Current tends to "crowd" the tops of the bars during starting, causing bending stresses as the top of the bars try to expand more than the bottoms. This is depicted in Figure 2-7. As speed increases during acceleration, centrifugal forces add mechanical "hoop" stresses to the thermal and other stresses already mentioned.

The mechanical and electrical forces also affect the stator windings. The excessive starting current leads to rapid heating of the windings, and consequently, rapid thermal expansion resulting in physical stress. The torque forces associated with starting are many times greater than normal. This leads to winding movement and possible motion between adjacent conductors, or between conductors and frame or core, which can result in a short circuit or ground fault.

Each acceleration period is a fatigue cycle, the cumulative effects of which shorten the life of the motor based on the number of starts. However, there are no standards or guidelines for the minimum number of starts for a motor, so always use caution with motor applications. Do not assume that because a motor can drive a running load, it also has the capability to accelerate that load up to rated speed.

Note: This article was first published in *EASA Currents* (September 2007); it was reviewed and updated as necessary in August 2016.

MOTOR APPLICATION FORMULAS†

OUTPUT

$$\text{Horsepower} = \frac{\text{Torque (lb•ft) x rpm}}{5252}$$

$$\text{Torque (lb•ft)} = \frac{\text{Horsepower x 5252}}{\text{rpm}}$$

For an approximation use:

Full load torque = 1.5 lb•ft per horsepower per pole pair at 60 Hz

Examples:
2 pole, 1 hp—1.5 lb•ft
2 pole, 2 hp—3 lb•ft
4 pole, 1 hp—3 lb•ft

$$\text{Kilowatts} = \frac{\text{Torque (N•m) x rpm}}{9550}$$

$$\text{Torque (N•m)} = \frac{\text{Kilowatts x 9550}}{\text{rpm}}$$

For an approximation use:

Full load torque = 3.2 N•m per kilowatt per pole pair at 50 Hz

Examples:
2 pole, 1 kW—3.2 N•m
2 pole, 2 kW—6.4 N•m
4 pole, 1 kW—6.4 N•m

SPEED—AC MACHINERY

$$\text{Synchronous rpm} = \frac{\text{120 x Frequency (Hz)}}{\text{Number of poles}}$$

$$\text{Percent slip} = \frac{\text{Synchronous rpm - Full-load rpm}}{\text{Synchronous rpm}} \text{ x 100}$$

SHEAR STRESS*

$$\text{Shear stress (psi)} = \frac{\text{hp x 321,000}}{\text{rpm x } D^3} *$$

Where:		
D	=	Shaft diameter (in)
hp and kW	=	Motor output
psi	=	Pounds per square inch
rpm	=	Revolutions per minute

*This equation applies to static cases only and should not be used for design purposes.

$$\text{Shear stress (kg per mm}^2) = \frac{\text{kW x 4.96 x } 10^6}{\text{rpm x } D^3} *$$

Where:		
D	=	Shaft diameter (mm)
hp and kW	=	Motor output
kg/mm^2	=	Kilograms per millimeter squared
rpm	=	Revolutions per minute

*This equation applies to static cases only and should not be used for design purposes.

†See also Section 11 of this manual: “Formulas and Conversion Factors.”

MOTOR APPLICATION FORMULAS—CONTINUED †

CENTRIFUGAL APPLICATIONS

Affinity Laws

$$\frac{Flow_1}{Flow_2} = \frac{rpm_1}{rpm_2}$$

$$\frac{Pressure_1}{Pressure_2} = \frac{(rpm_1)^2}{(rpm_2)^2}$$

$$\frac{hp_1}{hp_2} = \frac{(rpm_1)^3}{(rpm_2)^3}$$

Pumps

$$hp = \frac{\text{gpm x ft x Specific gravity}}{\text{3960 x Efficiency of pump}}$$

$$hp = \frac{\text{gpm x psi x Specific gravity}}{\text{1713 x Efficiency of pump}}$$

Fans and Blowers

$$hp = \frac{\text{cfm x psf}}{\text{33000 x Efficiency of pump}}$$

$$hp = \frac{\text{cfm x piw}}{\text{6343 x Efficiency of fan}}$$

$$hp = \frac{\text{cfm x psi}}{\text{229 x Efficiency of fan}}$$

$$hp = \frac{hp_2}{hp_1} = \left(\frac{od_2}{od_1}\right)^5$$

$$Volume = \frac{cfm_2}{cfm_1} = \left(\frac{od_2}{od_1}\right)^3$$

$$Pressure = \frac{sp_2}{sp_1} = \left(\frac{od_2}{od_1}\right)^2$$

Where:

cfm	=	Cubic feet per minute	od	=	Outside diameter	psi	=	Pounds per square inch
ft	=	Head in ft*	piw	=	Inches of water gauge	rpm	=	Revolutions per minute
gpm	=	Gallons per minute	Pres	=	Pressure	sp	=	Static pressure
hp	=	Horsepower	psf	=	Pounds per square foot			

* Head in feet = 2.31 x pounds per square inch gravity.

VOLUME OF LIQUID IN A TANK

Gallons = 5.875 x D^2 x H

1 gallon (US) of water weighs 8.35 lb

Specific gravity of water = 1.0

Where:

D = Tank diameter (ft)
H = Height of liquid (ft)

†See also Section 11 of this manual: "Formulas and Conversion Factors."

TEMPERATURE RISE AT HIGH ALTITUDE OPERATION*

Motors and generators will operate satisfactorily at altitudes of 3,300 feet (1,000 meters) or less. The temperature rise of electrical machines operating above this limit may be calculated as follows:

Altitude in feet

$$T_{alt} = \frac{T_{sl}}{1.10 - \frac{H}{33,000}}$$

Altitude in meters

$$T_{alt} = \frac{T_{sl}}{1.10 - \frac{H}{10,000}}$$

Where:

T_{alt} = Temperature rise (°C) at operating altitude
T_{sl} = Temperature rise (°C) at sea level
H = Altitude above sea level in feet or meters

The temperature rise of the winding at sea level may be obtained from the nameplate data or the manufacturer.

Example: Determine the temperature rise of a motor operating at 6,500 feet (1,980 meters) elevation. The sea level temperature rise is 95°C.

$$T_{alt} = \frac{95}{1.10 - \frac{6,500}{33,000}} = 105.2°C$$

$$T_{alt} = \frac{95}{1.10 - \frac{1,980}{10,000}} = 105.3°C$$

When operating at the higher altitude, the temperature rise of the motor will be 105°C (approximately).

*References: NEMA Stds. MG 1, 14.4, and IEC Stds. 60034-1.

DERATING MOTOR CAPACITY BASED ON ALTITUDE

Electric motors are rated to operate within their design limits at altitudes up to 3300 ft (1000 meters). They should be derated for operation at higher elevations because the air is thinner and dissipates less heat.

For example, based on typical derating factors for an ambient temperature of 40°C, a 100 hp motor operated at 6000 ft (1800 m) would be derated to 94 hp (see table below)

TYPICAL ALTITUDE DERATING FACTORS*

Altitude in ft (m)	Horsepower derating factor at 40°C
3300-5000 (1000-1500)	0.97
5001-6600 (1500-2000)	0.94
6601-8300 (2000-2500)	0.90
8301-9900 (2500-3000)	0.86
9901-11500 (3000-3500)	0.82

* Whenever possible, confirm derating factors with the original manufacturer.

Note that the altitude derating formula in NEMA MG 1 assumes that the air is cooler at higher elevations. The fallacy is that many of the electric motors in service at high elevations are inside buildings that protect them from snow and ice and provide productive work areas for employees.

There are other implications beyond the reduced cooling available due to the thinner air. If the original equipment manufacturer was aware of the application and altitude, it is very likely that a larger motor was derated and supplied with a new nameplate. For instance, a motor labeled as a 1000 hp and operating at 10,000 feet of elevation was probably manufactured as a 1250 hp. A KVA code letter that is one or two letters higher than normal could be a clue to such a rerate, but the code letters are ambiguous enough that this may not be obvious to most observers.

The implication for repairers: Use pricing guides cautiously when quoting rewinds of motors in use at higher elevations.

Space heating to prevent damage from condensation

Space heating is often necessary to address issues caused by condensation in idle motors (or generators). Motors arguably can be subject to more harm when idle than when they are in service. Especially in humid environments condensation can accelerate deterioration of winding insulation materials and machined surfaces.

Condensation forms when the temperature falls below the dew point. This meteorological term refers to the amount of water vapor the air can hold. The higher the humidity, the closer the ambient temperature will be to the dew point. This becomes a condensation problem when warm, moist air cools, especially at nightfall. Condensation does not form while the motor is running because the heat generated by the motor keeps the motor dry.

Space heating is intended to keep the surfaces of the motor at about 10ºC (18ºF) above the ambient temperature so the dew point is never reached inside the machine. This is an auxiliary heating source that should only be used when the motor is idle. Anything that increases the temperature of the motor while it is in operation will decrease the winding life.

Two methods of space heating are used, the most common of which is to install small electric heating elements inside the motor. The other recommended method of combating condensation is the use of single-phase, low-voltage "trickle heating." A description of both methods follows. This section discusses various methods to apply this space heating and their merits and shortcomings.

TYPES OF ELECTRIC HEATING ELEMENTS

Cartridge and strip steel space heaters

Many motor manufacturers use wire wound, resistive or ceramic cartridge heaters to prevent condensation in motors (see Figure 2-8). These units must be supplied with a separate power supply that is controlled to energize only when the motor is de-energized.

One drawback to cartridge heaters is that, since they are often mounted to the end bracket, they heat the bearing and lubricant. (One manufacturer installs a shield to minimize this problem.) Retrofitting with these units requires disassembly of the machine, mounting the heaters with an appropriate bracket and supplying a properly controlled voltage supply.

FIGURE 2-8

Cartridge space heaters.

Cartridge heaters are also available to use in oil sumps to prevent condensation from contaminating the oil. To avoid burning the oil, these should be limited to no more than 12 watts per square inch (1.9 watts per cm^2) and typically 50-75 watts maximum.

FIGURE 2-9

Steel strip heaters.

Steel strip heaters (see Figure 2-9) are used in a similar manner. They offer localized heating and are usually installed in the end brackets of the machine. They are fairly efficient for enclosed machines, but lose effectiveness in open machines since they are not in contact with the affected parts. Often the temperature and wattage is increased in these units to make up for the lack of proximity. This requires adequate space between the winding and the hot surfaces of the heater to avoid damage to the winding insulation.

Because cartridge heaters are small, they must operate at a high surface watt density and consequently high temperature. This often subjects them to rapid failure, sometimes within the first year. To combat high failure rates, many smart users specify that cartridge heaters are to be operated at one-half their rated voltage. This lowers the surface watt density to one-fourth the value with rated voltage and increases heater life more than proportionally.

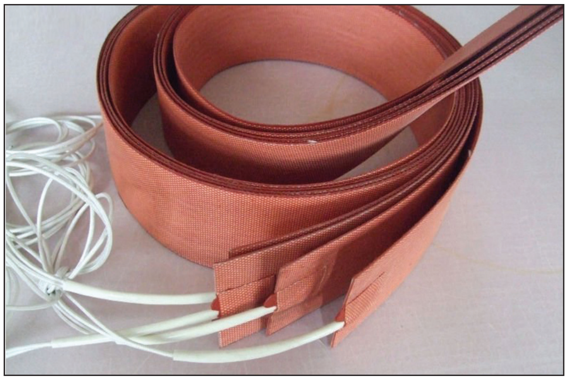
Silicone rubber strip heaters

Another way to reduce the failure rate is to use flexible silicone rubber strip heaters (see Figure 2-10). These heaters consist of a resistance network (wire mesh, etched circuit, or stranded wire) that is covered on both sides by a thin layer of silicone rubber/glass-cloth.

Strip heaters are more common than cartridge heaters. They also prevent condensation more effectively when operated at ± 10% of rated voltage while consuming less power, because they are applied directly to the motor winding–i.e., the more vulnerable part to be protected.

Like cartridge heaters, strip heaters require a separate

FIGURE 2-10



Silicone rubber strip heaters

power supply that is controlled to energize only when the motor is de-energized.

Installation. Silicone rubber strip heaters typically are wrapped around one or both end-turns of a wound stator and laced in place with high-temperature cord to provide a heat source directly on the winding.

Heater leads (marked H) are brought to the main outlet box unless otherwise specified, or unless the motor voltage is greater than 600 volts, in which case a separate outlet box is provided.

Retrofitting with motors silicone rubber strip heaters units requires disassembling the machine, lacing the strip heaters to the end turns, and installing a properly controlled power supply.

Silicone rubber strip heaters are designed for low surface watt density by providing a large surface area. For example, a heater measuring 45” x 2.5” (11.5 x 6.4 cm) is rated at 169 watts, or 1.5 watts per square inch (0.25 mm^2). In operation, these heaters are cool enough to touch with your bare hand without being burned, and typically last longer than the motor.

Circuit voltage. Heaters are available for most voltages between 115 and 600 volts. 115V, 230V, 460V and 575V are standard.

The watt density of the strip heater should be no more than two watts per square inch (0.3 watts per cm^2). If the watt density is greater, insulation such as phase insulation paper should be placed between the end turns and the strip heater to prevent damage to the winding insulation. This insulation will inhibit the effectiveness of the heat transfer to the winding.

Many vendors specify the watt density of their heaters. If the required density is not available, heaters can be powered at lower voltage to limit the watt density. One half voltage is commonly used in these cases. This will produce one-fourth the watts per square inch or square centimeter and will require adequate surface area to yield sufficient total wattage. Often, users feel this will provide a more robust application and will make the heater last longer. Experience has shown that silicone rubber space heaters are very reliable. The inconvenience of dealing with a much larger area in a confined space of the reduced voltage scheme offsets any advantage in extended life.

The main advantages of these heaters

- Easily replaced in event of failure
- Longer life than cartridge heaters–rated beyond the life of the motor
- Extremely low surface temperature
- Installation on completed core welded units
- Moisture and corrosion resistant
- Installation on all size motors

Both cartridge heaters and strip heaters are localized heat sources that with additional parts and effort can be distributed in both ends of the machine to improve performance. It is not likely that the heat from a single heater will permeate the entire core evenly, especially if the heater is poorly positioned. Since heat rises, lacing a strip heater to the upper end turn of a vertical motor, or a horizontal motor that is mounted vertically, will have little impact on the lower part of the motor.

HOW TO SIZE SPACE HEATERS

When a motor received for repair has space heaters, or the customer wants to add them to a motor that does not currently have them, the correct size heater is often unknown. Different manufacturers use various sizes based on motor type and frame size, but the following equation can be used to determine the approximate wattage needed to prevent condensation with any of the space heating methods described here.

W = 2DL (inch)

Or

W = 0.0031DL (millimeter)

Where: W = wattage

D = Stator outside diameter

L = Stator length

Depending on the manufacturer, the calculated values may be very close, or very different. These are just approximations, and it may be necessary to test the heaters after installation to ensure that the temperature rise is correct.

For small motors, the correct wattage is generally as high as or slightly higher than calculated. For larger motors, you normally can use a wattage between the two calculated values.

A common way to extend space heater life (and reduce surface temperature) is to apply reduced voltage to the heater(s). Generally, this is done by applying 120 volts to a heater rated for 230 volts, or by connecting heaters in series so as to apply half voltage. As with any resistive load, watts = volts x amps.

Given the same resistance, applying one-half voltage will result in half the current. Since W = V x I, cutting both voltage and current in half will result in only one-quarter total watts.

Where: W = Watts

V = Volts

I = Amps

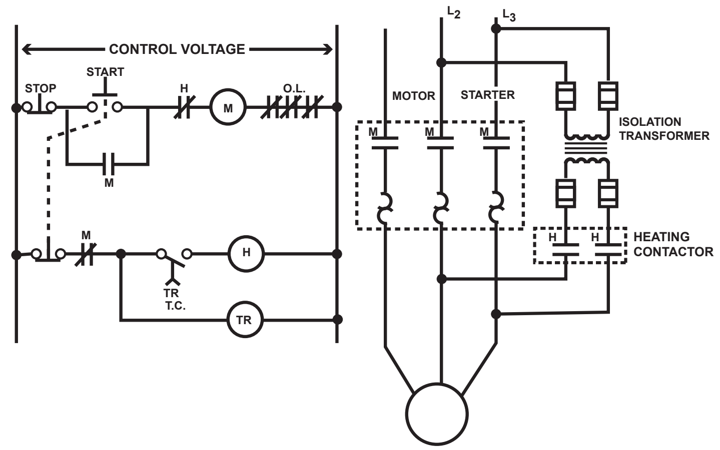
Be sure to factor in the applied voltage when specifying heaters, in order to get the correct actual wattage.

SPACE HEATER TESTING

All space heaters should be tested for function and insulation resistance whenever the motor is tested, whether during repairs or routine scheduled maintenance. To avoid erroneous results, always measure heater current with the appropriate meter scale.

TRICKLE VOLTAGE HEATING

FIGURE 2-11



Trickle voltage control circuit

Another method of space heating is known as trickle voltage heating applies a low voltage (typically 10-20 percent of rated voltage and 25-35 percent of rated current) to two of the three motor leads when the machine is not energized. A single-phase, two-winding dry type transformer applies the voltage after the three-phase power has been removed. Since the applied power is low voltage single phase, the motor will not rotate with the trickle voltage applied.

The current required to maintain a 10°C (18°F) rise in the windings is approximately 25 percent of full load (nameplate) amps. The voltage required to achieve this amperage is a function of the motor's single phase impedance, and therefore, will vary from motor to motor. Generally speaking, however, this voltage will vary from 8-12 percent of nameplate volts. The dry type two-winding transformer should have ±5% and ±10% voltage taps for final voltage adjustment. Refer to the manufacturer for the required transformer secondary voltage and kVA rating recommendations, since this will vary with motor ratings.

The trickle voltage heating method is especially adaptable to various methods of insulation. It also can be added in the field without any changes to the motor.

Advantages and disadvantages

Other advantages of trickle voltage heating over conventional space heaters include:

- The heat is more evenly distributed, not localized as in the case of heating elements.
- The AC current reaction heats the rotor as well as the windings, which means heat can travel along the shaft by conduction (direct contact) to warm the bearings more effectively than by convection (heat transfer by moving air) from heaters.
- The resistance of the motor winding becomes the heating coil, which eliminates disassembly and reassembly procedures to replace defective heaters.
- Trickle voltage heating can prolong winding insulation life because it reduces thermal shocks. When the motor is started, the winding is already "warmed up." Conversely, when the motor is stopped, the winding will gradually cool from running temperature to "trickle" heating temperature.
- No additional UL approval is required as in the case of heaters. This is a special advantage, since field installation of space heaters cannot be done on hazardous location motors.
- Small motors, especially totally enclosed units, have very little room available for installation of heaters.
- Installed costs may compare favorably with heater installation. Replacement motors also do not have to be equipped with space heaters.
- It is not necessary to run additional wiring to the motor since the power leads are used for trickle voltage heating.

The main disadvantage to trickle voltage heating is that the voltage rating required to pull sufficient amperage is a function of the specific motor design. Therefore each system must be finely tuned, which may result in unforeseen labor costs.

How to determine the proper current level

A little trial and error with the applied voltage will determine the proper current level to maintain a winding temperature approximately 10°C (18°F) above ambient and prevent condensation. Start at the low end of the voltage range and work up measuring the current at each step. Use the formula below with your experimental voltages until the watts are equal to the watts from the formula below.

W = I x V x PF

Where: I = Measured amperage
V = Applied reduced voltage
PF = Power factor (use 0.25)

The circuit in Figure 2-11shows how to connect a step-down transformer through auxiliary contacts to provide the voltage determined by the formula only when the unit is off. The transformer should have ±5% and ±10% taps so the voltage can be tuned to the application. The time delay relay should be 10-180 seconds to allow the magnetic field of the motor to collapse before energizing the single-phase connection. This will prevent re-closure damage to the motor or transformer.

Trickle voltage units that are available commercially take a lot of the experimentation out of the process. These units offer the ability to "plug in" with the engineering and control already done. This is particularly useful for retrofit situations since the motor will not need to be removed or disassembled. All the work can be accomplished in the motor control cabinet.

Note: The information on space heaters is based on an article from *EASA Currents* (July 2013); it was reviewed and updated as necessary in September 2019. Some information on space heaters was also provided by Howard Barr of U.S. Electrical Motors.

2.8 PERFORMANCE CHARACTERISTICS OF AC MOTORS

FULL-LOAD CURRENT OF SINGLE-PHASE MOTORS

FOR CONDUCTOR SIZING ONLY **FULL-LOAD CURRENT IN AMPERES**

	Rated voltage			
hp	115V	200V	208V	230V
1/6	4.4	2.5	2.4	2.2
1/4	5.8	3.3	3.2	2.9
1/3	7.2	4.1	4.0	3.6
1/2	9.8	5.6	5.4	4.9
3/4	13.8	7.9	7.6	6.9
1	16	9.2	8.8	8
1 1/2	20	11.5	11	10
2	24	13.8	13.2	12
3	34	19.6	18.7	17
5	56	32.2	30.8	28
7 1/2	80	46	44	40
10	100	57.5	55	50

Branch-circuit conductors supplying a single motor shall have an ampacity not less than 125 percent of the motor full-load current rating.

Based on Table 430.148 of the *National Electrical Code*®.

There are no IEC equivalents for motor full-load current.

LOCKED-ROTOR CURRENT OF 60-HERTZ SINGLE-PHASE SMALL MOTORS

NEMA DESIGN N AND O **LOCKED-ROTOR CURRENT IN AMPERES**

	2-, 4-, 6- and 8-pole			
	Design N motors		Design O motors	
hp	115 volts	230 volts	115 volts	230 volts
1/6 and smaller	20	12	50	25
1/4	26	15	50	25
1/3	31	18	50	25
1/2	45	25	50	25
3/4	61	35		
1	80	45		

The locked-rotor current of Design N and O, 60-hertz, single-phase motors shall not exceed the values given in the table above. The locked-rotor current of single-phase general-purpose motors shall not exceed the values for Design N motors.

Reference: NEMA Stds. MG 1, 12.33.

There are no IEC equivalents for motor locked-rotor current.

LOCKED-ROTOR CURRENT OF 60-HERTZ SINGLE-PHASE MEDIUM MOTORS

NEMA DESIGN L AND M **LOCKED-ROTOR CURRENT IN AMPERES**

	Design L motors		Design M motors
hp	115 volts	230 volts	230 volts
1/2	45	25	
3/4	61	35	
1	80	45	
1 1/2		50	40
2		65	50
3		90	70
5		135	100
7 1/2		200	150
10		260	200

The locked-rotor current of single-phase, 60-hertz, Design L and M motors of all types, when measured with rated voltage and frequency impressed and with rotor locked, shall not exceed the above values.

Reference: NEMA Stds. MG 1, 12.34.

LOCKED-ROTOR TORQUE OF 60- AND 50-HERTZ SINGLE-PHASE, GENERAL PURPOSE SMALL INDUCTION MOTORS

MINIMUM LOCKED-ROTOR TORQUE IN OUNCE-FEET*

	60 Hz Synchronous speed, rpm			50 Hz Synchronous speed, rpm		
hp	3600	1800	1200	3000	1500	1000
1/8		24	32		29	39
1/6	15	33	43	18	39	51
1/4	21	46	59	25	55	70
1/3	26	57	73	31	69	88
1/2	37	85	100	44	102	120
3/4	50	119		60	143	
1	61			73		

* On the high-voltage connection of the dual-voltage motors, minimum locked-rotor torques up to 10% less than these values may be expected.

The locked-rotor torque of single-phase, general-purpose small motors, with rated voltage and frequency applied, shall be not less than the above values.

Reference: NEMA Stds. MG 1, 12.32.2.

LOCKED-ROTOR TORQUE OF 60-HERTZ SINGLE-PHASE, GENERAL PURPOSE MEDIUM INDUCTION MOTORS

MINIMUM LOCKED-ROTOR TORQUE IN POUND-FEET

hp	Synchronous speed, rpm 3600	1800	1200
3/4			8.0
1		9.0	9.5
1 1/2	4.5	12.5	13.0
2	5.5	16.0	16.0
3	7.5	22.0	23.0
5	11.0	33.0	
7 1/2	16.0	45.0	
10	21.0	52.0	

The locked-rotor torque of single-phase general-purpose medium motors, with rated voltage and frequency applied, shall be not less than the above values.

Reference: NEMA Stds. MG 1, 12.32.3.

BREAKDOWN TORQUE OF 60- AND 50-HERTZ, SHADED-POLE AND PERMANENT SPLIT-CAPACITOR MOTORS FOR FAN AND PUMP APPLICATIONS

	60 Hz Synchronous speed, rpm			50 Hz Synchronous speed, rpm	
	1800	1200	900	1500	1000
hp	BREAKDOWN TORQUE IN OUNCE-FEET				
1/20	3.20—4.13	4.70—6.09	6.20—8.00	3.80-4.92	5.70—7.31
1/15	4.13—5.23	6.09—7.72	8.00—10.1	4.92—6.23	7.31—9.26
1/12	5.23—6.39	7.72—9.42	10.1—12.4	6.23—7.61	9.26—11.3
1/10	6.39—8.00	9.42—11.8	12.4—15.5	7.61—9.54	11.3—14.2
1/8	8.00—10.4	11.8—15.3	15.5—20.1	9.54—12.4	14.2—18.4
1/6	10.4—12.7	15.3—18.8	20.1—24.6	12.4—15.1	18.4—22.5
1/5	12.7—16.0	18.8—23.6	24.6—31.0	15.1—19.1	22.5—28.3
1/4	16.0—21.0	23.6—31.5	31.0—41.0	19.1—25.4	28.3—37.6
1/3	21.0—31.5	31.5—47.0	41.0—61.0	25.4—37.7	37.6—56.5
1/2	31.5—47.5	47.0—70.8	*	37.7—57.3	56.5—84.8
3/4	47.5—63.5	*	*	57.3—76.5	*
hp	BREAKDOWN TORQUE IN POUND-FEET				
1/2	†	†	3.81—5.81	†	†
3/4	†	4.42—5.88	5.81—7.62	†	5.30—7.06
1	3.97—5.94	5.88—8.88	7.62—11.6	4.78—7.06	7.06—10.6
1 1/2	5.94—7.88	8.88—11.8	11.6—15.2	7.06—9.56	10.6—14.1

* The breakdown torque is given in pound-feet. See lower part of the table.

† The breakdown torque is given in ounce-feet. See upper part of the table.

The breakdown torque range includes the higher figure down to, but not including, the lower figure.

The horsepower rating of motors designed to operate on two or more frequencies shall be determined by the torque at the highest rated frequency.

Reference: NEMA Stds. MG 1, 10.34 (Table 10-6).

BREAKDOWN TORQUE OF 60- AND 50-HERTZ, SINGLE-PHASE, GENERAL PURPOSE SMALL INDUCTION MOTORS

BREAKDOWN TORQUE IN OUNCE-FEET

	60 Hz Synchronous speed, rpm				50 Hz Synchronous speed, rpm		
hp	3600	1800	1200	900	3000	1500	1000
1/20	2.0—3.7	4.0—7.1	6.0—10.4	8.0—13.5	2.4—4.4	4.8—8.5	7.2—12.4
1/12	3.7—6.0	7.1—11.5	10.4—16.5	13.5—21.5	4.4—7.2	8.5—13.8	12.4—19.8
1/8	6.0—8.7	11.5—16.5	16.5—24.1	21.5—31.5	7.2—10.5	13.8—19.8	19.8—28.9
1/6	8.7—11.5	16.5—21.5	24.1—31.5	31.5—40.5	10.5—13.8	19.8—25.8	28.9—37.8
1/4	11.5—16.5	21.5—31.5	31.5—44.0	40.5—58.0	13.8—19.8	25.8—37.8	37.8—53.0
1/3	16.5—21.5	31.5—40.5	44.0—58.0	58.0—77.0	19.8—25.8	37.8—48.5	53.0—69.5
1/2	21.5—31.5	40.5—58.0	58.0—82.5		25.8—37.8	48.5—69.5	69.5—99.0
3/4	31.5—44.0	58.0—82.5			37.8—53.0	69.5—99.0	
1	44.0—58.0				53.0—69.5		

The breakdown torque of single-phase, general-purpose small induction motors shall be the higher figure in each torque range as given in the table above, subject to tolerances in manufacturing and all other conditions given in NEMA Stds. MG 1, 10.34.

The breakdown torque range includes the higher figure down to, but not including, the lower figure.

The horsepower ratings of motors designed to operate on two or more frequencies shall be determined by the torque at the highest rated frequency.

Reference: NEMA Stds. MG 1, 10.34 (Table 10-5) and 12.32.1.

BREAKDOWN TORQUE OF 60- AND 50-HERTZ, SINGLE-PHASE, GENERAL PURPOSE MEDIUM INDUCTION MOTORS

BREAKDOWN TORQUE IN POUND-FEET

	60 Hz Synchronous speed, rpm			50 Hz Synchronous speed, rpm	
hp	3600	1800	1200	3000	1500
3/4			5.16—6.9		
1		5.16—6.8	6.9—9.2		6.19—8.2
1 1/2	3.6—4.6	6.8—10.1	9.2—13.8	4.3—5.5	8.2—12.1
2	4.6—6.0	10.1—13.0	13.8—18.0	5.5—7.2	12.1—15.6
3	6.0—8.6	13.0—19.0	18.0—25.8	7.2—10.2	15.6—22.8
5	8.6—13.5	19.0—30.0	25.8—40.5	10.2—16.2	22.8—36.0
7 1/2	13.5—20.0	30.0—45.0	40.5—60.0	16.2—24.0	36.0—54.0
10	20.0—27.0	45.0—60.0		24.0—32.4	54.0—72.0

The breakdown torque of single-phase general-purpose medium induction motors shall be the higher figure in each torque range as given in the table above, subject to tolerances in manufacturing and all other conditions given in NEMA Stds. MG 1, 10.34.

The breakdown torque range includes the higher figure down to, but not including, the lower figure.

The horsepower ratings of motors designed to operate on two or more frequencies shall be determined by the torque at the highest rated frequency.

Reference: NEMA Stds. MG 1, 10.34 (Table 10-5) and 12.32.1.

BREAKDOWN TORQUE AND LOCKED-ROTOR CURRENT OF 60-HERTZ, SINGLE-PHASE HERMETIC MOTORS

Synchronous speed, rpm			
3600		1800	
Breakdown torque Ounce-feet	Locked-rotor current Amperes at 115 volts	Breakdown torque Ounce-feet	Locked-rotor current Amperes at 115 volts
5.25	20	10.5	20
6.25	20	12.5	20
7.5	20	15	20
9.0	20	18	20
10.75	21	21.5	20
13.0	23	26	21.5
15.5	26	31	23
18.5	29	37	28 23*
22.0	33	44.5	34 23*
27.0	38	53.5	40
32.0	43	64.5	48 46*
38.5	49	77	57 46*
46.0	56	92.5	68 46*
Pound-feet	**Amperes at 230 volts**	**Pound-feet**	**Amperes at 230 volts**
3.5	32	7	36
4.5	39	9	38
5.5	46	11	44
7.0	56	14	56
9.0	69	18	68
11.5	85	23	85
14.5	104	29	104
18.0	126	36	126
22.5	154	45	155

* Motors having locked-rotor currents within these values usually have lower locked-rotor torques than motors with the same breakdown torque ratings and the higher locked-rotor current values.

The breakdown torque of 60-hertz, single-phase hermetic motors, with rated voltage and frequency applied, shall be in accordance with the values given in the table above, which represent the upper limit of the range of application for these motors.

The locked-rotor current of 60-hertz, single-phase hermetic motors, with rated voltage and frequency applied and with rotor locked, shall not exceed the above values.

Reference: NEMA Stds. MG 1, 18.7.

There are no IEC equivalents for locked-rotor current.

NEMA CODE LETTERS USUALLY APPLIED TO RATINGS OF SINGLE-PHASE MOTORS NORMALLY STARTED ON FULL VOLTAGE*

Code letter	G	H	J	K	L
Horsepower	5	3	2 - 1.5	1 - .75	.5

* See "NEMA Code Letters for Locked-Rotor kVA" below.

There are no code letters for IEC motors. To calculate starting kVA per horsepower, use the equation below.

STARTING KVA PER HORSEPOWER FOR SINGLE-PHASE MOTORS

$$\text{Starting kVA per hp} = \frac{\text{Volts x Locked-rotor amps}}{\text{1000 x hp}}$$

NEMA CODE LETTERS FOR LOCKED-ROTOR KVA

The letter designations for locked-rotor kVA per horsepower as measured at full voltage and rated frequency are as follows.

Letter designation	kVA per horsepower*			Letter designation	kVA per horsepower*		
A	0	-	3.15	K	8.0	-	9.0
B	3.15	-	3.55	L	9.0	-	10.0
C	3.55	-	4.0	M	10.0	-	11.2
D	4.0	-	4.5	N	11.2	-	12.5
E	4.5	-	5.0	P	12.5	-	14.0
F	5.0	-	5.6	R	14.0	-	16.0
G	5.6	-	6.3	S	16.0	-	18.0
H	6.3	-	7.1	T	18.0	-	20.0
J	7.1	-	8.0	U	20.0	-	22.4
				V	22.4	-	and up

* Locked kVA per horsepower range includes the lower figure up to, but not including, the higher figure. For example, 3.14 is designated by letter A and 3.15 by letter B. There are no code letters for IEC motors.

Reference: NEMA Stds. MG 1, 10.37.2.

LOCKED-ROTOR AMPS FOR SINGLE-PHASE MOTORS

$$\text{Locked-rotor amps} = \frac{\text{Starting kVA per hp x hp x 1000}}{\text{Volts}}$$

Note that two calculations will be needed to determine the range of current possible with each kVA code letter.

FULL-LOAD CURRENT OF THREE-PHASE AC INDUCTION TYPE SQUIRREL CAGE AND WOUND-ROTOR MOTORS*

*FOR CONDUCTOR SIZING ONLY FULL-LOAD CURRENT IN AMPERES

	Rated voltage						
hp	**115V**	**200V**	**230V**	**460V**	**575V**	**2300V**	**4000V**
0.5	4.4	2.5	2.2	1.1	0.9		
0.75	6.4	3.7	3.2	1.6	1.3		
1	8.4	4.8	4.2	2.1	1.7		
1.5	12.0	6.9	6.0	3.0	2.4		
2	13.6	7.8	6.8	3.4	2.7		
3		11.0	9.6	4.8	3.9		
5		17.5	15.2	7.6	6.1		
7.5		25.3	22	11	9		
10		32.2	28	14	11		
15		48.3	42	21	17		
20		62.1	54	27	22		
25		78.2	68	34	27		
30		92	80	40	32		
40		120	104	52	41		
50		150	130	65	52		
60		177	154	77	62	16	9
75		221	192	96	77	20	11
100		285	248	124	99	26	14
125		359	312	156	125	31	18
150		414	360	180	144	37	21
200		552	480	240	192	49	28
250				302	242	60	35
300				361	289	72	41
350				414	336	83	48
400				477	382	95	55
450				515	412	103	59
500				590	472	118	68
Over 200 hp							
Approx. amps/hp	2.75	2.64	2.4	1.2	.96	.24	.14

Branch-circuit conductors supplying a single motor shall have an ampacity not less than 125 percent of the motor full-load current rating. Based on Table 430.150 of the *National Electrical Code*®.

FULL-LOAD CURRENT OF THREE-PHASE SYNCHRONOUS MOTORS

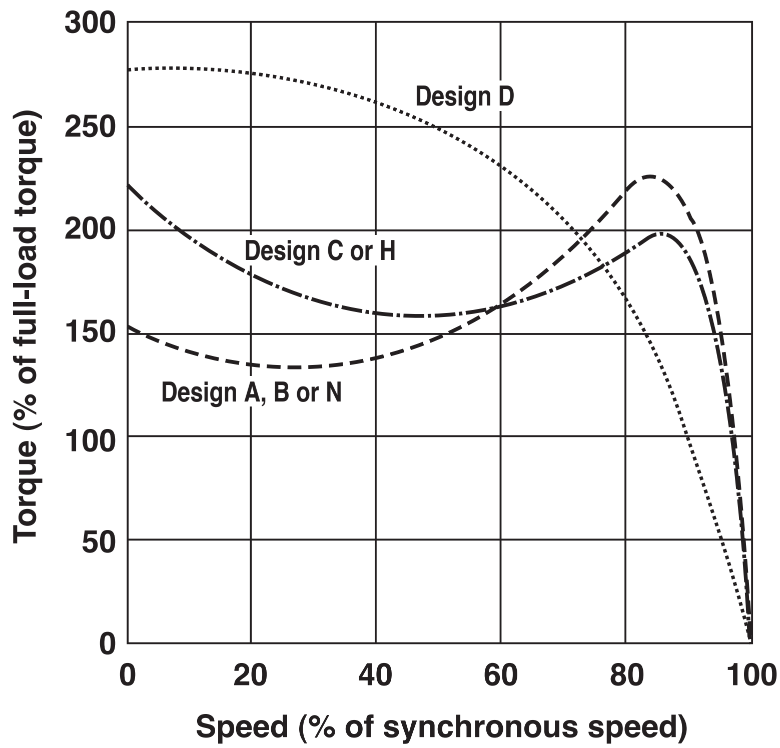
UNITY POWER FACTOR

***FOR CONDUCTOR SIZING ONLY** **FULL-LOAD CURRENT IN AMPERES**

	Rated voltage			
hp	**460V**	**575V**	**2300V**	**4000V**
100	100	80	20	12
125	125	100	25	14
150	150	120	30	17
200	200	160	40	23
250	250	200	50	29
300	300	240	60	35
350	353	282	71	41
400	403	322	81	46
500	500	400	100	58
600	600	480	120	69
700	705	564	141	81
800	805	644	161	93
900	905	724	181	104
1000	960	768	192	110

Branch-circuit conductors supplying a single motor shall have an ampacity not less than 125 percent of the motor full-load current rating.
Based on Table 430.248 of the *National Electrical Code*®.
There are no IEC equivalents for motor full-load current.

GENERAL SPEED-TORQUE CHARACTERISTICS OF THREE-PHASE INDUCTION MOTORS



	NEMA A	NEMA B	NEMA C	NEMA D	IEC H	IEC N
Locked rotor torque	70 - 275%*	70 - 275%*	200 - 285%*	275%	200 - 285%*	75 - 190%*
Breakdown torque	175 - 300%*	175 - 300%*	190 - 225%*	275%	190 - 200%*	160 - 200%*
Locked rotor current	Not defined	600 - 800%	600 - 800%	600 - 800%	800 - 1000%	800 - 1000%
Slip	0.5% - 5%	0.5% - 5%	1 - 5%	≥ 5%	1 - 5%	0.5 - 3%
Applications	†	†	† †	† † †	† †	†

Based on NEMA Stds. MG 10, Table 1.

* Higher values are for motors having lower horsepower ratings.

† Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.

†† Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required.

††† High peak loads with or without flywheels, such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping, and wire-drawing machines.

MAXIMUM LOCKED-ROTOR CURRENT OF THREE-PHASE, 60-HERTZ, SINGLE-SPEED, SQUIRREL-CAGE MEDIUM MOTORS

NEMA DESIGN B, C & D **LOCKED-ROTOR CURRENT IN AMPERES**

hp	Rated voltage, 60 Hz						Design letters
	200V	230V	460V	575V	2300V	4000V	
0.5	23	20	10	8			B, D
0.75	29	25	12	10			B, D
1	34	30	15	12			B, D
1.5	46	40	20	16			B, D
2	57	50	25	20			B, D
3	74	64	32	26			B, C, D
5	106	92	46	37			B, C, D
7.5	146	127	63	51			B, C, D
10	186	162	81	65			B, C, D
15	267	232	116	93			B, C, D
20	333	290	145	116			B, C, D
25	420	365	182	146			B, C, D
30	500	435	217	174			B, C, D
40	667	580	290	232			B, C, D
50	834	725	362	290			B, C, D
60	1000	870	435	348	87	50	B, C, D
75	1250	1085	542	434	108	62	B, C, D
100	1665	1450	725	580	145	83	B, C, D
125	2085	1815	907	726	181	104	B, C, D
150	2500	2170	1085	868	217	125	B, C, D
200	3335	2900	1450	1160	290	167	B, C
250	4200	3650	1825	1460	365	210	B
300	5060	4400	2200	1760	440	253	B
350	5860	5100	2550	2040	510	293	B
400	6670	5800	2900	2320	580	333	B
450	7470	6500	3250	2600	650	374	B
500	8340	7250	3625	2900	725	417	B

The locked-rotor current of Design B, C and D constant-speed induction motors, when measured with rated voltage and frequency impressed and with rotor locked, shall not exceed the above values.

Reference: NEMA Stds. MG 1, 12.35.1.

There are no IEC equivalents for motor locked-rotor current.

MAXIMUM LOCKED-ROTOR CURRENT OF THREE-PHASE, 50-HERTZ,SINGLE-SPEED SQUIRREL-CAGE MEDIUM MOTORS AT 380 VOLTS

NEMA DESIGN B, C & D

hp	Locked-rotor current, amperes*	Design letters
0.75 or less	20	B, D
1	20	B, C, D
1.5	27	B, C, D
2	34	B, C, D
3	43	B, C, D
5	61	B, C, D
7.5	84	B, C, D
10	107	B, C, D
15	154	B, C, D
20	194	B, C, D
25	243	B, C, D
30	289	B, C, D
40	387	B, C, D
50	482	B, C, D
60	578	B, C, D
75	722	B, C, D
100	965	B, C, D
125	1207	B, C, D
150	1441	B, C, D
200	1927	B, C
250	2534	B
300	3026	B
350	3542	B
400	4046	B
450	4539	B
500	5069	B

* The locked-rotor current of motors designed for voltages other than 380 volts shall be inversely proportional to the voltages.

Reference: NEMA Stds. MG 1, 12.35.2.

There are no IEC equivalents for locked-rotor current.

LOCKED-ROTOR TORQUE OF 60- AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN B, C & D **LOCKED-ROTOR TORQUE IN PERCENT OF FULL-LOAD TORQUE**

	Synchronous speed, rpm							
hp	60 hertz 50 hertz	3600 3000	1800 1500	1200 1000	900 750	720	600	514
0.5					140	140	115	110
0.75				175	135	135	115	110
1			275	170	135	135	115	110
1.5		175	250	165	130	130	115	110
2		170	235	160	130	125	115	110
3		160	215	155	130	125	115	110
5		150	185	150	130	125	115	110
7.5		140	175	150	125	120	115	110
10		135	165	150	125	120	115	110
15		130	160	140	125	120	115	110
20		130	150	135	125	120	115	110
25		130	150	135	125	120	115	110
30		130	150	135	125	120	115	110
40		125	140	135	125	120	115	110
50		120	140	135	125	120	115	110
60		120	140	135	125	120	115	110
75		105	140	135	125	120	115	110
100		105	125	125	125	120	115	110
125		100	110	125	120	115	115	110
150		100	110	120	120	115	115	
200		100	100	120	120	115		
250		70	80	100	100			
300		70	80	100				
350		70	80	100				
400		70	80					
450		70	80					
500		70	80					

The locked-rotor torque of Design A and B motors, with rated voltage and frequency applied, shall be not less than the above values.
Reference: NEMA Stds. MG 1, 12.38.1.

LOCKED-ROTOR TORQUE OF 60- AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN C **LOCKED-ROTOR TORQUE IN PERCENT OF FULL-LOAD TORQUE**

hp	Synchronous speed, rpm			
	60 hertz 50 hertz	1800 1500	1200 1000	900 750
1		285	255	225
1.5		285	250	225
2		285	250	225
3		270	250	225
5		255	250	225
7.5		250	225	200
10		250	225	200
15		225	210	200
20-200 inclusive		200	200	200

The locked-rotor torque of Design C motors, with rated voltage and frequency applied, shall be not less than the above values.
Reference: NEMA Stds. MG 1, 12.38.2.

LOCKED-ROTOR TORQUE OF 60- AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN D **LOCKED-ROTOR TORQUE IN PERCENT OF FULL-LOAD TORQUE**

hp	Synchronous speed, rpm			
	60 hertz 50 hertz	1800 1500	1200 1000	900 750
150 and smaller		275	275	275

The locked-rotor torque of Design D motors, with rated voltage and frequency applied, shall be not less than the above values.
Reference: NEMA Stds. MG 1, 12.38.3.

BREAKDOWN TORQUE OF 60-AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN A & B **BREAKDOWN TORQUE IN PERCENT OF FULL-LOAD TORQUE**

	Synchronous speed, rpm							
hp	60 hertz 50 hertz	3600 3000	1800 1500	1200 1000	900 750	720	600	514
0.5					225	200	200	200
0.75				275	220	200	200	200
1			300	265	215	200	200	200
1.5		250	280	250	210	200	200	200
2		240	270	240	210	200	200	200
3		230	250	230	205	200	200	200
5		215	225	215	205	200	200	200
7.5		200	215	205	200	200	200	200
10-125 inclusive		200	200	200	200	200	200	200
150		200	200	200	200	200	200	
200		200	200	200	200	200		
250		175	175	175	175			
300-350		175	175	175				
400-500 inclusive		175	175					

The breakdown torque of Design A and B motors, with rated voltage and frequency applied, shall be not less than the above values.
Reference: NEMA Stds. MG 1, 12.39.1.

BREAKDOWN TORQUE OF 60- AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN C **BREAKDOWN TORQUE IN PERCENT OF FULL-LOAD TORQUE**

	Synchronous speed, rpm			
hp	60 hertz 50 hertz	1800 1500	1200 1000	900 750
1		200	225	200
1.5		200	225	200
2		200	225	200
3		200	225	200
5		200	200	200
7.5-20		200	190	190
25-200 inclusive		190	190	190

The breakdown torque of Design C motors, with rated voltage and frequency applied, shall be not less than the above values.
Reference: NEMA Stds. MG 1, 12.39.2.

BREAKDOWN TORQUE OF 60- AND 50-HERTZ POLYPHASE WOUND-ROTOR MEDIUM MOTORS WITH CONTINUOUS RATINGS

BREAKDOWN TORQUE IN PERCENT OF FULL-LOAD TORQUE

hp	Synchronous speed, rpm			
	60 hertz 50 hertz	1800 1500	1200 1000	900 750
1				250
1.5				250
2		275	275	250
3		275	275	250
5		275	275	250
7.5		275	275	225
10		275	250	225
15		250	225	225
20-200 inclusive		225	225	225

The breakdown torque of wound-rotor medium motors, with rated voltage and frequency applied, shall be not less than the above values.

Reference: NEMA Stds. MG 1, 12.41.

BREAKDOWN TORQUE AND LOCKED-ROTOR CURRENT OF 60-HERTZ POLYPHASE SQUIRREL-CAGE INDUCTION HERMETIC MOTORS

Synchronous speed, rpm			
3600		1800	
Breakdown torque Pound-feet	Locked-rotor current Amperes at 230 volts	Breakdown torque Pound-feet	Locked-rotor current Amperes at 230 volts
4.5	24	9	24
5.5	30	11	30
7.0	38	14	38
9.0	48	18	48
11.5	59	23	59
14.5	71	29	71
18.0	85	36	85
22.5	102	45	102
28.0	125	56	125
		70	153
		88	189

The breakdown torque of 60-hertz, polyphase hermetic motors, with rated voltage and frequency applied, shall be in accordance with the values given in the table above, which represent the upper limit of the range of application for these motors.

The locked-rotor current of 60-hertz, polyphase hermetic motors, with rated voltage and frequency applied and with rotor locked, shall not exceed the above values.

Reference: NEMA Stds. MG 1, 18.7, 18.7.1 and 18.7.2.

PULL-UP TORQUE OF 60- AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN A & B **PULL-UP TORQUE IN PERCENT OF FULL-LOAD TORQUE**

	Synchronous speed, rpm							
hp	60 hertz 50 hertz	3600 3000	1800 1500	1200 1000	900 750	720	600	514
0.5					100	100	100	100
0.75				120	100	100	100	100
1			190	120	100	100	100	100
1.5		120	175	115	100	100	100	100
2		120	165	110	100	100	100	100
3		110	150	110	100	100	100	100
5		105	130	105	100	100	100	100
7.5		100	120	105	100	100	100	100
10		100	115	105	100	100	100	100
15		100	110	100	100	100	100	100
20		100	105	100	100	100	100	100
25		100	105	100	100	100	100	100
30		100	105	100	100	100	100	100
40		100	100	100	100	100	100	100
50		100	100	100	100	100	100	100
60		100	100	100	100	100	100	100
75		95	100	100	100	100	100	100
100		95	100	100	100	100	100	100
125		90	100	100	100	100	100	100
150		90	100	100	100	100	100	
200		90	90	100	100	100		
250		65	75	90	90			
300		65	75	90				
350		65	75	90				
400		65	75					
450		65	75					
500		65	75					

The pull-up torque of Design A and B motors, with rated voltage and frequency applied, shall be not less than the above values.

Reference: NEMA Stds. MG 1, 12.40.1.

PULL-UP TORQUE OF 60- AND 50-HERTZ SINGLE-SPEED POLYPHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA DESIGN C **PULL-UP TORQUE IN PERCENT OF FULL-LOAD TORQUE**

hp	Synchronous speed, rpm			
	60 hertz 50 hertz	1800 1500	1200 1000	900 750
1		195	180	165
1.5		195	175	160
2		195	175	160
3		180	175	160
5		180	175	160
7.5		175	165	150
10		175	165	150
15		165	150	140
20		165	150	140
25		150	150	140
30		150	150	140
40		150	150	140
50		150	150	140
60		140	140	140
75		140	140	140
100		140	140	140
125		140	140	140
150		140	140	140
200		140	140	140

The pull-up torque of Design C motors, with rated voltage and frequency applied, shall be not less than the above values.
Reference: NEMA Standards MG 1, 12.40.2.

FULL-LOAD EFFICIENCIES OF SINGLE-SPEED THREE-PHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

ENERGY-EFFICIENT OPEN MOTORS

NEMA DESIGN A & B OPEN MOTORS

	2 pole		4 pole		6 pole		8 pole	
hp	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency
1.0			82.5	80.0	80.0	77.0	74.0	70.0
1.5	82.5	80.0	84.0	81.5	84.0	81.5	75.5	72.0
2.0	84.0	81.5	84.0	81.5	85.5	82.5	85.5	82.5
3.0	84.0	81.5	86.5	84.0	86.5	84.0	86.5	84.0
5.0	85.5	82.5	87.5	85.5	87.5	85.5	87.5	85.5
7.5	87.5	85.5	88.5	86.5	88.5	86.5	88.5	86.5
10.0	88.5	86.5	89.5	87.5	90.2	88.5	89.5	87.5
15.0	89.5	87.5	91.0	89.5	90.2	88.5	89.5	87.5
20.0	90.2	88.5	91.0	89.5	91.0	89.5	90.2	88.5
25.0	91.0	89.5	91.7	90.2	91.7	90.2	90.2	88.5
30.0	91.0	89.5	92.4	91.0	92.4	91.0	91.0	89.5
40.0	91.7	90.2	93.0	91.7	93.0	91.7	91.0	89.5
50.0	92.4	91.0	93.0	91.7	93.0	91.7	91.7	90.2
60.0	93.0	91.7	93.6	92.4	93.6	92.4	92.4	91.0
75.0	93.0	91.7	94.1	93.0	93.6	92.4	93.6	92.4
100.0	93.0	91.7	94.1	93.0	94.1	93.0	93.6	92.4
125.0	93.6	92.4	94.5	93.6	94.1	93.0	93.6	92.4
150.0	93.6	92.4	95.0	94.1	94.5	93.6	93.6	92.4
200.0	94.5	93.6	95.0	94.1	94.5	93.6	93.6	92.4
250.0	94.5	93.6	95.4	94.5	95.4	94.5	94.5	93.6
300.0	95.0	94.1	95.4	94.5	95.4	94.5		
350.0	95.0	94.1	95.4	94.5	95.4	94.5		
400.0	95.4	94.5	95.4	94.5				
450.0	95.8	95.0	95.8	95.0				
500.0	95.8	95.0	95.8	95.0				

The full load efficiency of Design A and B motors rated 600 volts or less, when operating at rated voltage and frequency, shall not be less than the minimum efficiency listed in the table above for the motor to be classified as "energy efficient." Nominal efficiency represents a value which should be used to compute the energy consumption of a motor or group of motors.

Reference: NEMA Stds. MG 1, 12.59, Table 12-11.

The Energy Policy Act of 1992 (USA): The nominal full-load efficiency of 2-, 4- and 6-pole electric motors as specified in the Energy Policy Act of 1992 is the same as that listed in the table for 1.0 to 200.0 hp motors.

FULL-LOAD EFFICIENCIES OF SINGLE-SPEED THREE-PHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

ENERGY-EFFICIENT ENCLOSED MOTORS

NEMA DESIGN A & B ENCLOSED MOTORS

	2 pole		4 pole		6 pole		8 pole	
hp	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency
1.0	75.5	72.0	82.5	80.0	80.0	77.0	74.0	70.0
1.5	82.5	80.0	84.0	81.5	85.5	82.5	77.0	74.0
2.0	84.0	81.5	84.0	81.5	86.5	84.0	82.5	80.0
3.0	85.5	82.5	87.5	85.5	87.5	85.5	84.0	81.5
5.0	87.5	85.5	87.5	85.5	87.5	85.5	85.5	82.5
7.5	88.5	86.5	89.5	87.5	89.5	87.5	85.5	82.5
10.0	89.5	87.5	89.5	87.5	89.5	87.5	88.5	86.5
15.0	90.2	88.5	91.0	89.5	90.2	88.5	88.5	86.5
20.0	90.2	88.5	91.0	89.5	90.2	88.5	89.5	87.5
25.0	91.0	89.5	92.4	91.0	91.7	90.2	89.5	87.5
30.0	91.0	89.5	92.4	91.0	91.7	90.2	91.0	89.5
40.0	91.7	90.2	93.0	91.7	93.0	91.7	91.0	89.5
50.0	92.4	91.0	93.0	91.7	93.0	91.7	91.7	90.2
60.0	93.0	91.7	93.6	92.4	93.6	92.4	91.7	90.2
75.0	93.0	91.7	94.1	93.0	93.6	92.4	93.0	91.7
100.0	93.6	92.4	94.5	93.6	94.1	93.0	93.0	91.7
125.0	94.5	93.6	94.5	93.6	94.1	93.0	93.6	92.4
150.0	94.5	93.6	95.0	94.1	95.0	94.1	93.6	92.4
200.0	95.0	94.1	95.0	94.1	95.0	94.1	94.1	93.0
250.0	95.4	94.5	95.0	94.1	95.0	94.1	94.5	93.6
300.0	95.4	94.5	95.4	94.5	95.0	94.1		
350.0	95.4	94.5	95.4	94.5	95.0	94.1		
400.0	95.4	94.5	95.4	94.5				
450.0	95.4	94.5	95.4	94.5				
500.0	95.4	94.5	95.8	95.0				

The full load efficiency of Design A and B motors rated 600 volts or less, when operating at rated voltage and frequency, shall not be less than the minimum efficiency listed in the table above for the motor to be classified as “energy efficient.” Nominal efficiency represents a value which should be used to compute the energy consumption of a motor or group of motors.

Reference: NEMA Stds. MG 1, 12.59, Table 12-11.

The Energy Policy Act of 1992 (USA): The nominal full-load efficiency of 2-, 4- and 6-pole electric motors as specified in the Energy Policy Act of 1992 is the same as that listed in the table for 1.0 to 200.0 hp motors.

FULL-LOAD EFFICIENCIES OF THREE-PHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA PREMIUM™ EFFICIENCY OPEN MOTORS

NEMA DESIGN A & B OPEN MOTORS

	2 pole		4 pole		6 pole	
hp	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency
1.0	77.0	74.0	85.5	82.5	82.5	80.0
1.5	84.0	81.5	86.5	84.0	86.5	81.5
2.0	85.5	82.5	86.5	84.0	87.5	81.5
3.0	85.5	82.5	89.5	84.0	88.5	86.5
5.0	86.5	84.0	89.5	84.0	89.5	87.5
7.5	88.5	86.5	91.0	89.5	90.2	88.5
10.0	89.5	87.5	91.7	90.2	91.7	90.2
15.0	90.2	88.5	93.0	91.7	91.7	90.2
20.0	91.0	89.5	93.0	91.7	92.4	91.0
25.0	91.7	90.2	93.6	92.4	93.0	91.7
30.0	91.7	90.2	94.1	93.0	93.6	92.4
40.0	92.4	91.0	94.1	93.0	94.1	93.0
50.0	93.0	91.7	94.5	93.6	94.1	93.0
60.0	93.6	92.4	95.0	94.1	94.5	93.6
75.0	93.6	92.4	95.0	94.1	94.5	93.6
100.0	93.6	92.4	95.4	94.5	95.0	94.1
125.0	94.1	93.0	95.4	94.5	95.0	94.1
150.0	94.1	93.0	95.8	95.0	95.4	94.5
200.0	95.0	94.1	95.8	95.0	95.4	94.5
250.0	95.0	94.1	95.8	95.0	95.4	94.5
300.0	95.4	94.5	95.8	95.0	95.4	94.5
350.0	95.4	94.5	95.8	95.0	95.4	94.5
400.0	95.8	95.0	95.8	95.0	95.8	95.0
450.0	95.8	95.0	96.2	95.4	96.2	95.4
500.0	95.8	95.0	96.2	95.4	96.2	95.4

The full load efficiency of Design A and B motors rated 600 volts or less, when operating at rated voltage and frequency, shall not be less than the minimum efficiency listed in the table above for the motor to be classified as "energy efficient." Nominal efficiency represents a value which should be used to compute the energy consumption of a motor or group of motors.

Reference: NEMA Stds. MG 1, 12.60, Table 12-12.

The Energy Policy Act of 1992 (USA): The nominal full-load efficiency of 2-, 4- and 6-pole electric motors as specified in the Energy Policy Act of 1992 is the same as that listed in the table for 1.0 to 200.0 hp motors.

FULL-LOAD EFFICIENCIES OF THREE-PHASE SQUIRREL-CAGE MEDIUM MOTORS WITH CONTINUOUS RATINGS

NEMA PREMIUM™ EFFICIENCY ENCLOSED MOTORS

NEMA DESIGN A & B ENCLOSED MOTORS

	2 pole		4 pole		6 pole	
hp	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency
1.0	77.0	74.0	85.5	82.5	82.5	80.0
1.5	84.0	81.5	86.5	84.0	87.5	85.5
2.0	85.5	82.5	86.5	84.0	88.5	86.5
3.0	86.5	84.0	89.5	87.5	89.5	87.5
5.0	88.5	86.5	89.5	87.5	89.5	87.5
7.5	89.5	87.5	91.7	90.2	91.0	89.5
10.0	90.2	88.5	91.7	90.2	91.0	89.5
15.0	91.0	89.5	92.4	91.0	91.7	90.2
20.0	91.0	89.5	93.0	91.7	91.7	90.2
25.0	91.7	90.2	93.6	92.4	93.0	91.7
30.0	91.7	90.2	93.6	92.4	93.0	91.7
40.0	92.4	91.0	94.1	93.0	94.1	93.0
50.0	93.0	91.7	94.5	93.6	94.1	93.0
60.0	93.6	92.4	95.0	94.1	94.5	93.6
75.0	93.6	92.4	95.4	94.5	94.5	93.6
100.0	94.1	93.0	95.4	94.5	95.0	94.1
125.0	95.0	94.1	95.4	94.5	95.0	94.1
150.0	95.0	94.1	95.8	95.0	95.8	95.0
200.0	95.4	94.5	96.2	95.4	95.8	95.0
250.0	95.8	95.0	96.2	95.4	95.8	95.0
300.0	95.8	95.0	96.2	95.4	95.8	95.0
350.0	95.8	95.0	96.2	95.4	95.8	95.0
400.0	95.8	95.0	96.2	95.4	95.8	95.0
450.0	95.8	95.0	96.2	95.4	95.8	95.0
500.0	95.8	95.0	96.2	95.4	95.8	95.0

The full load efficiency of Design A and B motors rated 600 volts or less, when operating at rated voltage and frequency, shall not be less than the minimum efficiency listed in the table above for the motor to be classified as "energy efficient." Nominal efficiency represents a value which should be used to compute the energy consumption of a motor or group of motors.

Reference: NEMA Stds. MG 1, 12.60, Table 12-12.

The Energy Policy Act of 1992 (USA): The nominal full-load efficiency of 2-, 4- and 6-pole electric motors as specified in the Energy Policy Act of 1992 is the same as that listed in the table for 1.0 to 200.0 hp motors.

NOMINAL EFFICIENCY LIMITS (%) FOR 50 HZ IE3 MACHINES

P_N kW	NUMBER OF POLES/SYNCHRONOUS SPEED min–1			
	2/3000	**4/1500**	**6/1000**	**8/750**
0.12	60.8	64.8	57.7	50.7
0.18	65.9	69.9	63.9	58.7
0.20	67.2	71.1	65.4	60.6
0.25	69.7	73.5	68.6	64.1
0.37	73.8	77.3	73.5	69.3
0.40	74.6	78.0	74.4	70.1
0.55	77.8	80.8	77.2	73.0
0.75	80.7	82.5	78.9	75.0
1.1	82.7	84.1	81.0	77.7
1.5	84.2	85.3	82.5	79.7
2.2	85.9	86.7	84.3	81.9
3	87.1	87.7	85.6	83.5
4	88.1	88.6	86.8	84.8
5.5	89.2	89.6	88.0	86.2
7.5	90.1	90.4	89.1	87.3
11	91.2	91.4	90.3	88.6
15	91.9	92.1	91.2	89.6
18.5	92.4	92.6	91.7	90.1
22	92.7	93.0	92.2	90.6
30	93.3	93.6	92.9	91.3
37	93.7	93.9	93.3	91.8
45	94.0	94.2	93.7	92.2
55	94.3	94.6	94.1	92.5
75	94.7	95.0	94.6	93.1
90	95.0	95.2	94.9	93.4
110	95.2	95.4	95.1	93.7
132	95.4	95.6	95.4	94.0
160	95.6	95.8	95.6	94.3
200 up to 1000	95.8	96.0	95.8	94.6

Reference: IEC 60034-30-1, 5.4.3, Table 7.

NOMINAL EFFICIENCY LIMITS (%) FOR 60 HZ IE3 MACHINES

P_N kW	NUMBER OF POLES/SYNCHRONOUS SPEED min–1			
	2/3600	**4/1800**	**6/1200**	**8/900**
0.12	62.0	66.0	64.0	59.5
0.18	65.6	69.5	67.5	64.0
0.25	69.5	73.4	71.4	68.0
0.37	73.4	78.2	75.3	72.0
0.55	76.8	81.1	81.7	74.0
0.75	77.0	83.5	82.5	75.5
1.1	84.0	86.5	87.5	78.5
1.5	85.5	86.5	88.5	84.0
2.2	86.5	89.5	89.5	85.5
3.7	88.5	89.5	89.5	86.5
5.5	89.5	91.7	91.0	86.5
7.5	90.2	91.7	91.0	89.5
11	91.0	92.4	91.7	89.5
15	91.0	93.0	91.7	90.2
18.5	91.7	93.6	93.0	90.2
22	91.7	93.6	93.0	91.7
30	92.4	94.1	94.1	91.7
37	93.0	94.5	94.1	92.4
45	93.6	95.0	94.5	92.4
55	93.6	95.4	94.5	93.6
75	94.1	95.4	95.0	93.6
90	95.0	95.4	95.0	94.1
110	95.0	95.8	95.8	94.1
150	95.4	96.2	95.8	94.5
185 up to 1000	95.8	96.2	95.8	95.0

Reference: IEC 60034-30-1, 5.4.3, Table 8.

NOMINAL EFFICIENCY LIMITS (%) FOR 50 HZ IE4 MACHINES

P_N kW	NUMBER OF POLES/SYNCHRONOUS SPEED min–1			
	2/3000	4/1500	6/1000	8/750
0.12	66.5	69.8	64.9	62.3
0.18	70.8	74.7	70.1	67.2
0.20	71.9	75.8	71.4	68.4
0.25	74.3	77.9	74.1	70.8
0.37	78.1	81.1	78.0	74.3
0.40	78.9	81.7	78.7	74.9
0.55	81.5	83.9	80.9	77.0
0.75	83.5	85.7	82.7	78.4
1.1	85.2	87.2	84.5	80.8
1.5	86.5	88.2	85.9	82.6
2.2	88.0	89.5	87.4	84.5
3	89.1	90.4	88.6	85.9
4	90.0	91.1	89.5	87.1
5.5	90.9	91.9	90.5	88.3
7.5	91.7	92.6	91.3	89.3
11	92.6	93.3	92.3	90.4
15	93.3	93.9	92.9	91.2
18.5	93.7	94.2	93.4	91.7
22	94.0	94.5	93.7	92.1
30	94.5	94.9	94.2	92.7
37	94.8	95.2	94.5	93.1
45	95.0	95.4	94.8	93.4
55	95.3	95.7	95.1	93.7
75	95.6	96.0	95.4	94.2
90	95.8	96.1	95.6	94.4
110	96.0	96.3	95.8	94.7
132	96.2	96.4	96.0	94.9
160	96.3	96.6	96.2	95.1
200	96.5	96.7	96.3	95.4
250	96.5	96.7	96.5	95.4
315 up to 1000	96.5	96.7	96.6	95.4

Reference: IEC 60034-30-1, 5.4.4, Table 9.

Note: Tables 9 and 10 supercede Annex A of IEC 60034031:2010.

NOMINAL EFFICIENCY LIMITS (%) FOR 60 HZ IE4 MACHINES

P_N kW	NUMBER OF POLES/SYNCHRONOUS SPEED min–1			
	2/3600	4/1800	6/1200	8/900
0.12	66.0	70.0	68.0	64.0
0.18	70.0	74.0	72.0	68.0
0.25	74.0	77.0	75.5	72.0
0.37	77.0	81.5	78.5	75.5
0.55	80.0	84.0	82.5	77.0
0.75	82.5	85.5	84.0	78.5
1.1	85.5	87.5	88.5	81.5
1.5	86.5	88.5	89.5	85.5
2.2	88.5	91.0	90.2	87.5
3.7	89.5	91.0	90.2	88.5
5.5	90.2	92.4	91.7	88.5
7.5	91.7	92.4	92.4	91.0
11	92.4	93.6	93.0	91.0
15	92.4	94.1	93.0	91.7
18.5	93.0	94.5	94.1	91.7
22	93.0	94.5	94.1	93.0
30	93.6	95.0	95.0	93.0
37	94.1	95.4	95.0	93.6
45	94.5	95.4	95.4	93.6
55	94.5	95.8	95.4	94.5
75	95.0	96.2	95.8	94.5
90	95.4	96.2	95.8	95.0
110	95.4	96.2	96.2	95.0
150	95.8	96.5	96.2	95.4
185	96.2	96.5	96.2	95.4
220	96.2	96.8	96.5	95.4
250 up to 1000	96.2	96.8	96.5	95.8

Reference: IEC 60034-30-1, 5.4.4, Table 10.

Note: Tables 9 and 10 supercede Annex A of IEC 60034031:2010.

NEMA CODE LETTERS USUALLY APPLIED TO RATINGS OF THREE-PHASE MOTORS NORMALLY STARTED ON FULL VOLTAGE*

Code letter	F	G	H	J	K	L
Horsepower	15 up	10 - 7.5	5	3	2 - 1.5	1

* See "NEMA Code Letters for Locked-Rotor kVA" below.

There are no code letters for IEC motors. To calculate starting kVA per horsepower, use the equation below.

STARTING KVA PER HORSEPOWER FOR THREE-PHASE MOTORS

$$\text{Starting kVA per hp} = \frac{1.732 \times \text{Volts} \times \text{Locked-rotor amps}}{1000 \times \text{hp}}$$

NEMA CODE LETTERS FOR LOCKED-ROTOR KVA

The letter designations for locked-rotor kVA per horsepower as measured at full voltage and rated frequency are as follows.

Letter designation	kVA per horsepower*			Letter designation	kVA per horsepower*		
A	0	-	3.15	K	8.0	-	9.0
B	3.15	-	3.55	L	9.0	-	10.0
C	3.55	-	4.0	M	10.0	-	11.2
D	4.0	-	4.5	N	11.2	-	12.5
E	4.5	-	5.0	P	12.5	-	14.0
F	5.0	-	5.6	R	14.0	-	16.0
G	5.6	-	6.3	S	16.0	-	18.0
H	6.3	-	7.1	T	18.0	-	20.0
J	7.1	-	8.0	U	20.0	-	22.4
				V	22.4	-	and up

* Locked kVA per horsepower range includes the lower figure up to, but not including, the higher figure. For example, 3.14 is designated by letter A and 3.15 by letter B.

Reference: NEMA Stds. MG 1, 10.37.2.

LOCKED-ROTOR AMPS FOR THREE-PHASE MOTORS

$$\text{Locked-rotor amps} = \frac{\text{Starting kVA per hp} \times \text{hp} \times 1000}{1.732 \times \text{Volts}}$$

Note that two calculations will be needed to determine the range of current possible with each kVA code letter.

2.9 FACTORS AFFECTING THE PERFORMANCE OF AC MOTORS

The impact of voltage and frequency variation on motor life and performance

By Austin H. Bonnett
EASA Technical and Educational Consultant

ABSTRACT

Operation of AC Induction motors at voltage and frequencies other than the nominal value can effect significant changes in the motor operating costs, performance characteristics and life expectancy. This paper explores these changes using NEMA Standard MG 1: *Motors and Generators* as the benchmark for acceptable performance and variations.

(This article is an update of a 1999 IEEE Pulp & Paper Conference Presentation which has been expanded to commercial and general industrial applications.)

INTRODUCTION

Motor reliability, performance and life-cycle cost are key elements of a successful motor application when viewed from the user's perspective. Industrial motor specifications usually address bearing life, vibration, geometry and efficiency with considerable detail to achieve desired results.

When the power supply is defined, the nominal voltage is stated with the understanding that NEMA MG 1 will apply. This standard allows for variations in voltage and frequency, along with voltage unbalance.

The part of this standard that is not fully understood is that when allowing these variations, the motor performance and life are usually adversely affected. The purpose of this presentation is to review these NEMA MG 1 standards and the impact they have on motor performance and life. The amazing thing is that the standards do an excellent job of pointing these issues out, but the issues usually go unnoticed, partly due to the very limited distribution of MG 1.

TABLE 2-1: NOMINAL VOLTAGES

Voltage	60 Hz	50 Hz
200	√	—
220	—	√
230	√	—
380	—	√
460	√	—
575	√	—
2300	√	—
4000	√	—
4600	√	—
6600	√	—

Appendix I gives a more detailed breakdown.

VOLTAGE CONDITIONS—NOMINAL THREE-PHASE VOLTAGES

The voltages in Table 2-1 are defined as standard in accordance with MG 1, 10.30.

This article is limited to motors operating on sinusoidal power and does not consider the impact of adjustable-speed drives. However, NEMA MG 1 Parts 30 and 31 do cover this condition.

VARIATION FROM RATED VOLTAGE AND RATED FREQUENCY

NEMA MG 1, 12.44 says the following about variations from rated voltage and frequency.

> **12.44.1 Running.** Alternating-current motors shall operate successfully under running conditions at rated load with a variation in the voltage or the frequency up to the following:
>
> a. Plus or minus 10 percent of rated voltage, with rated frequency for induction motors.
> b. Plus or minus 6 percent of rated voltage, with rated frequency for universal motors.
> c. Plus or minus 5 percent of rated frequency, with rated voltage.
> d. A combined variation in voltage and frequency of 10 percent (sum of absolute values) of the rated values, provided the frequency variation does not exceed plus or minus 5 percent of rated frequency. . . .
>
> Performance within these voltage and frequency variations will not necessarily be in accordance with the standards established for operation at rated voltage and frequency.

EFFECTS OF VARIATION OF VOLTAGE AND FREQUENCY ON MOTOR PERFORMANCE

Regarding the effects of voltage and frequency variations on motor performance, NEMA MG 1, 14.30 says:

> **14.30.1 General.** Induction motors are at times operated on circuits of voltage or frequency other than those for which the motors are rated. Under such conditions, the performance of the motor will vary from the rating. The following are some of the operating results caused by small variations of voltage and frequency and are indicative of the general character of changes produced by such variation in operating conditions.
>
> **14.30.2 Effects of Variation in Voltage on Tem-**

perature. With a 10 percent increase or decrease in voltage from that given on the nameplate, the heating at rated horsepower load may increase. Such operation for extended periods of time may accelerate the deterioration of the insulation system.

14.30.3 Effect of Variation in Voltage on Power Factor. In a motor of normal characteristics at full rated horsepower load, a 10 percent increase of voltage above that given on the nameplate would usually result in a decided lowering in power factor. A 10 percent decrease of voltage below that given on the nameplate would usually give an increase in power factor.

14.30.4 Effect of Variation in Voltage on Starting Torques. The locked-rotor and breakdown torque will be proportional to the square of the voltage applied.

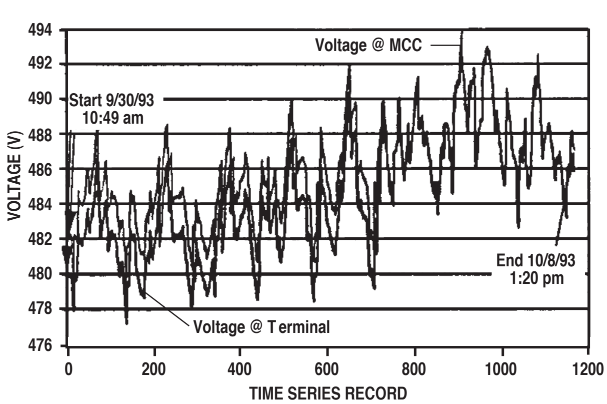
14.30.5 Effect of Variation in Voltage on Slip. An increase of 10 percent in voltage will result in a decrease of slip of about 17 percent, while a reduction of 10 percent will result in an increase slip amount of about 21 percent. Thus, if the slip at rated voltage were 5 percent, it would be increased to 6.05 percent if the voltage were reduced 10 percent.

14.30.6 Effect of Variation in Frequency. A frequency higher than the rated frequency usually improves the power factor but decreases locked rotor torque and increases the speed and friction and windage loss. At a frequency lower than the rated frequency, the speed is decreased, locked-rotor torque is increased and power factor is decreased. For certain kinds of motor load, such as, textile mills, close frequency regulation is essential.

14.30.7 Effect of Variations in Both Voltage and Frequency. If variations in both voltage and frequency occur simultaneously, the effect will be superimposed. Thus, if the voltage is high and the frequency low, the locked-rotor torque will be very greatly increased, but the power factor will be decreased and the temperature rise increased with normal load.

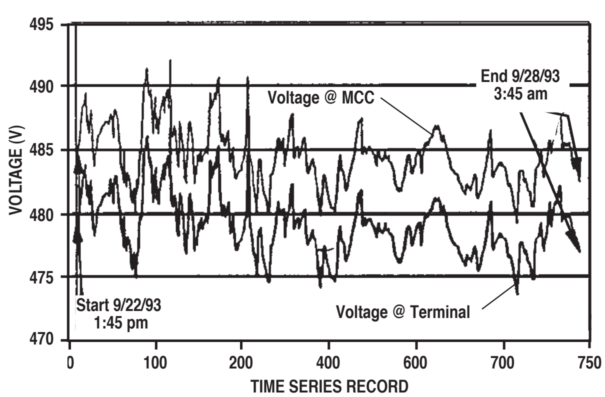
14.30.8 Effect on Special-Purpose or Small Motors. The foregoing facts apply particularly to general-purpose motors. They may not always be true

FIGURE 2-12



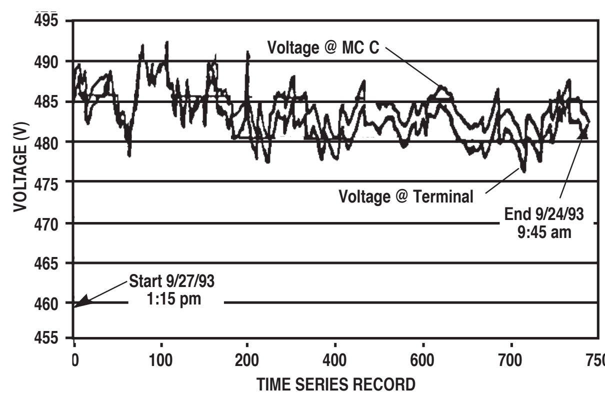
Voltage—200 hp motor driving a pump.

FIGURE 2-13



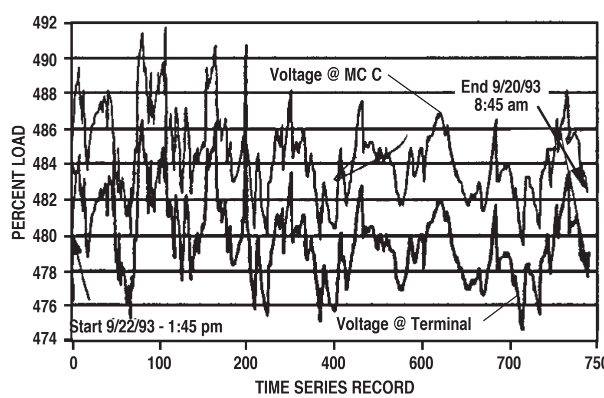
Voltage—100 hp motor driving a fan.

FIGURE 2-14



Voltage—50 hp motor driving a pump.

FIGURE 2-15



Voltage—30 hp motor driving an agitator.

in connection with special-purpose motors, built for a particular purpose, or for very small motors.

AN INDUSTRIAL STUDY ON VOLTAGE VARIATION

In 1995, Dr. P. Pillay conducted a study to determine the amount of voltage variation experienced in a typical petro-chemical application and its impact on motor performance. Figure 2-12, Figure 2-13, Figure 2-14 and Figure 2-15 illustrate the amount of variation experienced over a relatively short period of time. Although the extremes are within the NEMA standards, they will definitely affect the motor performance and life.

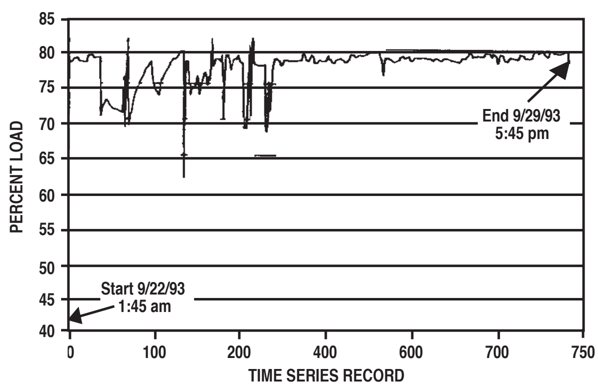
> Motors are designed to operate off 460 volts; measurements in the petro-chemical industry have revealed that the actual operating voltages can be somewhat higher, as shown in Figure 2-12, Figure 2-13, Figure 2-14 and Figure 2-15 for a 50 hp motor driving a pump, a 200 hp motor driving a pump, a 100 hp motor driving a fan, and a 30 hp motor driving an agitator. The corresponding loadings are shown in Figure 2-16 and Figure 2-17. These graphs show both the motor control center voltage as well as the actual motor terminal voltage obtained by subtracting off the line impedance drop. Coincidence of the two voltages indicated periods of no load or complete shut down." [5]

SPEED-TORQUE STARTING CHARACTERISTICS

Variations in the voltage will have a significant impact on the motor starting torque since it will vary as the square of the flux density. Here is what NEMA MG 1, 12.44 says about starting torque.

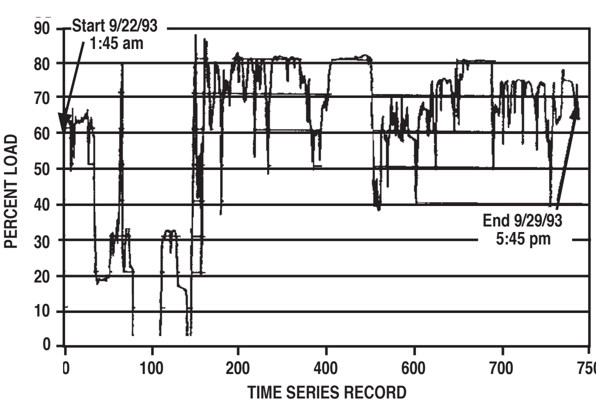
> **12.44.2 Starting.** Medium motors shall start and accelerate to running speed a load which has a torque characteristic and an inertia value not exceeding that listed in MG 1, 12.54 with the voltage and frequency variations specified in 12.44.1.
>
> The limiting values of voltage and frequency under which a motor will successfully start and accelerate to running speed depend on the margin between the speed-torque curve of the motor at rated voltage and

FIGURE 2-16



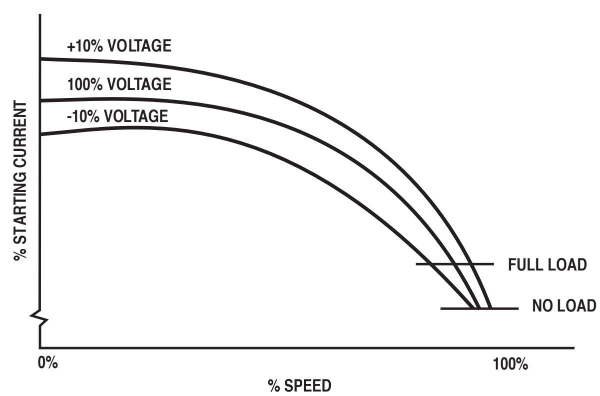
Percent load—100 hp motor driving a fan.

FIGURE 2-17



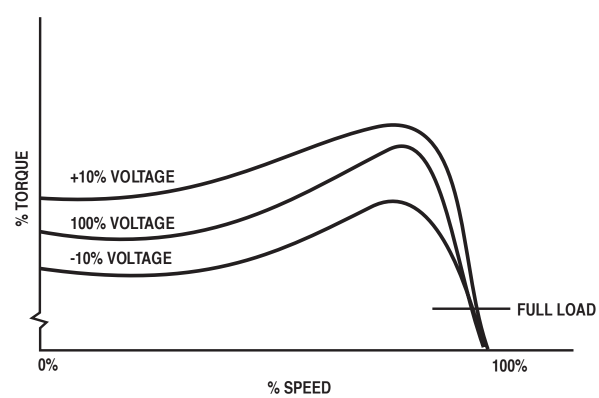
Percent load—50 hp motor driving a pump.

FIGURE 2-18



Starting current vs. speed.

FIGURE 2-19



Torque vs. speed.

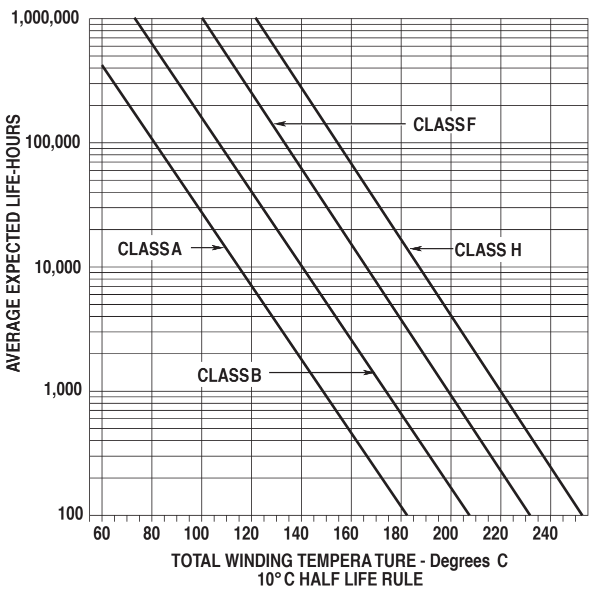
frequency and the speed-torque curve of the load under starting conditions. Since the torque developed by the motor at any speed is approximately proportional to the square of the voltage and inversely proportional to the square of the frequency, it is generally desirable to determine what voltage and frequency variations will actually occur at each installation, taking into account any voltage drop resulting from the starting current drawn by the motor. This information and the torque requirements of the driven machine define the motor-speed-torque curve, at rated voltage and frequency, which is adequate for the application.

The curves in Figure 2-18 and Figure 2-19 illustrate the impact of voltage variation on the speed-torque characteristics. The motor flux density varies directly with the voltage, and the torque varies as the square of the voltage.

MOTOR INSULATION LIFE AS AFFECTED BY TEMPERATURE

Figure 2-20 helps estimate the impact that voltage/frequency variations have on the winding insulation life once the temperature change is determined.

FIGURE 2-20



Temperature vs. life curves for insulation systems. Reference: Based on IEEE 117-2015, Table 1.

As shown in Figure 2-20, for every 10° C increase in winding temperature, the expected thermal life of the winding is reduced by half. There may also be a notable decrease in bearing lubricant life as the operating temperature of the motor increases.

SUMMARY OF EFFECTS OF VOLTAGE CHANGE

There are numerous tables available that indicate the effects of voltage variation on motor performance. Table 2-2 is typical for energy efficient motors.

TABLE 2-2: TYPICAL EFFECTS OF VOLTAGE CHANGE

	Effect of voltage change		
Operating characteristic	90% voltage	110% voltage	120% voltage
Starting and max. running torque	-19%	+21%	+44%
Synchronous speed	No change	No change	No change
Percent slip	+23%	-17%	-30%
Full load speed	-1.5%	+1.5%	+1.5%
Efficiency			
Full load, high eff.	-1 to -2 pts	+.5 to 1 pts	Small increase
T frame	+.5 to 1 pts	-1 to -4 pts	-7 to -10 pts
.75 load, high eff.	Pract. no change	Pract. no change	-.5 to -2 pts
T frame	+1 to 2 pts	-2 to -5 pts	-9 to -12 pts
.5 load, high eff.	+1 to 2 pts	-1 to -2 pts	-7 to -20 pts
T frame	+2 to 4 pts	-4 to -7 pts	-14 to -16 pts
Power factor			
Full load, high eff.	+1 pt	-3 pts	-5 to -15 pts
T frame	+9 to 10 pts	-10 to -15 pts	-10 to -30 pts
0.75 load, high eff.	+2 to 3 pts	-4 pts	-10 to -30 pts
T frame	+10 to 12 pts	-10 to -15 pts	-10 to -30 pts
0.5 load, high eff.	+4 to 5 pts	-5 to -6 pts	-15 to -40 pts
T frame	+10 to 15 pts	-10 to -15 pts	-10 to -30 pts
Full load current			
High eff.	+11%	-7%	-11%
T frame	+3 to 6%	+2 to 11%	+15 to 35%
Starting current	-10 to -12%	+10 to 12%	+25%
Temperature rise			
Full load, high eff.	+23%	-14%	-21%
T frame	+6 to 12%	+4 to 23%	+30 to 80%
Mag. noise, any load	Slight decrease	Slight increase	Noticeable increase

Reference: P. Pillay, IEEE PCIC-95-21, Sept. 1995.

MAGNETIC SATURATION

There has been some concern about the possibility of magnetic core saturation for the newer generation of energy efficient motors since the advent of EPACT motors. For the most part this concern is unfounded as long as the motor terminal voltage does not exceed the allowable 10% over-voltage limit, which would be 506 volts for a 460-volt or 253 volts for a 230-volt nameplated motor.

This concern may have been valid for earlier generations of the "T" frame motors, which were designed nearer the upper limit for flux densities in order to meet the temperature requirements of re-rating. However, current energy efficient motors normally operate at much lower temperatures and corresponding flux densities. It should also be pointed out that the electrical steels used today have improved permeability and lower losses. Hence, higher flux densities are not required.

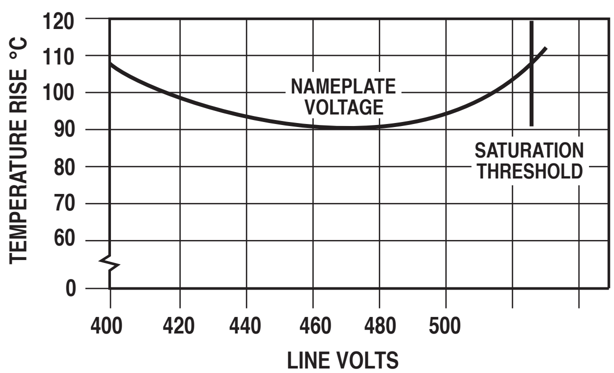
Table 2-3 illustrates the levels of flux densities used today in energy efficient motors. It is acknowledged that if the voltage does increase to the levels where saturation can occur, then motor performance will start to decrease. Because of the wide variety of electrical steel used today by the various manufacturers, it is not always possible to declare the point at which saturation will start to occur. Table 2-3 provides values for a typical energy efficient motor, both at nominal

TABLE 2-3: TYPICAL MOTOR FLUX DENSITIES FOR ENERGY EFFICIENCT MOTORS

50 hp	2 pole			4 pole			6 pole		
Densitites	B_g	B_T	B_c	B_g	B_T	B_c	B_g	B_T	B_c
Nominal voltage	25	96	101	27	93	100	24	103	111
10% over voltage	29	110	116	32	108	115	28	119	127
Saturation threshold	35	130	130	35	130	130	35	130	131

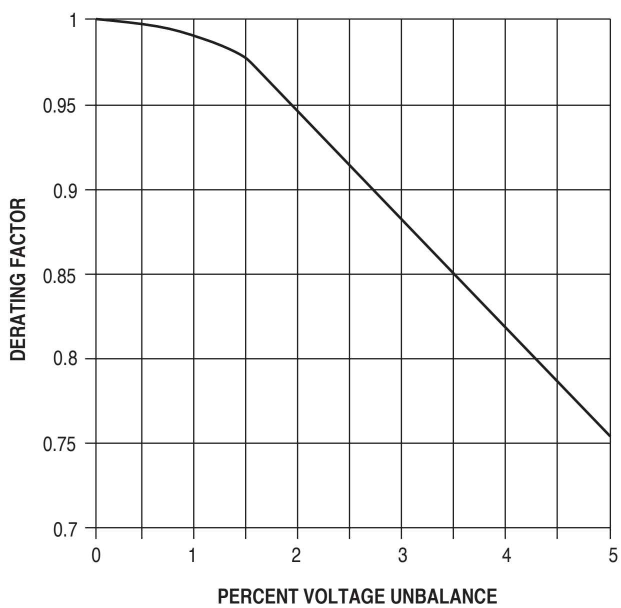
Note: Flux densities in kilolines/sq in
B_g is air gap; B_T is stator teeth; B_c is core density

FIGURE 2-21



Winding temperature rise °C vs. line voltage.

FIGURE 2-22



Medium motor derating factor due to unbalanced voltage (NEMA MG 1, Figure 14-1).

voltage and at 10% over voltage. It would be safe to say that saturation would not start until the densities exceed the 130 kilolines per square inch range. The best indicators of when saturation is reached are: increased line current and motor temperature and decreased efficiency and power factor. Figure 2-21 illustrates this point.

UNBALANCED VOLTAGE

Far too many assumptions are made when dealing with the symmetry of a voltage supply. In order to accurately assess the quality of the voltage supply, it is necessary to verify it at a number of places within the service and over a reasonable period of time and seasons. NEMA MG 1, 14.36 offers the following explanation of the effects of unbalanced voltage, along with a load derating curve.

> **14.36 Effects of Unbalanced Voltages on the Performance of Polyphase Induction Motors.** When the line voltages applied to a polyphase induction motor are not equal, unbalanced currents in the stator windings will result. A small percentage voltage unbalance will result in a much larger percentage current unbalance. Consequently, the temperature rise of the motor operating at a particular load and percentage voltage unbalance will be greater than for the motor operating under the same conditions with balanced voltages.
>
> Voltages should be evenly balanced as closely as can be read on a voltmeter. Should voltages be unbalanced, the rated horsepower of the motor should be multiplied by the factor shown in Figure 2-22 to reduce the possibility of damage to the motor. Operation of the motor above a 5 percent voltage unbalance condition is not recommended.
>
> When the derating curve of Figure 2-22 is applied for operation on unbalanced voltages, the selection and setting of the overload device should take into account the combination of the derating factor applied to the motor and increase in current resulting from the unbalanced voltages. This is a complex problem involving the variation in motor current as a function of load and voltage unbalance in addition to the characteristics for the overload device relative to $I_{maximum}$ or $I_{average}$. In the absence of specific information, it is recommended that overload devices be selected or adjusted, or both, at the minimum value that does not result in tripping for the derating factor and voltage unbalance that applies. When unbalanced voltages are anticipated, it is recommended that the overload devices be selected so as to be responsive to $I_{maximum}$ in preference to overload devices responsive to $I_{average}$.

14.36.1 Effect on Performance–General. The effect of unbalanced voltages on polyphase induction motors is equivalent to the introduction of a "negative sequence voltage" having a rotation opposite to that occurring with balanced voltages. This negative sequence voltage produces in the air gap a flux rotating against the rotation of the rotor, tending to produce high currents. A small negative-sequence voltage may produce in the windings currents considerably in excess of those present under balanced voltage conditions.

14.36.2 Unbalance Defined. The voltage unbalance in percent may be defined as follows:

$$\text{Percent voltage unbalance} = 100 \times \frac{\text{Max voltage deviation from avg. voltage}}{\text{Avg. voltage}}$$

Example: With voltages of 460, 467, and 450, the average is 459, the maximum deviation from average is 9, and the percent unbalance equals:

$$\text{Percent voltage unbalance} = 100 \times \frac{9}{459} = 1.96 \text{ percent}$$

14.36.3 Torques. The locked-rotor torque and breakdown torque are decreased when the voltage is unbalanced. If the voltage unbalance should be extremely severe, the torques might not be adequate for the application.

14.36.4 Full-Load Speed. The full-load speed is reduced slightly when the motor operates with unbalanced voltages.

14.36.5 Currents. The locked-rotor current will be unbalanced to the same degree that the voltages are unbalanced, but the locked-rotor kVA will increase only slightly.

The currents at normal operating speed with unbalanced voltages will be greatly unbalanced in the order of approximately 6 to 10 times the voltage unbalance.

IMPACT ON WINDING TEMPERATURES [4]

A good assumption for the impact of unbalanced voltage on the winding temperature rise is that the rise equals two times the percent voltage unbalance squared.

$$\text{Increased temp. rise } (\Delta°C) = 2 \times (\%\text{ V unblanace})^2$$

Figure 2-23 shows the drastic impact voltage unbalance has on temperature rise and the winding insulation life.

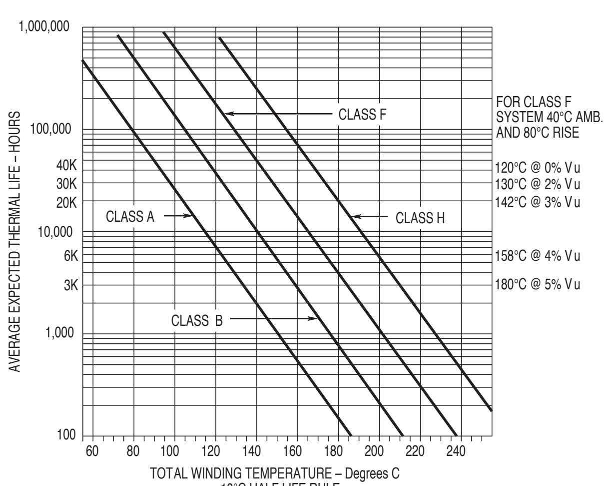
VIBRATION AND NOISE

Figure 2-24 and Figure 2-25 illustrate the relationship between voltage unbalance and vibration noise. Note that in both cases there is a significant impact on motor performance as it relates to acceptable vibration levels and sound power levels.

TEST RESULTS

The following study was conducted at the Emerson Motor Technology Center in St. Louis, Missouri to compare the standard efficiency motor to a premium efficient motor under unbalanced voltage conditions. (See Table 2-4.)

FIGURE 2-23

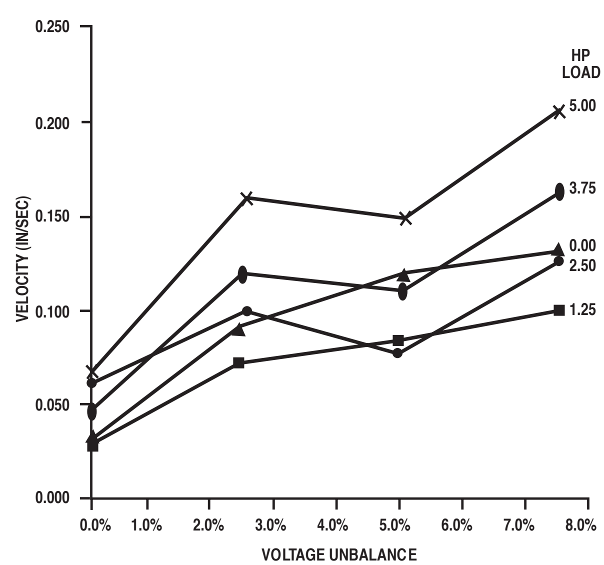


Increased Temp. Rise = 2 x (% V unbalance)^2

Vu @ 0% = 0%	Δt = 120°C
Vu @ 2% = 8%	Δt = 130°C
Vu @ 3% = 18%	Δt = 142°C
Vu @ 4% = 32%	Δt = 158°C
Vu @ 5% = 50%	Δt = 180°C

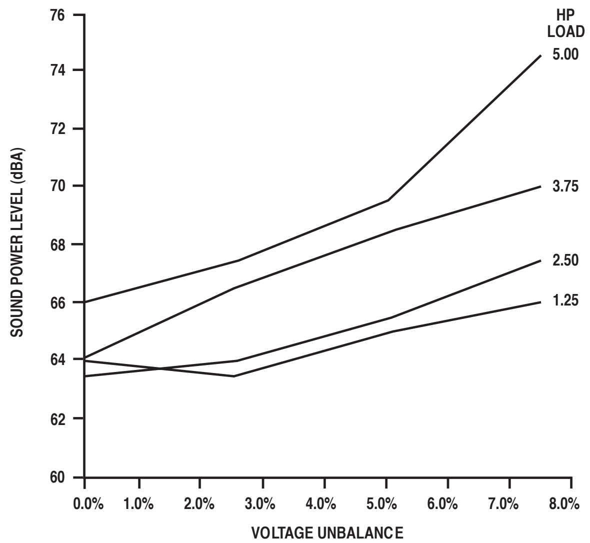
Assume 40°C ambient, normal temperature rise 80°C @ zero voltage unbalance (Vu), and a total temperature of 120°C.

FIGURE 2-24



Vibration vs. voltage unbalance (drive end bracket).

FIGURE 2-25



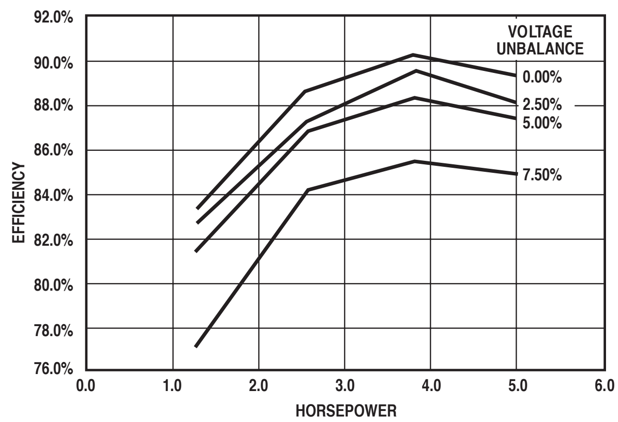
Noise—Outlet box side.

The increase in winding temperature causes additional I^2R losses. The rotor losses also increase because of the impact the "Negative Sequence Component" has on the rotor. Therefore,

TABLE 2-4: MOTORS DESIGN DATA

Description	Premium efficient	Standard efficient
Model number	7965	E398
Type	TCE	CT
HP rating	5	5
Voltage/Freq.	230/60	230/60
No. of poles	4	4
Syn. speed	1800	1800
Connections	Wye	Wye
Full load performance		
Amps	12.56	13.47
rpm	1750	1738
Slip p.u.	0.0280	0.0344
Losses (watts)	445	611
Efficiency %	89.3	85.9
Power factor %	83.4	80.9
Flux density: Kl/in^2		
Stator core	107	110
Stator teeth	114	120
Air gap	0.0325"	0.0359"
Rotor core	43	51
Rotor teeth	116	116

FIGURE 2-26



Efficiency variation vs. horsepower.

as shown in Figure 2-26, there is a significant drop in motor efficiency.

FREQUENCY VARIATIONS

Variations from the system nominal frequency are less common than voltage variations. When this does occur, variation of frequency affects motor performance in the following manner:

1. The locked-rotor torque and breakdown torque vary inversely as the square of the frequency.
2. The synchronous speed will vary directly with the frequency.
3. The locked-rotor current will vary inversely as the frequency.

OPERATION OF 60 HZ MEDIUM INDUCTION MOTORS ON 50HZ

A more common situation is to apply a 60-hertz motor to a 50-hertz system. NEMA MG 1, 14.34 offers the following information.

> **14.34 Operation of General-Purpose Alternating Current Polyphase, 2-, 4-, 6-, and 8-Pole, 60 hertz Medium Induction Motors Operated on 50 hertz.** While general-purpose alternating-current polyphase, 2-, 4-, 6-, and 8-pole, 60-hertz medium induction motors are not designed to operate at their 60-hertz ratings on 50-hertz circuits, they are capable of being operated satisfactorily on 50-hertz circuits if their voltage and horsepower ratings are appropriately reduced. When such 60-hertz motors are operated on 50-hertz circuits, the applied voltage at 50 hertz should be reduced to 5/6 of the 60 hertz voltage rating of the motor, and the horsepower load at 50 hertz should be reduced to 5/6 of the 60 hertz horsepower rating of the motor. should be reduced to 5/6 of the 60-hertz horsepower.
>
> When a 60-hertz motor is operated on 50-hertz at 5/6 of the 60-hertz voltage and horsepower ratings, the other performance characteristics for 50-hertz opera-

tion are as follows:

14.34.1 Speed. The synchronous speed will be 5/6 of the 60-hertz synchronous speed, and the slip will be 5/6 of the 60-hertz slip.

14.34.2 Torques. The rated load torque in pound-feet will be approximately the same as the 60-hertz rated load torque in pound feet. The locked-rotor and breakdown torques in pound-feet of 50-hertz motors will be approximately the same as the 60-hertz locked-rotor and breakdown torques in pound-feet.

14.34.3 Locked-Rotor Current. The locked-rotor current (amperes) will be approximately 5 percent less than the 60-hertz locked-rotor current (amperes). The code letter appearing on the motor nameplate to indicate locked-rotor kVA per horsepower applies only to the 60-hertz rating of the motor.

14.34.4 Service Factor. The service factor will be 1.0.

14.34.5 Temperature Rise. The temperature rise will not exceed 90° C (see 14.30).

Table 2-5 and Table 2-6 compare motor performance for a typical TEFC, 4-pole motor that was designed for 460 volts and 60 hertz but which is operating at 50 hertz, 380 volts.

TABLE 2-5: 50 HZ - 60 HZ CURRENT COMPARISONS AT RATED HP

hp	460V/60 Hz	380V/50 Hz	% increase
10	12	15	22
20	25	31	24
50	37	71	24
100	113	128	22
200	228	278	22

Notes: Range 22 - 24%.
A rule of thumb: $I_{50\ Hz} \sim I_{60\ Hz}$ x 1.28
If the volts/Hz is held constant

Often the 50-hertz horsepower will be reduced to 5/6 of the 60-hertz value to assure that the winding temperature stays below the 90° C limit.

Table 2-6 establishes a useful relationship between 50 hertz and 60 hertz motor currents under load.

MOTOR PERFORMANCE CHARACTERISTICS FOR 60 VS. 50 HERTZ

There are occasions when 460-volt, 60-hertz motors are applied to 380-volt, 50-hertz power supplies. The question is frequently asked, "What is the impact on motor performance?" From Table 6, the following general rules can be made.

1. Speed will drop by 1/6.
2. Starting torque and kVA/hp will both drop at least 30%.
3. The efficiency will drop 2 to 3 percentage points.
4. The winding temperature will increase 40-60%.
5. It may be necessary to derate the motor and drop the service factor to 1.0.

On applications where the load torque is variable and follows the affinity laws, there is the probability that the brake horsepower will be greatly reduced and the existing motor will work satisfactorily. Some product lines are designed for dual frequency, but when in doubt, check with the manufacturer.

OPERATION OF 230-VOLT MOTORS ON 208-VOLT SYSTEMS

NEMA MG 1, 14.35 says the following about operating 230-volt motors on 208-volt systems.

14.35.1 General. Induction motors intended for operation on 208-volt systems should be rated for 200 volts.

Operation of a motor rated 230 volts on a 208-volts systems is not recommended (except as described in 14.35.2) because utilization voltages are commonly encountered below the -10-percent tolerance on the voltage rating for which the motor is designed. Such operation will generally result in overheating and seri-

TABLE 2-6: 50 HZ VS 60 HZ PERFORMANCE CHARACTERISTICS FOR THE SAME MOTOR

Power supply/hp	460 volts - 60 Hz			380 volts - 50 Hz		
Performance	10 hp	50 hp	100 hp	10 hp	50 hp	100 hp
Synchronous speed	1800	1800	1800	1500	1500	1500
Slip speed (rpm)	1760	1775	1784	1442	1461	1478
Avg. winding temp. rise	49°C	75°C	63°C	76°C	126°C	88°C
Avg. rotor temp. rise	78°C	92°C	84°C	125°C	156°C	121°C
CFM	139	564	923	116	470	770
Percent efficiency	91.7	94.0	95.4	88.6	91.3	94.4
Percent power factor	85.7	88.3	87.0	86.8	88.1	87.6
kVA/hp	6.2	5.4	5.6	4.8	4.2	4.4
Full-load amps	11.9	56.4	113	14.7	70.4	137
Starting torque	224%	189%	149%	173%	143%	120%
Air gap density (kl/in^2)	31.2	27.5	28.6	30.9	27.3	28.4

ous reduction in torques.

14.35.2 Nameplate Marking of Usable @ 200 V. Motors rated 230 volts, but capable of operating satisfactorily on 208 volt systems shall be permitted to be labeled "Usable at 200 Volts." Motors so marked shall be suitable for operation at rated (1.0 service factor) horsepower at a utilization voltage of 200 volts at rated frequency, with a temperature rise not exceeding the values given in 12.44, item a.2., for the class of insulation system furnished. The service factor, horsepower, and corresponding value of current shall be marked on the nameplate; i.e., "Usable @ 200 V. _____ hp, ______ amps, 1.0 S.F."

14.35.3 Effect on Performance of Motor. When operated on a 208-volt system the motor slip will increase approximately 30% and the motor locked-rotor, pull-up and breakdown torque values will be reduced by approximately 20-30%. Therefore, it should be determined that the motor will start and accelerate the connected load without injurious heating, and that the breakdown torque is adequate for the application.

NOTE–Utilization voltage tolerance is 200 minus 5% (190 volts)–Ref. ANSI C84.1, "Voltage Range A." Performance within this voltage tolerance will not necessarily be in accordance with that stated in 14.35.2.

In recent years it has been a common practice to apply 230-volt motors for 208-volt applications. Under this condition the motor usually will exhibit lower efficiency, run hotter, slip more, and have shorter life.

CONCLUSIONS

The bottom line to this whole article is the need to keep the voltage and frequency as close as possible and practical to the nominal nameplate values, even when the various motor standards allow for significant variations. Failure to place a priority on doing so can result in significant reductions in the motor performance and life.

APPENDIX I

SYSTEM NOMINAL VOLTAGES

There continues to be some confusion between the system or service voltage and utilization or equipment voltage. Table 2-7 provides these relationships for the normal range "A" and for range "B" when the voltage moves outside of the normal voltage range.

NOTE: That the four-wire systems have a center or neutral tap that provides a lower voltage with the ratio of the √3. (i.e., for a 4160-volt system the neutral voltage is 4000/√3 or 2300 volts.)

TABLE 2-7: STANDARD NOMINAL SYSTEM VOLTAGES AND VOLTAGE RANGES

Nominal system voltage		Voltage range "A"			Voltage range "B"		
		Minimum		Maximum	Minimum		Maximum
Three-wire	Four-wire	Utilization voltage	Service voltage	Utilization and service voltage	Utilization voltage	Service voltage	Utilization and service voltage
Single-phase systems							
120/240	—	110 110/120	114 114/228	126 126/252	106 106/212	110 110/220	127 127/254
Three-phase systems							
	208Y/120	191Y/110	197Y/114	218Y/126	184Y/106	191Y/110	220Y/127
	240/120	220/110	228/114	252/126	(Note d) 212/106	(Note d) 220/110	220/127
240	480Y/277	220 440Y/254	228 456Y/263	252 504Y/291	212 424Y/245	220 440Y/254	254 508Y/293
480		440	456	504	424	440	508
600		550	570	630	530	550	635
2400	4160Y/2400	2160 3740Y/2160	2340 4050Y/2340	2520 4370Y/2520	2080 3600Y/2080	2280 3950Y/2280	2540 4400Y/2540
4160		3740	4050	4370	3600	3950	4400
4800		4320	4680	5040	4160	4560	5080
6900		6210	6730	7240	5940	6560	7260
	8320Y/4800		8110Y/4680	8730Y/5040		7900Y/4560	8800Y/5080
	12000Y/6930		11700Y/6760	12600Y/7270		11400Y/6580	12700Y/7330

Reference: ANSI C84.1-1995

APPLICATION OF VOLTAGE RANGES [7]

According to ANSI C84.1.2.4.1, application of voltage ranges are as follows.

C84.1.2.4.1 Range "A"–Service Voltage. Electric supply systems shall be so designed and operated that most service voltages will be within the limits specified for Range "A". The occurrence of service voltages outside of these limits should be infrequent.

C84.1.2.4.2 Range "A"–Utilization Voltage. User systems shall be so designed and operated that with service voltages within Range "A" limits, most utilization voltages will be within the limits specified for this range.

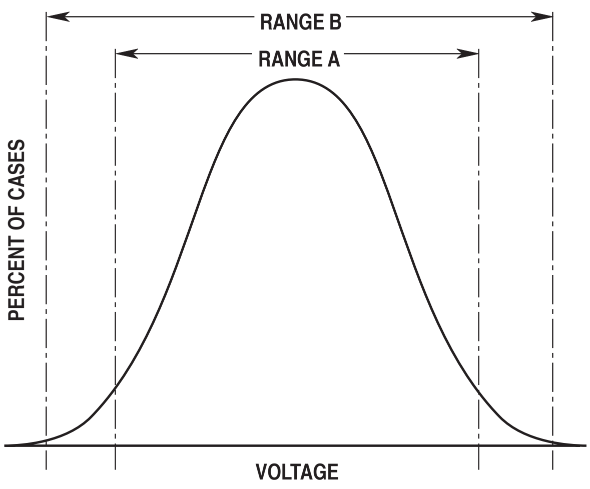
Utilization equipment shall be designed and rated to give fully satisfactory performance throughout this range.

C84.1.2.4.3 Range "B"–Service and Utilization Voltages. Range "B" includes voltages above and below Range "A" limits that necessarily result from practical design and operating conditions on supply or user systems, or both. Although such conditions are a part of practical operations, they shall be limited in extent, frequency, and duration. When they occur, corrective measures shall be undertaken within a reasonable time to improve voltages to meet Range "A" requirements.

Insofar as practicable, utilization equipment shall be designed to give acceptable performance in the extremes of this range of utilization voltages, although not necessarily as good performance as in Range "A".

It must be recognized that because of conditions beyond the control of the supplier or user, or both, there will be infrequent and limited periods when sustained voltages outside of Range "B" limits will occur. Utilization equipment may not operate satisfactorily under these conditions, and protective devices may operate to protect the equipment. When voltage occurs outside the limits of Range "B", prompt corrective action is recommended. The urgency for such action will depend upon many factors, such as location and nature of load or circuits involved, and magnitude and nature of the deviation beyond Range "B" limits.

FIGURE 2-27



APPENDIX II

EFFECT OF VOLTAGES OVER 600 VOLTS ON LOW-VOLTAGE MOTOR PERFORMANCE

NEMA MG 1, 14.33 says the following about the effect of voltages over 600 volts on the performance of low-voltage motors.

> **14.33 Effects of Voltages Over 600 Volts on the Performance of Low-Voltage Motors.** Polyphase motors are regularly built for voltage ratings of 575 volts or less (see 10.30) and are expected to operate satisfactorily with a voltage variation of plus or minus 10 percent. This means that motors of this insulation level may be successfully applied up to an operating voltage of 635 volts.
>
> Based on the motor manufacturers' high-potential tests and performance in the field, it has been found that where utilization voltage exceed[s] 635 volts, the safety factor of the insulation has been reduced to a level inconsistent with good engineering procedure.
>
> In view of the foregoing, motors of this insulation level should not be applied to power systems either with or without grounded neutral where the utilization voltage exceeds 635 volts, regardless of the motor connection employed.
>
> However, there are some definite-purpose motors that are intended for operation on a grounded 830-volt system. Such motors are suitable for 460-volt operation when delta connected and for 796-volt operation when wye connected when the neutral of the system is solidly grounded.

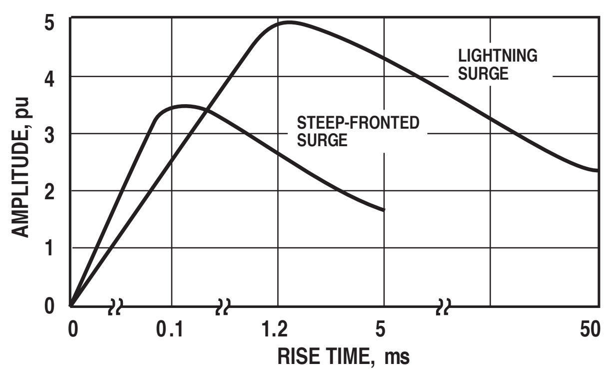
APPENDIX III

VOLTAGE SURGES

Most people would not consider voltage surge to be a voltage variation. Yet in reality it is, except of a much higher magnitude and of a much shorter duration. For ease of reference it has been added to this report.

Introduction. Steep-fronted voltage surges have been recorded with values as high as 6 per unit (pu), where the definition of pu is the line voltage times $\sqrt{2}/\sqrt{3}$, or pu equals $.817V_1$. The two basic causes of these surges are lightning strikes and switching action. The shape of these surges can vary drastically. For illustration purposes, the wave forms can be characterized by stating the crest value and the rise time, as shown in Figure 2-28.

FIGURE 2-28



Lightning and steep-fronted surges [6].

The first turn or coils of the stator winding will absorb these surges and place a very high dielectric stress across this part of the winding. In most cases, if a winding fails because of a steep-fronted surge, it will be identified by turn-to-turn shorts in this area and sometimes accompanied by a ground fault in the same area or phase-to-phase fault.

FACTORS CAUSING STEEP-FRONTED VOLTAGES

Line-to-line, line-to-ground, 2-line-to-ground, and 3-phase faults cause over-shoot and line-to-line voltages that will reach 3-1/2 times their normal values during very short time periods.

Other sources include: repetitive restriking, failure of current-limiting fuses, rapid bus transfers, opening or closing of circuit breakers, capacitor switching, insulation failure, lightning, variable-frequency drive waveforms, and standing waves.

APPENDIX IV

THE IMPACT OF THE VOLTAGE SINGLE PHASE

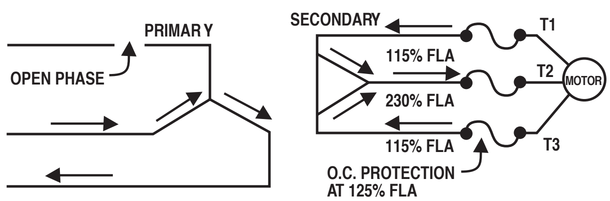
Single-phasing is an extreme case of voltage (variation) unbalance. This can occur when one phase becomes “open” anywhere in the power system. However, it usually happens at the distribution transformer or in the motor controls. On rare occasions, it can happen in the feeders or motor connections.

The impact on the motor will depend on where the open occurs, the type of transformer transformation (i.e., wye-delta, wye-wye, etc.), and the motor winding connection (i.e., wye or delta).

The following examples will illustrate.

Example 1: Current relationships at the motor are served from a wye-delta transformer with one primary phase open. The same current relationships would exist for a motor served from a delta-wye transformer with an open phase on primary.

FIGURE 2-29

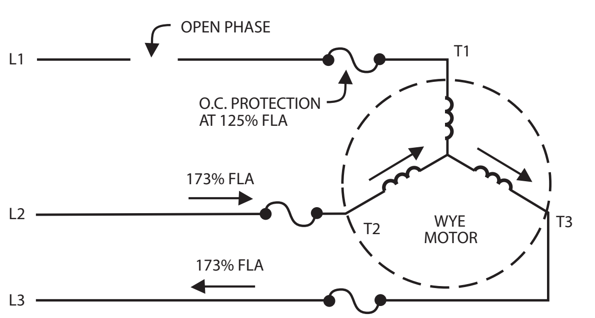


Wye-delta transformer with either wye- or delta-connected motor.

Example 2: With motor operating at full load, two legs will sense 173 percent of full load amperes; at least one overload element will sense the overcurrent. If the single-phase fault occurs during starting, the motor normally will not start regardless of the load.

Example 3: The motor will continue to try to carry the load, but the heating will be enormous.

FIGURE 2-30

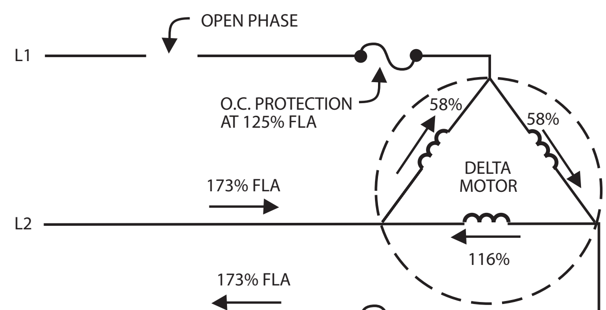


Wye-wye transformer and a wye-connected motor for ungrounded neutrals. The impact will be the same at the motor terminals (T1, T2 and T3) regardless of which side of the transformer is single phased.

In conclusion, a wide variety of events can happen during single phasing. It is imperative that the proper overcurrent protection be provided in each phase to protect the motor. A wide variety of relays and protection equipment is available to accomplish this.

If the motor does fail from single phasing, the winding will have several unique possible burn out patterns. One or two phases may show signs of overheating, but not all phases will be overheated. In all cases, the rotor may shown signs of overheating due to the negative sequence component that will be present.

FIGURE 2-31



Wye-wye transformer with delta-connected motor.

APPENDIX V

3-PHASE AC VOLTAGE RELATIONSHIPS

1. Voltage = Current x Impedance

   $V = I \times Z$, where $Z = \sqrt{R^2 + x^2}$

2. For delta circuits:

   Line voltage = Phase voltage, or $V_L = V_P$

   For wye circuits:

   Line voltage = $\sqrt{3}$ x Phase voltage, $V_L = \sqrt{3} V_P$

3. $$\text{Voltage} = \frac{\text{Power}}{\sqrt{3} \times \text{Current} \times \text{Cos } q}$$

4. $$\text{kVA per hp} = \frac{\text{Voltage} \times \text{Current} \times \sqrt{3}}{1000 \times \text{hp}} = \frac{\sqrt{3} V_L}{1000\text{hp}}$$

5. $$\% \text{ voltage unbalance} = \frac{(V_{max} - V_{avg})\,100}{V_{avg}}$$

6. $$\text{Voltage for AC hipot} = (2 \times V_L) + 1000$$

$$\text{Voltage for DC hipot} = (2 \times 1.7 \times V_L) + 1000$$

7. $$\text{Slip } \mu \ \frac{1}{(\text{Voltage})^2}$$

8. $$\text{Line current } \mu \ \frac{1}{\text{Voltage}}$$

(For different design voltages)

9. Flux density µ Voltage

(Below saturation)

10. No load motor current µ V^2

(Below saturation)

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Note: This article was originally published as part of a 1999 IEEE Pulp & Paper Conference Presentation. It then was updated for presentation at the 2003 EASA Convention in San Francisco. For this publication, all references to NEMA Stds. MG 1: *Motors and Generators* have been updated to the 2014 edition.

Variables to consider when making motor frequency changes between 50, 60 Hz

By Thomas H. Bishop, P.E.
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Apparatus repair businesses don't always realize how global their work is until a customer sends in a motor to be redesigned for use on a different power frequency. The most common frequency conversion requests are between 50 and 60 hertz (Hz). Motors intended for use in North America typically are rated at 60 Hz, whereas in the remainder of the globe most are rated at 50 Hz.

The speed of a three-phase motor is determined by the number of poles it has and the power frequency it operates on. As much as service centers are aware of this relationship, it remains a mystery to most end users. How often have you had a customer request a 50-to-60 Hz conversion of a 4-pole motor and want it to operate at about the same speed of 1500 rpm? Not only would such a conversion be impossible, but other considerations related to the type of load would also have to be taken into account.

FREQUENCY CHANGE ON PUMP OR FAN

Changing the frequency from 50 to 60 Hz on a pump or fan increases the operating speed, and consequently increases the load on the motor and driven equipment. That is because fan and pump loads vary by the cube of the speed. A 50 Hz motor operating on 60 Hz power will attempt to rotate 20% faster. The load therefore becomes 1.23 (1.2 x 1.2 x 1.2) or 1.73 times (173%) greater than on the original frequency. Redesigning a motor for that much of an increase in horsepower is simply not realistic; the motor's magnetic material would be driven into saturation long before reaching the 73% increased horsepower level. Very few motors can be redesigned for a horsepower increase of 30% or greater.

The typical solution when increasing speed due to a frequency change is to modify the driven equipment so that the increased horsepower requirement falls within the motor's capability. For example, the diameter of a fan wheel or a pump impeller can be trimmed to provide the same performance at 60 Hz as the unit had at 50 Hz. Before making such a modification, however, always consult the original equipment manufacturer. Not all pumps and fans behave exactly in accordance with the cube rule; thus the OEM may specify a diameter that differs from the rule.

For fans and blowers, the diameter change follows a 5th power rule. That discussion is one that usually takes place between the end user and the OEM–i.e., the motor rebuilder seldom modifies the driven equipment.

ASK THE CUSTOMER

What questions should you ask when a customer requests a frequency change? Besides the new frequency and voltage, you'll need to know the new horsepower requirement in order to determine if the motor can develop it. In communicating with the customer, be sure to explain that the speed change, and its impact on the load requirement, are beyond your control. It is better for the customer to understand what the outcome will be in terms of speed and horsepower before the conversion is undertaken.

Much of what has been stated so far applies to conversions from 50 to 60 Hz. What if the conversion is from 60 to 50 Hz? In such cases, the speed will be reduced and, almost always, the horsepower requirement will be reduced. The cube rule that applies to fans and pumps makes this an "easy" conversion for the motor. Theoretically, the horsepower requirement at 50 Hz will be only 58% of that needed at 60 Hz for the same application.

Another factor to consider is the inertia of the driven load. If the impeller or fan wheel is relatively large, it may take more horsepower to get it up to speed in a time frame that doesn't overheat or damage the motor. Constant-torque conversions, such as for conveyors, do not usually introduce other concerns such as inertia, unless the application must start with a greater than normal load.

HEAT DISSIPATION

In addition to torque and horsepower considerations, there is the issue of heat dissipation. Frequency changes from 50 to 60 Hz cause an increase in speed, and the motor's cooling fan will theoretically produce 20% more airflow. The fan airflow varies directly with the speed, as long as there are no other variables such as a change in friction loss.

A rule of thumb is that temperature rise is proportional to watts loss divided by airflow in cfm or m^3/sec. Therefore the 20% increase in airflow more than makes up for the increased losses associated with the higher horsepower rating at the higher frequency.

Conversely, when reducing speed, the lower horsepower usually results in reduced losses. The reduced airflow, however, often results in a net increase in temperature. For that reason, it is best to increase the insulation by one class. Thus, if the insulation class for the original 60 Hz rating was Class B, use at least a Class F insulation system for the 50 Hz redesign.

EXAMPLES

The following examples illustrate common frequency change requests. Most conversions from 50 to 60 Hz (or vice versa) involve applications with a constant- or variable-torque characteristic.

Example 1: 380V 50 Hz on 460V 60 Hz

For constant-torque applications like conveyors, the horsepower requirement at 50 Hz will be 5/6 of that needed at 60 Hz. If a 380V 50 Hz motor is now going to be used on 460V 60 Hz, should it be rewound or will it be usable as-is? Mathematically, the horsepower in this case is within 1% of

FIGURE 2-32

Torque is proportional to: $(E_2/E_1) \times (F_1/F_2)$

Where:

E_1 = Original voltage rating
E_2 = New voltage rating
F_1 = Original frequency
F_2 = New frequency

Inserting the values from Example 1:

Torque change = (460/380) x (50/60)
= 1.009 [about a 1% increase]

the ratio of the speed change, as explained in Figure 2-32.

That means the torque will be almost constant at either frequency, so from that perspective, the motor need not be rewound. Further, since the increased airflow more than offsets the losses associated with the higher horsepower at 60 Hz, the motor should operate at a lower temperature.

The rated current will also be only slightly higher, so the I^2R losses of the stator and rotor will not change appreciably. Magnetically, the flux levels will be almost unchanged, which means the core losses will not measurably increase. The friction and windage losses will be greater, however, due to the increased speed. Not only is the motor capable of operating at the higher frequency and voltage without rewinding, but it may run cooler and possibly be more efficient.

Example 2: 460V 60 Hz motor on 380V 50 Hz

What will happen if the scenario is reversed–that is, if the motor is to be used on 50 Hz? Using a 460V 60 Hz motor on 380V 50 Hz will of course reduce the speed by the ratio of 5/6 (50/60) and also reduce the horsepower in proportion to the speed change. The torque will remain constant, however, so from that perspective a rewind would not be necessary.

Another factor that must be considered, though, is the impact of the losses on temperature rise, as was done for the speed increase. At the lower frequency and speed the flux levels will remain virtually unchanged, as will the stator and rotor currents. The variables are again the friction and windage losses. Although both are reduced, a negative byproduct of reducing windage is decreased airflow. The 17% reduction in speed equates to a 17% reduction in airflow.

Consider airflow, losses and temperature. The rule of thumb about airflow, losses and temperature rise tells us that for the same watts loss and a 17% reduction in airflow, the temperature will rise about 20%.

Although it might seem as though the watts loss should be less because of reduced friction and windage, the increased temperature rise will actually cause I^2R losses to increase in both the stator and rotor. Figuring out the exact change with two independent variables (temperature rise and winding resistance) is a complex issue beyond the scope of this article.

For the sake of simplicity, assume these variables offset each other, and therefore that the motor in this example will run 20% hotter. For a Class B winding with a temperature rise of 60°C, a 20° increase would add 12°C (60 x 0.2) to the temperature of the winding. According another rule of thumb–that every 10°C increase in temperature reduces winding life by half–this winding will have less than half its normal life at the reduced frequency and speed. The right thing to do in this case is to rewind to a higher temperature class; that will more than make up for the effect of the increased temperature on winding life.

Of course, not all frequency changes work out as well as in Examples 1 and 2. Following the same steps as in those examples, consider a change from 400V-50 Hz to 460v-60 Hz.

Example 3: 400V-50 Hz to 460v-60 Hz

This frequency conversion involves a voltage value that was brought about by a change in an international standard. A few decades ago U.S. voltage standards changed; as an example, the 440V motor rating became the 460V motor rating. The International Electrotechnical Commission (IEC) has made a similar change that affects many countries in Europe and elsewhere. The former 380V standard rating has been changed to 400V.

The horsepower increase in this case will be effectively reduced because of the voltage change ratio. See Figure 2-33 for the mathematics involved in determining this value.

FIGURE 2-33

Torque is proportional to: $(E_2/E_1) \times (F_1/F_2)$

Where:

E_1 = Original voltage rating
E_2 = New voltage rating
F_1 = Original frequency
F_2 = New frequency

Inserting the values from Example 2:

Torque change = (460/400) x (50/60)
= 0.958 [about a 4% reduction]

If the 60 Hz value were 480V, the horsepower would have changed in proportion to the frequency change–i.e., it would have increased by 20%. The horsepower in this example will only increase about 15% if the motor is not rewound. The mathematics behind these relationships are given in Figure 2-34.

If torque must be maintained or increased, a redesign and rewind will be necessary. The airflow will increase, which will help cool the motor, although the losses will be higher if the winding is redesigned for increased torque. That new wind-

FIGURE 2-34

Relationship between speed, horsepower and torque

HP = (T x rpm)/K

Where:

T = Torque
rpm = Speed
K = A constant factor depending on the units of measurement

Speed is proportional to frequency; therefore at 60 Hz, speed will be (60/50) 1.20 times faster than at 50 Hz.

If T is constant (and K is constant), we can think of them as having a value of 1.0 before and after the frequency change. Since speed increases by 1.20, then the change in HP can be calculated as:

HP = (1 x 1.20)/1 = 1.20

For the case where torque is reduced about 4%, the formula becomes:

HP = (0.958 x 1.20)/1 = 1.15

ing will have higher magnetic flux densities, with associated higher losses. The friction and windage losses will also be greater due to the increased speed. The motor may run cooler at the higher speed; however, its efficiency will be reduced somewhat due to the higher magnetic flux levels.

This article was originally published in *EASA Currents* (August 2002). It was reviewed and updated as necessary in August 2016.

Guidelines for maintaining motor efficiency during rebuilding

The challenge for every motor repair firm is twofold: to repair the equipment properly; and to demonstrate to their customers by means of adequate testing and documentation that rewound motors retain their operating efficiency. Following the guidelines in the "DOs" and "DON'Ts" below will help you accomplish both.

Numerous studies have been done to determine the effect rewinding has on motor efficiency. These studies identified several variables that can impact the efficiency of a rewound motor, including core burnout temperature, winding design, bearing type, air gap and winding resistance. The following guidelines were developed as a result of those studies, which found that the efficiency of both standard and energy efficient electric motors can be maintained during rebuilding and rewinding.

To ensure that motors retain their efficiencies when rewound, EASA also strongly recommends that electric motor repair centers comply with ANSI/EASA Standard AR100: *Recommended Practice For The Repair Of Rotating Electrical Apparatus* and strictly adhere to the "DOs" and "DON'Ts" that follow. These guidelines, which contain safe values (based on available data) and correct procedures, apply to both energy efficient and standard motors. Further study of the matter continues, and these guidelines will be revised if additional information warrants.

DO:

1. **Have a quality assurance program.**
2. **Implement a calibration program that will assure the accuracy of all measuring and test equipment.**
3. **Conduct a stator core test before and after stripping.**
4. **Repair or replace all defective laminations.**
5. **Evaluate the impact on efficiency before changing the winding design.**
6. **Measure and record winding resistance and room temperature.**
7. **Measure and record amperes and voltage during the final test.**

DON'T:

1. **Don't overheat the stator core.**
2. **Don't use an open flame for stripping.**
3. **Don't sandblast the core iron.**
4. **Don't short the laminations when grinding or filing.**
5. **Don't increase the air gap.**
6. **Don't increase the resistance of the stator windings.**
7. **Don't knurl, peen or paint bearing fits.**
8. **Don't make mechanical modifications without the customer's prior approval.**

What follows is a discussion of the individual points.

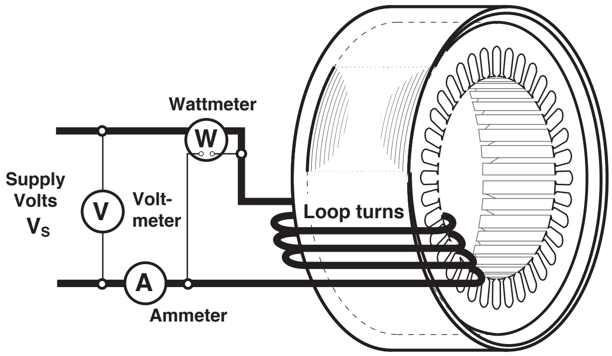
DO:

1. **Have a quality assurance program.** Be sure that your suppliers are shipping you what you ordered. Measure your wire to be sure the spools are properly marked. Check your lead wire and insulating materials for proper size. Maintain written documentation of your tests, and especially of your stripping and bake oven temperature cycles and times. Test your varnish at the intervals recommended by the varnish manufacturer.
2. **Implement a calibration program that will assure the accuracy of all measuring and test equipment.** Have your instruments calibrated at least annually by an instrument testing service whose calibration is traceable to National Institute of Standards & Technology (NIST), National Research Council of Canada (NRC) or an equivalent standards laboratory. For core testing, use test instruments that read "true rms" values because core test voltage and currents may contain harmonics.
3. **Conduct a stator core test *before* and *after* stripping.** Record the "before" and "after" core test readings–and retain them as proof to your customer that you have not damaged the core.

   If you do not have a core tester, follow the procedure outlined in EASA *Tech Note 17* (also contained in Section 7 of the *EASA Technical Manual*). To test for core loss using this method, you must connect a single-phase wattmeter in the circuit. You must also adjust the induced voltage to the value used in your calculations. It is also important to make sure that the coil used for the "after" test duplicates as closely as possible the one used for the "before" test.
4. **Repair or replace all defective laminations.** Separate all shorted laminations. When restacking a core, use an interlaminar insulation varnish on one side of the laminations, cure the varnish at the recommended temperature, and stack an unpainted side against a dry painted side. If new laminations must be cut, send a sample to your supplier. Be sure to specify that losses in the new laminations must be equal to or less than those of the original laminations. Deburr all new or restacked laminations.
5. **Evaluate the impact on efficiency before changing the winding design.** Before changing the winding from concentric to lap or vice versa, determine the effect the change will have on efficiency. This type of change can affect stray load losses and increase winding resistance. Avoid changes that will reduce the cross-sectional area of the total conductors, increase mean turn length, or otherwise affect total winding resistance. Incorrect conversions may change other motor characteristics, not just efficiency.

   It is sometimes possible to improve efficiency when changing a 2-layer concentric winding to a 2-layer lap. Evaluate the effects of winding changes before proceeding with them.
6. **Measure and record winding resistance and room temperature.** Since resistance is affected by temperature,

Stator core test



Test stator cores *before* and *after* you remove the windings, using a commercial tester or the method outlined in your *EASA Technical Manual*. Give the customer a copy of the computer printout or test records to assure them that you have not damaged the core.

measure and record both the resistance and the temperature of the winding.

7. **Measure and record amperes and voltage during the final test.** Measure and record the amperes and voltage on all phases. Voltages on utility power lines change with load, so do not assume you have a particular voltage. A high voltage will cause the no-load current to increase. Unbalanced voltages cause currents to be unbalanced in a much greater percentage than the voltage unbalance. If currents are unbalanced, interchange all three leads in such a way that the motor's direction of rotation does not change. Now retest the motor, noting whether the high current leg stays with the power lead or the motor lead. If it stays with the power lead, the motor is okay. If not, there may be a problem with the motor. Be sure to record and retain all readings.

DON'T:

1. **Don't overheat the stator core**. *The Effect of Repair/Rewinding on Motor Efficiency* (2003), a joint study by EASA and the Association of Electrical and Mechanical Trades (AEMT), demonstrates that the effects of burnout temperature depend on the type of lamination insulation. Organic material (C3) tends to break down at lower temperatures than inorganic materials (C5). The obvious conclusion is that stripping stators at too high a temperature damages the core plating on the laminations. This causes shorts between laminations, increasing core losses. Based on the results of the EASA/AEMT study, *The Effect of Repair/Rewinding on Motor Efficiency* (2003), it is recommended that the maximum core temperature not exceed 700°F (370°C). If the interlaminar insulation is known to be inorganic (C5), then the temperature limit can be increased to 750°F (400°C). Most newer cores may be safely processed at the higher temperature. If in doubt about the type of interlaminar insulation used in a particular motor, contact the motor manufacturer.

   To prevent overheating, follow the recommendations of the oven manufacturer when loading the oven. Different oven designs call for different procedures. *Do not pile* stators on top of one another or place small stators inside the bores of larger ones. Burnout ovens should also be equipped with a water spray device that activates automatically if something inside the oven ignites, or if the part temperature exceeds the setpoint. Part temperature, which can vary depending on location within the oven, should be monitored with a chart recorder.

2. **Don't use an open flame for stripping.** Using uncontrolled heat degrades interlaminar insulation and warps cores.
3. **Don't sandblast the core iron.** Blasting with sand or other hard materials can cause shorts between laminations if the laminations are struck at certain angles. Shorted laminations increase core losses. Use glass beads, walnut shells, corncobs or similar materials.
4. **Don't short the laminations when grinding or filing.** This procedure, if done improperly, can cause shorts between laminations, thereby increasing core losses. When removing varnish from the stator bore after baking, take care to avoid enlarging the diameter of the bore or causing shorts in the laminations.
5. **Don't increase the air gap.** Enlarging the diameter of the stator bore or taking a cut off the rotor increases the air gap. This produces a higher magnetizing (no-load) current and may adversely affect losses.
6. **Don't increase the resistance of the stator windings.** Measure the wire size carefully with a micrometer after first removing the varnish coating. Since many motor manufacturers today use half size or metric wire, do not use a wire gauge to determine wire size. The total circular mil area of the conductors-in-hand should not be reduced. No change should be made that changes the *effective turns* of the windings.

   Before disturbing the winding, carefully measure and record the coil dimensions: inside nose-to-nose; span; core length and coil extensions. Count the turns carefully, being sure to count the turns in a full group. If you find different turns in coils of the same group, check another group for same pattern.

   When making replacement coils, measure the wire after the first group of coils has been wound. Too much tension can stretch the wire, thereby decreasing its diameter and increasing resistance and stator copper losses.

7. **Don't knurl, peen or paint bearing fits.** Bearing fits should not be knurled, peened or painted because they could become loose in service. Loose fits increase friction losses and cause early bearing failure.
8. **Don't make mechanical modifications without the customer's prior approval.** Changes to the fan can adversely affect the cooling system of the motor and possibly increase the temperature rise. Making mechanical modifications to bearings and seals can affect friction losses. Altering shaft material can also affect rotor core losses. The result in each case could be lower efficiency.

CONCLUSION

Following the above guidelines and complying with ANSI/EASA Standard AR100: *Recommended Practice For The Repair Of Rotating Electrical Apparatus* will help assure that the motors you rewind and repair retain the same efficiency. By adhering to these guidelines, you will also have the appropriate documentation to demonstrate the quality of your work to your customers.

Note: This article was originally published as *EASA Tech Note 16* (May 1992); it was reviewed and updated as necessary in August 2016.

The effect of repair/rewinding on motor efficiency

Note: This article summarizes the results of the *EASA/AEMT Rewind Study and Good Practice Guide to Maintain Motor Efficiency* (2003).

INTRODUCTION

Electric motors are key components in most industrial plants and equipment. They account for two-thirds of all the electrical energy used by industrial/commercial applications in the developed world with lifetime energy costs normally totaling many times the original motor purchase price. In Europe and the USA alone, the annual cost of energy used by motors is estimated at over $100 billion (U.S.). Yet motor failure can cost more in terms of lost production, missed shipping dates and disappointed customers. Even a single failure can adversely impact a company's short-term profitability; multiple or repeated failures can reduce future competitiveness in both the medium and long term.

Clearly, industrial companies need effective motor maintenance and management strategies to minimize overall motor purchase and running costs while avoiding the pitfalls caused by unexpected motor failures.

Experienced users long have known that having motors repaired or rewound by a qualified service center reduces capital expenditures while assuring reliable operation. Rising energy costs in recent years, however, have led to questions about the energy efficiency of repaired/rewound motors.

To help answer these questions, the Electrical Apparatus Service Association (EASA) and the Association of Electrical and Mechanical Trades (AEMT) studied the effects of repair/rewinding on motor efficiency. This article describes the methodology and results of that study. [See Part 2 of the *EASA/AEMT Rewind Study and Good Practice Guide to Maintain Motor Efficiency* for procedures for maintaining or even improving the efficiency of repaired/rewound motors.]

BACKGROUND

Simple, robust and efficient, induction motors often convert 90% - 95% of input electrical power into mechanical work. Still, given the huge amount of energy they use, even minor changes in efficiency could have a big effect on operating costs.

Over the past two decades, rising energy costs and governmental intervention have led to significant improvements in motor efficiency. In the USA, for example, the Energy Policy Act of 1992 (EPAct) and new premium efficiency designs have boosted efficiency levels to the highest currently available. In Europe, voluntary agreements among leading motor manufacturers and the European Commission (EC) are aiming at the same result with EFF1 category motors.

Meanwhile, claims that repair/rewinding inevitably decreases motor efficiency have been commonplace. Based largely on a handful of studies of mostly smaller motors (up to 30 hp or 22.5 kW), they often assert that efficiency drops 1 - 5% when a motor is rewound–even more with repeated rewinds [Refs. 1-5]. This perception persists, despite evidence to the contrary provided by a more recent study by Advanced Energy [Ref. 6].

In this context, decision makers today are carefully evaluating both the reliability and the efficiency of the motors they buy or have repaired. The difficulty they face, however, is how to separate fact from fiction, reality from myth.

OBJECTIVES

EASA and AEMT designed this study to find definitive answers to efficiency questions, particularly as regards repaired/rewound motors. The primary objective of the project was to determine the impact of rewinding/repair on induction motor efficiency. This included studying the effects of a number of variables:

- Rewinding motors with no specific controls on stripping and rewind procedures.
- Overgreasing bearings.
- How different burnout temperatures affect stator core losses.
- Repeated rewinds.
- Rewinding low- versus medium-voltage motors.
- Using different winding configurations and slot fills.
- Physical (mechanical) damage to stator core.

A second goal was to identify procedures that degrade, help maintain or even improve the efficiency of rewound motors and prepare a *Good Practice Guide to Maintain Motor Efficiency* [ref 7].

A final objective was to attempt to correlate results obtained with the running core loss test and static core loss tests.

PRODUCTS EVALUATED

This research focused on induction motors with higher power ratings than those in previous studies (i.e., those most likely to be rewound), subjecting them to independent efficiency tests before and after rewinding [Refs. 1 - 6]. Throughout this study EASA and the AEMT sought a balanced approach that takes account of practical constraints and overall environmental considerations.

The results of tests carried out by Nottingham University (UK) for EASA and the AEMT show that good practice repair methods maintain efficiency to within the range of accuracy that it is possible to measure using standard industry test procedures (± 0.2%), and may sometimes improve it.

Twenty-two new motors ranging from 50 to 300 hp (37.5 to 225 kW) and 2 smaller motors [7.5 hp (5.5 kW)] were selected for the study. These included:

- 50 and 60 Hz motors
- Low- and medium-voltage motors
- IEC and NEMA designs
- Open dripproof (IP 23) and totally enclosed fan-cooled (IP 54) enclosures
- 2- and 4-pole motors
- 7.5 hp (5.5 kW) motors (for checking earlier results of

multiple burnout cycles)

- Round robin tests on a new 40 hp (30 kW) motor, which indicate that such factors as supply voltage, repeatability of the test procedures, and instrumentation, taken together, can affect test results.

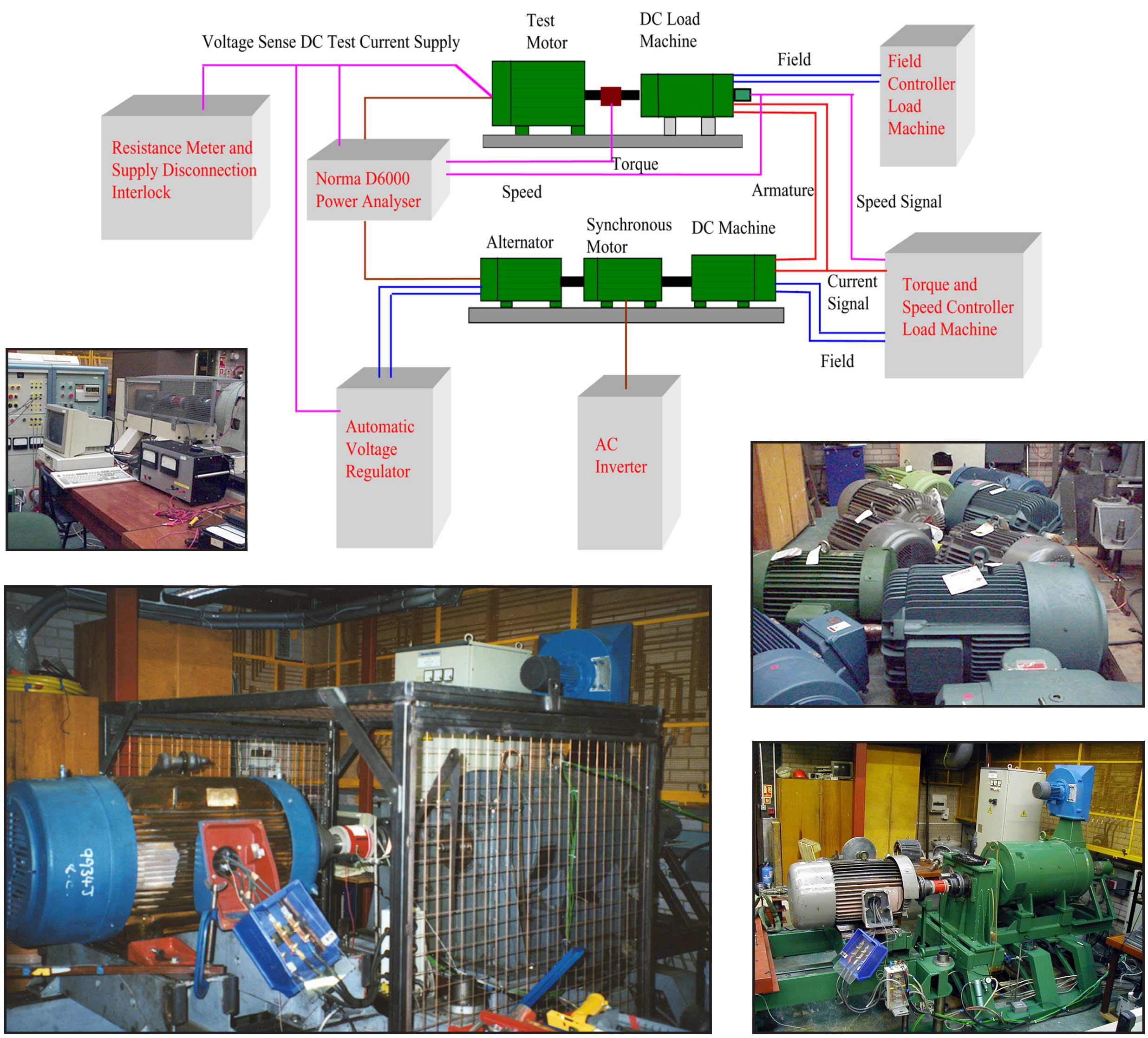
STANDARDS FOR EVALUATING LOSSES

Two principal standards are relevant to this work. IEC 60034-2 is the current European standard (BS EN 60034-2 is the British version), and IEEE 112 is the American standard. The IEEE standard offers several methods of translating test results into a specification of motor efficiency. IEEE 112 Method B (IEEE 112B) was used for this study because it provides an indirect measurement of stray load loss, rather than assuming a value as the IEC standard does. IEEE 112B therefore measures efficiency more accurately than the IEC method.

Both IEC 60034-2 and IEEE 112B efficiency test procedures require no-load, full-load and part-load tests. The IEEE approach requires no-load tests over a range of voltages and a wider range of loads for the part-load conditions. The IEEE 112B also requires precise torque measurement, whereas the IEC test does not.

Although the study was conducted in accordance with IEEE 112B test procedures, the results are quoted to both IEC and IEEE standards. Interestingly, the most significant difference between them is in the area of stray load loss. (For an in-depth comparison of IEEE 112B and IEC 60034-2, see Page 2-104; and for an explanation of loss segregation according to IEEE 112-1996, see Page 2-105.)

FIGURE 2-35



Schematic of test rig used for IEEE 112 Method B Tests.

METHODOLOGY

All tests were carried out in accordance with IEEE 112B using a dynamometer test rig (Figure 2-35). Instrumentation accuracy exceeded that required by the standard. A new 40 hp (30 kW) motor was tested at four different locations (see "Round Robin Testing and Test Protocol" below) to verify the accuracy of the test equipment and methods used by Nottingham University. For comparison, efficiencies also were calculated in accordance with BS EN 60034-2, which is the current standard in Europe (see Page 2-105) for discussion of IEEE and IEC methods for calculating stray load losses).

Each motor was initially run at full load until steady-state conditions were established and then load tested. The motors were then dismantled, the stators were processed in a controlled-temperature oven, and the windings were removed. Next, each motor was rewound, reassembled and retested using the same test equipment as before. In most cases, core losses were measured before burnout and after coil removal using a loop (ring) test and/or two commercial core loss testers. To minimize performance changes due to factors other than normal rewind procedures, rotor assemblies were not changed.

POTENTIAL SOURCES OF ERROR

Ideally, the electrical supply to a machine under test should be a perfectly sinusoidal and balanced set of three-phase voltages. Unbalance in the phase voltages (line-to-line as only three wire supplies are used) or imperfection in the 120 electrical degree phase difference between adjacent phases will increase machine losses. Although losses change with the changing unbalance during the day in the normal supply system, phase voltage regulation can mitigate this.

The presence of voltage harmonics or distortion in the supply also will increase the power loss in a machine. The considerable distortion present on normal mains supplies changes constantly throughout the day and from day to day.

Such potential sources of error were avoided in this project by rigorously adhering to the IEEE 112B test procedures and using a well-designed test rig.

REPEATABILITY OF RESULTS

Although accuracy of the highest order obviously was required, repeatability was even more important. Therefore, the test rig for this project (Figure 2-35) was designed to control three of four basic factors that contribute to repeatability: the power supply system, the mechanical loading system, and the instrumentation. The fourth variable, test procedures, is discussed separately below.

Test rig and equipment. The test equipment used by the University of Nottingham consisted of a DC load machine that was coupled to the test motor by a torque transducer mounted in a universal joint. The AC supply to the test motors was provided by an AC generator that was driven by an inverter-fed synchronous motor. This setup provided a constant sinusoidal voltage of almost perfect balance and waveform purity. A second DC machine was coupled to the same shaft as the generator and synchronous motor to reclaim energy from the DC load machine.

A range of in-line torque transducers was employed in each rig to ensure maximum accuracy. Power, voltage, current, speed and torque were measured with a Norma D6000 wattmeter with motor option. All torque, speed and power readings were taken at the same instant and averaged over several slip cycles to minimize reading fluctuations. The winding resistance was measured at the motor terminals with a four-wire Valhalla electronic bridge with a basic accuracy of 0.02%.

The test setup therefore controlled three of the four potential sources of error–power supply, loading system and test equipment. That leaves just one–test procedures.

Test procedures. The tests for this study were performed in accordance with IEEE 112B. Test procedures, measurement intervals, and thermocouple location on the winding were optimized by comparing results for a 30 kW test motor with those obtained using direct measurement of loss by calorimeter.

As a precursor to the load test, each motor completed an entire thermal cycle of the test machine, running at full load until the temperature stabilized and the grease in the bearings settled. Typically, this took a minimum of four hours at load. The machine was then allowed to cool to room temperature.

No-load tests were essentially conducted at the temperature of the motor associated with constant, no-load, rated voltage operation. Winding temperatures were measured by thermocouples embedded in the coil extensions.

Once temperatures stabilized, a set of electrical and mechanical results was taken, and winding temperatures and resistance were determined. The test motor was then returned to full-load operation to restore the full-load temperature. Next, part-load readings were taken, starting with the highest load and working down to the lightest load. Readings were taken quickly in each case, after allowing a very brief interval for the machine to settle to its new load.

The techniques and equipment described above ensured **repeatability to within 0.1%** for tests conducted on a stock motor at intervals of several months. A 100 hp (75 kW) motor without any modifications was kept especially for this purpose.

ROUND ROBIN TESTING AND TEST PROTOCOL

As an additional check to ensure accurate test results, a 30 kW IEC motor was efficiency tested first by the University of Nottingham and then by three other test facilities. The other facilities were: U.S. Electrical Motors, St. Louis, Missouri; Baldor Electric Co., Fort Smith, Arkansas; and Oregon State University, Corvallis, Oregon.

Each facility tested the motor at 50 and 60 Hz using the IEEE 112B test procedure. All testing used the loss-segregation method (at no load and full load), which allowed for detailed analysis.

As a benchmark, the results were compared with those of round robin test programs previously conducted by members of the National Electrical Manufacturers Association (NEMA). Initial results of NEMA's tests varied by 1.7 points of efficiency; the variance subsequently was reduced to 0.5 points of efficiency by standardizing test procedures.

As Table 1 shows, the range of results for round robin tests of the 30 kW motor in this study did not exceed 0.9 points of efficiency at 60 Hz, and 0.5 points at 50 Hz. These results were achieved without standardization and compare favorably

TABLE 2-8: ROUND ROBIN TEST RESULTS OF 30 KW, 4-POLE MOTOR

Test location	Test	Full load efficiency	Full load power factor	Full load amps	Temperature rise	rpm
Baldor	400v/50 Hz	91.8%	86.8%	54.0	69.4°C	1469
Nottingham	400v/50 Hz	92.3%	87.0%	54.2	68.0°C	1469
U.S. Electrical Motors	400v/50 Hz	91.9%	86.7%	53.5	59.0°C	1470
Nottingham	460v/60 Hz	93.5%	85.9%	47.0	53.9°C	1776
Oregon State	460v/60 Hz	92.6%	85.9%	47.0	50.0°C	1774
U.S. Electrical Motors	460v/60 Hz	93.1%	86.4%	46.5	42.0°C	1774

TABLE 2-9: METHODS

IEEE 112B	IEC 60034-2
Input - output	Braking test
Input - output with loss segregation Indirect measurement of stray load loss	—
Duplicate machines	Mechanical back-to-back
Electrical power measurements under load with segregation of losses 1) Direct measurement of stray load loss 2) Assumed value of stray load loss-load point calibrated	Summation of losses (Calibrated driving machine)
Equivalent circuit 1) Direct measurement of stray load loss-loads point calibrated 2) Assumed value of stray load loss-load point calibrated	—
—	Electrical back-to-back

TABLE 2-10: INSTRUMENT ACCURACY

	IEEE 112-1996	IEC 60034-2
Genaral	± 0.2%	± 0.5%
Three-phase wattmeter	± 0.2%	± 1.0%
Transformers	± 0.2%	Included
Speed/slip	Stroboscope/ digital	Stroboscope/ digital
Torque		
a) Rating	≤ 15%	—
b) Sensitivity	± 0.25%	—
EPACT (IEEE 112-1996)		
General	± 0.2%	—
Transformers	± 0.2%	—
Combined	± 0.2%	—
Speed	± 1 rpm	—
Torque	± 0.2%	—

with the 1.7% variation of the non-standardized NEMA tests.

These results also verify that the test protocol for determining the impact of rewinding on motor efficiency is in accord with approved industry practice, and that the results obtained in this study are not skewed by the method of evaluation.

COMPARISON OF IEC 60034-2 AND IEEE 112-1996 LOAD TESTING METHODS

The IEEE 112B test procedure was selected over IEC method 60034-2 for the EASA/AEMT rewind study because it measures motor efficiency more accurately. Many of the differences between the two methods are explained below and illustrated in Table 2-9 through Table 2-14.

The most significant difference between the two methods, however, is how they determine stray load loss (SLL). IEEE 112B uses the segregated loss method, which is explained more fully on Page 2-105. IEC 60034-2 assumes a loss of 0.5% of the input power at rated load, which is assumed to vary as the square of the stator current at other load points. The effect can be to overstate the level of efficiency by up to 1.5 points, depending on what percent of the total loss is represented by the stray load loss. The differences in EASA/AEMT rewind study were less (see Table 2-9).

GENERAL DIFFERENCES BETWEEN IEEE 112B AND IEC 60034-2

- IEC does not require bearing temperature stabilization for determining core loss and friction and windage (F&W) loss from no-load test. IEEE requires successive readings of 3% or less in half-hour intervals.
- For load testing, IEC uses tested temperature for I^2R loss of the stator. IEEE uses tested temperature rise plus 25°C.
- For load testing, IEC does not specify any temperature correction for slip (rotor I^2R loss). IEEE corrects to specified stator temperature.
- For temperature correction of copper windings, IEC uses 234.5°C. IEEE proposes to use 235°C.

TABLE 2-11: REFERENCE TEMPERATURE

	IEEE 112-1996	IEC 60034-2
Ambient	25°C	20°C
Specified 1) Test	Preferred	Used only for load test
2) Other		
Class A/E	75°C	75°C
Class B	95°C	95°C
Class F	115°C	115°C
Class H	130°C	130°C

TABLE 2-12: IEEE 112 ASSUMED STRAY LOAD LOSS VS. HP/KW

Machine rating	Stray load loss % of rated output
1 - 125 hp / 0.75 - 93 kW	1.8%
126 - 500 hp / 94 - 373 kW	1.5%
501 - 2499 hp / 374 - 1864 kW	1.2%
2500 hp / 1865 kW and larger	0.9%

TABLE 2-13: TOLERANCES

	IEEE 112-1996	IEC 60034-1-1998	
Summation of losses	See note.	≤50 kW	-15% of (1 - eff.)
	See note.	>50 kW	-10% of (1 - eff.)
Input/output	See note.		-15% of (1 - eff.)
Total losses	See note.	>50 kW	+10% of (1 - eff.)

Note: Although IEEE does not specify any tolerance, NEMA and EPACT require that the minimum efficiency of 1 - 500 hp polyphase motors not exceed plus 20% increase in loss from the nominal value.

Stray load loss (SLL). Except for load tests (braking, back-to-back, and calibrated machine), IEC uses a specified percentage for SLL. The specified value is 0.5% of input at rated load, which is assumed to vary as the square of the stator current at other loads.

For all load tests except input-output, IEEE requires determination of the SLL by indirect measurement with data smoothing–i.e., raw SLL is the total loss minus remaining segregated (and measurable) losses.

For non-load tests, IEEE requires direct measurement of SLL unless otherwise agreed upon. Table 2-12 shows the assumed value at rated load. Values of SLL at other loads are assumed to vary as the square of the rotor current.

INPUT - OUTPUT TESTS: IEEE 112-1996 VS. IEC 60034-2

- IEC does not specify any limitations on dynamometer size or sensitivity.
- IEC does not specify dynamometer correction for friction and windage.
- IEC uses tested temperature rise without correction. IEEE uses tested temperature rise plus 25°C.
- IEEE specifies 6 load points. IEC does not specify any load points.

INPUT - OUTPUT TESTS WITH LOSS SEGREGATION (INDIRECT MEASUREMENT OF STRAY LOAD LOSS): IEEE 112-1996 VS. IEC 60034-2

IEC has no equivalent test method.

ELECTRICAL POWER MEASUREMENT WITH LOSS SEGREGATION: IEEE 112-1996 VS. IEC 60034-2

- IEEE requires actual measurement of SLL by reverse rotation test. Specified value accepted only by agreement. IEC uses a conservative specified value.
- IEEE requires actual loading of the machine at 6 load points. IEC does not specify the number of load points and allows the use of reduced voltage loading at constant slip and with vector correction of the stator current to determine load losses.
- Both IEEE and IEC correct stator I^2R losses to the same specified temperature. However, IEC makes no temperature correction for rotor I^2R losses.

MISCELLANEOUS INFORMATION: NEMA MG 1-1998, REV. 3 VS. IEC 60034-1-1998

- IEC does not use service factors.
- IEC allows less power supply variations.
- Temperature rise limits are generally the same.
- Torque characteristics are very similar.
- IEC inrush current requirements are not as tight as NEMA's and generally allow 20% or greater on 5 hp (3.5 kW) and larger.
- IEC does not assign a specific output rating to a frame, but does specify preferred outputs.

Note: Although IEEE does not specify any tolerance, NEMA and EPACT require that the minimum efficiency of 1 - 500 hp polyphase motors not exceed plus 20% increase in loss from the nominal value.

Table 2-14 compares the results of IEEE and IEC efficiency testing of the motors in the EASA/AEMT study. The figures represent the efficiency of each motor before rewind.

LOSS SEGREGATION METHOD USED IN EASA/AEMT REWIND STUDY

The EASA/AEMT rewind study used the IEEE 112-1996 method to segregate losses. Applicable sections of the standard are summarized below to help explain the process. The actual test procedures for determining these losses are described in the standard. Discussion of how instrumentation, dynamometer calibration, methods of temperature correction and numerous other procedural items can affect the accuracy of the acquired

TABLE 2-14: IEEE AND IEC EFFICIENCY COMPARISON FOR EASA/AEMT STUDY

Motor	IEEE Efficiency	IEC Efficiency	Difference
1A	94.1	94.7	0.6
2B	92.9	93.5	0.6
3C	94.5	95.3	0.8
4D	95.0	95.0	0.0
5E	92.3	92.3	0.0
6F	94.4	94.4	0.0
7B	93.7	94.0	0.3
8C	96.2	96.3	0.1
9E	90.1	90.3	0.2
10D	95.4	95.3	-0.1
11F	96.4	95.9	-0.5
12F	95.9	95.5	-0.4
13G	94.8	95.3	0.5
14H	89.9	91.2	1.3
15J	93.0	94.2	1.2
16H	95.4	95.5	0.1
17H	86.7	87.3	0.6
18G	94.2	94.2	0.0
19H	93.0	92.7	-0.3
20H	93.9	94.1	0.2
21J	93.7	94.6	0.9
22H	83.2	84.0	0.8
23K	95.7	95.7	0.0
24E	95.1	95.1	0.0

data is beyond the scope of this section.

Similar relevant testing standards include Canadian Standard C390, Australian/New Zealand Standard AS/NZS 1359.5, Japanese Standard JEC 2137-2000, and the recently adopted IEC 61972. As explained on Page 2-105, the test standard currently used in Europe (IEC 60034-2) differs from these standards.

Several key issues need to be emphasized in regard to procedure. First, the EASA/AEMT study confirmed that the friction loss does not stabilize until the grease cavity has been adequately purged, which may take considerable time. The study also suggests that in some cases a break-in heat run may affect other losses.

The test protocol employed for this project included a break-in heat run for each unit. Once this was done, care was taken not to alter the grease fill during disassembly, except on motors 1A and 3C, where grease was added.

DETERMINATION OF EFFICIENCY

Efficiency is the ratio of output power to total input power. Output power equals input power minus the losses. Therefore, if two of the three variables (output, input, or losses) are known, the efficiency can be determined by one of the following equations:

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

$$\text{Efficiency} = \frac{\text{Input power - losses}}{\text{Input power}}$$

TEST METHOD 112 B: INPUT - OUTPUT WITH LOSS SEGREGATION

This method consists of several steps. All data is taken with the machine operating either as a motor or as a generator, depending upon the region of operation for which the efficiency data is required. The apparent total loss (input minus output) is segregated into its various components, with stray load loss defined as the difference between the apparent total loss and the sum of the conventional losses (stator and rotor I^2R loss, core loss, and friction and windage loss). The calculated value of stray load loss is plotted vs. torque squared, and a linear regression is used to reduce the effect of random errors in the test measurements. The smoothed stray load loss data is used to calculate the final value of total loss and the efficiency.

TYPES OF LOSSES

Stator I^2R loss. The stator I^2R loss (in watts) equals 1.5 x I^2R for three-phase machines, where:

I = the measured or calculated rms current per line terminal at the specified load

R = the DC resistance between any two line terminals corrected to the specified temperature

Rotor I^2R loss. The rotor I^2R loss should be determined from the per unit slip, whenever the slip can be determined accurately, using the following equation:

Rotor I^2R loss = (Measured stator input power - Stator I^2R loss - Core loss) x Slip

Core loss and friction and windage loss (no-load test). The test is made by running the machine as a motor, at rated voltage and frequency without connected load. To ensure that the correct value of friction loss is obtained, the machine should be operated until the input has stabilized.

No-load current. The current in each line is read. The average of the line currents is the no-load current.

No-load losses. The reading of input power is the total of the losses in the motor at no-load. Subtracting the stator I^2R loss (at the temperature of this test) from the input gives the sum of the friction (including brush-friction loss on wound-rotor motors), windage, and core losses.

Separation of core loss from friction and windage loss. Separation of the core loss from the friction and windage loss may be made by reading voltage, current, and power input at rated frequency and at voltages ranging from 125% of rated voltage down to the point where further voltage reduction increases the current.

Friction and windage. Power input minus the stator I^2R loss is plotted vs. voltage, and the curve so obtained is extended to zero voltage. The intercept with the zero voltage axis is the friction and windage loss. The intercept may be determined more accurately if the input minus stator I^2R loss is plotted against the voltage squared for values in the lower voltage range.

Core loss. The core loss at no load and rated voltage is obtained by subtracting the value of friction and windage loss from the sum of the friction, windage, and core loss.

Stray-load loss. The stray load loss is that portion of the total loss in a machine not accounted for by the sum of friction and windage, stator I^2R loss, rotor I^2R loss, and core loss.

Indirect measurement of stray load loss. The stray load loss is determined by measuring the total losses, and subtracting from these losses the sum of the friction and windage, core loss, stator I^2R loss, and rotor I^2R loss.

Stray load loss cannot be measured directly since it has many sources and their relative contribution will change between machines of different design and manufacture. In IEEE 112B, residual loss is evaluated by subtracting the measured output power of the motor from the input power less all of the other losses.

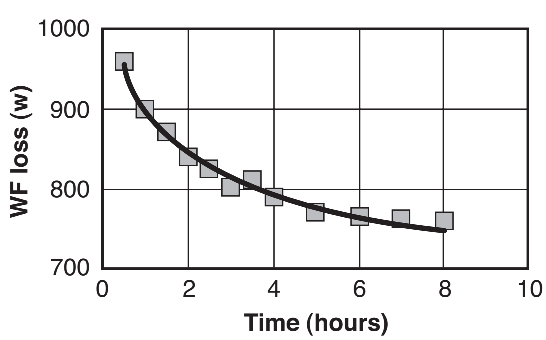
Residual loss will equal stray load loss if there is no measurement error. Since two large quantities of almost equal value are being subtracted to yield a very small quantity, a high degree of measurement accuracy is required. The biggest error, however, can come from the need for an accurate measurement of torque (of the order of 0.1% error or better) to evaluate output power precisely.

The determination of true zero torque is always a problem. The IEEE standard suggests comparing input and output powers at very light load, where most of the motor losses are due to windage and friction, the stator winding, and the machine core. Here stray load loss can be assumed to be insignificant. The torque reading can be adjusted under this condition so that input power less known losses equals output power.

IMPACT OF TOO MUCH BEARING GREASE

A number of studies have found that over-greasing the bearings can increase friction losses (see Part 2: *Good Practice Guide To Maintain Motor Efficiency* for more information). For the EASA/AEMT rewind study, grease was added to the bearings of two rewound test units in Group A. No change in lubrication was made on the rest of the motors in the test. As expected, bearing friction on the regreased motors increased and efficiency dropped 0.3 to 0.5 percent. Figure 2-36 illustrates the decrease in losses over time for a properly lubricated 60 hp (45 kW) motor in the EASA/AEMT study.

FIGURE 2-36

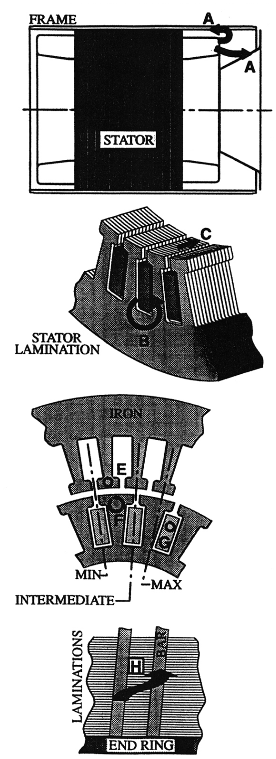


Reduction in friction and windage losses during the break-in run for a 60 hp (45 kW) motor with proper grease fill tested in the EASA/AEMT rewind study.

STRAY LOSS ANALYSIS

Figure 2-37 shows the components of stray loss. The stray load losses for the motors in Group A of the EASA/AEMT rewind study increased significantly. The cause was the mechanical damage done to the stator core (i.e., flared ends of lamination teeth) in removing the old windings and slot insulation. This, in turn, increased the pulsating or zig-zag losses (see Part 2: *Good Practice Guide To Maintain Motor Efficiency* for more information).

FIGURE 2-37



FUNDAMENTAL FREQUENCY COMPONENT

A) End turn leakage flux to air deflector and frame.
B) Nonuniform flux linking stator slot conductors, causing eddy current and circulating current losses.

SURFACE LOSS DUE TO SLOT AND MAGNETOMOTIVE FORCE HARMONICS

C) Rotor field generates stator surface loss.
D) Stator field generates rotor surface loss (not shown).

PULSATION LOSS DUE TO CHANGING MAGNETIC INDUCTION IN AIR GAP AS ROTOR TURNS

E) Stator tooth pulsation eddy current loss.
F) Rotor tooth pulsation eddy current loss.
G) Rotor cage bar pulsation loss.

ROTOR BAR CROSS CURRENT LOSSES DUE TO SKEW

H) Inner bar current.

Components of stray loss.

The burnout temperature for the motors in Group A was 660°F (350°C)–too low to completely break down the old winding insulation. As a result, it took excessive force and extra cleaning to strip out the old windings. The resulting mechanical damage increased stray load losses.

The burnout temperature for motors in Groups B, C and D of the study was increased to 680 - 700°F (360 - 370°C). This broke down the old insulation more completely, making it easier to remove the windings and clean the slots. Since lamination teeth were not damaged in the process, the stray load losses did not increase.

CORE LOSS TESTING

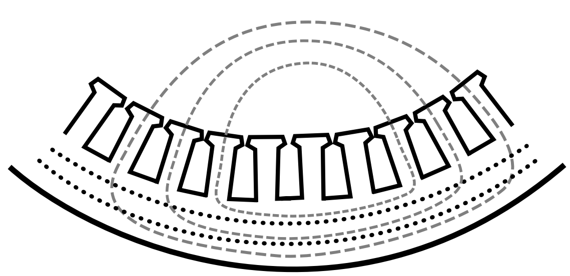
One objective of the EASA/AEMT rewind study was to evaluate the correlation between the actual stator core loss as tested in accordance with IEEE 112B and the various test methods that service centers use to determine the condition of the stator core before and after the windings have been removed. The test methods evaluated were the conventional loop test and two commercial devices from different manufacturers.

IEEE 112B core loss test. The stator core loss is determined in the IEEE 112B test by operating the motor at rated voltage and frequency without connected load. To ensure that the correct value of friction loss is obtained, measurements should not be taken until the input has stabilized. The first measurement is the no-load current. The current in each line is read and the average of the line currents is taken to be the no-load current. Next, the no-load losses are determined by measuring the total input power at no load. Subtracting the stator winding I^2R loss (at the temperature of the test) from the input power gives the sum of the friction, windage, and core losses.

Separation of the core loss from the friction and windage loss is accomplished by reading the voltage, current, and power input at rated frequency and at voltages ranging from 125% of rated voltage down to the point where further voltage reduction increases the no-load current. The power input minus the stator I^2R loss is plotted versus voltage, and the resulting curve is extended to zero voltage. The intercept with the zero voltage axis provides the value of the friction and windage loss. The intercept may be determined more accurately if the input minus stator I^2R loss is plotted against the voltage squared for values in the lower voltage range. The core loss at no load and rated voltage is obtained by subtracting the value of friction and windage loss from the sum of the friction, windage, and core loss.

Loop test. The loop test (also called the ring test) is a core testing technique primarily intended to detect hot spots (i.e., localized areas where interlaminar insulation is damaged) in a stator core. Calculations of the number of loop turns required for a desired core magnetizing flux level are made with a target flux level of 85,000 lines per square inch (85 kl/in^2 or 1.32 Tesla) being common. Some service centers calculate the loop turns required to magnetize the stator core to the core flux level of the winding design, calling this a "full flux" core test. The distribution of the flux induced in the core by the loop test, however, is not the same as that induced by the machine's winding, particularly when the rotor is removed (see Figure 2-38).

FIGURE 2-38



The short dashed lines (- - -) depict flux paths created by the stator winding. The dotted lines (. . .) illustrate the flux paths of a loop test.

The loop test is set up by inserting and wrapping turns of lead wire around the core–i.e., passing the leads through the stator bore and around the exterior of the core or stator frame. The core magnetization calculations provide an ampere-turn value that will excite the core to the desired magnetic flux level. For example, if 3600 ampere-turns were required for a magnetization level of 85 kl/in^2 (1.32T), and it was desired to limit the current though the loop turn lead wire to 80 amperes, then the loop turns required would be 45 (80 x 45 = 3600). The loop turns are typically wrapped in close proximity to each other, so as to maximize the area of the core that can be probed for hot spots.

A complete test of the core may require repeating the loop test with the loop turns placed in a different location to expose the area that was made inaccessible by the initial location of the loop test turns. The core can be probed for hot spots with an infrared thermal detector or thermocouples.

In terms of EASA/AEMT rewind study, the loop test was used to compare the core loss watts before and after winding removal. The measurement was made by inserting a one-turn search coil to detect voltage induced in the core and a true-RMS current transformer to detect the amperage in the loop turns. The voltage and current were then sensed by a wattmeter. The test was performed at the same level of magnetization for both the before winding removal and after winding removal loop tests.

Commercial core testers. Commercial core testers perform core tests that are equivalent in flux pattern to the loop test. The advantages of using the commercial testers over the conventional loop test are primarily to save time in performing the test and to improve the repeatability of test results. Commercial testers normally require only a single loop turn, because they can produce large amounts of current. Further, the testers usually have built-in metering to display current and power. Computer programs typically available from the tester manufacturers can calculate the value of current required to achieve a desired level of magnetic flux, as well as the actual flux level attained during the test. The core can be probed for hot spots, just as with the conventional loop test. Since the magnetic flux path is the same as that of the loop test, the core loss value indicated by the commercial device core test is not comparable to the core loss determined by IEEE 112B.

Core test acceptance levels. Most manufacturers of commercial core testers (including the two whose machines were used in the EASA/AEMT rewind study) suggest a test flux level of 85 kl/in^2 (1.32T) in the core back iron. A potential drawback to this approach is that the core material may be approaching the "knee" of the magnetic strength versus current curve–i.e., saturation. That being the case, a large increase in current might not result in a meaningful increase in magnetic flux, because the curve is just that, a curve, not a straight line. Since this condition can distort the results of a before and after core test, it is suggested that the tolerance on core loss after winding removal should be 20%. That is, the core loss value after winding removal, whether measured by conventional loop test or commercial tester, should not exceed that of the before test by more than 20%. To isolate a hot spot in the core, a higher flux level [from 85 kl/in^2 (1.32T) up to

97 kl/in² (1.5T)] is recommended.

Due to the wide variety of electrical magnetic steels used by motor manufacturers, it is impossible to set rigid rules for core test acceptance in terms of watts loss per pound. The criteria are greatly affected by the permeability of each type of steel. The EASA/AEMT study confirmed, however, that testing the core with the loop test or a commercial tester before and after winding removal can detect increased losses caused by burning out and cleaning the core.

Comparison of Results for Different Core Loss Test Methods. As part of the EASA/AEMT rewind study, core tests were performed on each motor in accordance with IEEE 112B before and after the core was stripped and cleaned. The loop test was performed on almost every core, again before and after winding removal. Motors representative of the various sizes in the study were also tested before and after winding removal using the commercial core testers. Not all cores were tested with the commercial devices, however, due to the availability of the test machines.

The results of the loop test and commercial core testers were compared with the changes in losses measured by the IEEE 112B method for tests performed before and after winding removal. This evaluation was inconclusive, however, because:

- The results from the three test methods varied significantly.
- In some cases the test data showed a drop in core loss after coil removal.
- Some difficulty was experienced in operating the commercial testers; this may have contributed to the erratic results.
- Evaluation of the test results indicated that the sample size was too small to draw any accurate conclusion.

Although the test results did not correlate well for the different test methods, it was apparent that core testing does produce repeatable and valid indications of core degradation or preservation. Therefore each of the methods can be useful in assessing the condition of the core before and after burnout.

TEST DATA FOR EASA/AEMT STUDY

The 24 new motors studied were divided into four groups to accommodate the different test variables. The test results summarized below show no significant change in the efficiency of motors rewound using good practice repair procedures (within the range of accuracy of the IEEE 112B test method), and that in several cases efficiency actually increased. The complete test data for the motors in the EASA/AEMT rewind study are provided in Table 2-15 and Table 2-18 through Table 2-21.

Group A Six low-voltage motors [100 - 150 hp (75 - 112 kW) rewound once. No specific controls on stripping and rewind processes with burnout temperature of 660°F (350°C).

Results: Initially showed **average efficiency change of -0.6% after 1 rewind (range -0.3 to -1.0%)**.

However, two motors that showed the greatest efficiency reduction had been relubricated during assembly, which increased the friction loss.

After this was corrected the **average efficiency change was -0.4% (range -0.3 to -0.5%)**.

Group B Ten low-voltage motors [60 - 200 hp (45 - 150 kW)] rewound once. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Average efficiency change of -0.1% (range +0.2 to -0.7%).

One motor was subsequently found to have faulty interlaminar insulation as supplied. Omitting the result from this motor, the **average efficiency change was -0.03% (range +0.2 to -0.2%)**.

Group C Low-voltage motors rewound more than once. Controlled stripping and rewind processes.

Group C1. Five low-voltage motors [100 - 200 hp (75 - 150 kW)] rewound two or three times. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Average efficiency change of -0.1% (range +0.6 to -0.4%) after 3 rewinds (3 machines) and 2 rewinds (2 machines).

Group C2. Two low-voltage motors [7.5 hp (5.5 kW)] processed in burnout oven three times and rewound once. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Average efficiency change of +0.5% (range +0.2 to +0.8%).

TABLE 2-15: COMPARISON OF LOSS DISTRIBUTION BY PERCENT FOR MOTORS TESTED IN THE EASA/AEMT STUDY

Losses	2 pole average	4 pole average	Design factors affecting losses
Core losses (W_c)	19%	21%	Electrical steel, air gap, saturation, supply frequency, condition of interlaminar insulation
Friction and windage losses (W_{fw})	25%	10%	Fan efficiency, lubrication, bearings, seals
Stator I²R losses (W_s)	26%	34%	Conductor area, mean length of turn, heat dissipation
Rotor I²R losses (W_r)	19%	21%	Bar end ring area and material
Stray load losses (W_i)	11%	14%	Manufacturing processes, slot design, air gap, condition of air gap surfaces and end laminations

EXPLANATION OF NAMEPLATE EFFICIENCY

Nameplate efficiency is the benchmark for comparing efficiencies before and after a motor rewind. It is important to understand the basis for and limitation of nameplate values.

The nameplate may state the nominal efficiency, the minimum (also called "guaranteed") efficiency, or both. If only one is listed, it usually is the nominal value, which always has an associated minimum value (to allow for higher losses). If no efficiency is shown on the nameplate, contact the motor manufacturer or consult catalogs or technical literature.

Nominal and minimum efficiencies are best understood as averages for particular motor designs–not as actual tested efficiencies for a particular motor. They are derived by testing sample motors of a single design.

As Table 2-16 and Table 2-17 show, the efficiencies for NEMA and IEC motors cover a range of values (between the minimum and nominal efficiencies). They are not discrete values. Consequently, it can be misleading to compare the tested efficiency of a new or rewound motor with its nameplate efficiency.

The minimum efficiency is based on a "loss difference" of 20% for NEMA motors and 10 or 15% for IEC motors. This allows for variations in material, manufacturing processes, and test results in motor-to-motor efficiency for a given motor in a large population of motors of a single design.

Nominal and minimum efficiency values are only accurate at full load, with rated and balanced sinusoidal voltage and frequency applied at sea level and at an ambient of 25°C. Therefore, it usually is impractical to measure efficiency in situ to the levels of accuracy implied by the three significant figures that may be shown on the nameplate. The fact that the tested efficiency does not match the nominal nameplate efficiency does not imply that the motor was made or repaired improperly.

Figure 2-39 and Figure 2-40 show typical nameplates for IEC and NEMA motors.

Reference: NEMA MG 1-1998 (Rev. 3).

TABLE 2-16: NEMA/EPACT EFFICIENCY LEVELS

Nominal efficiency	Minimum efficiency based on 20% loss difference
94.1	93.0
93.6	92.4
93.0	91.7
92.4	91.0
91.7	90.2
91.0	89.5
90.2	88.5
89.5	87.5
88.5	86.5
87.5	85.5

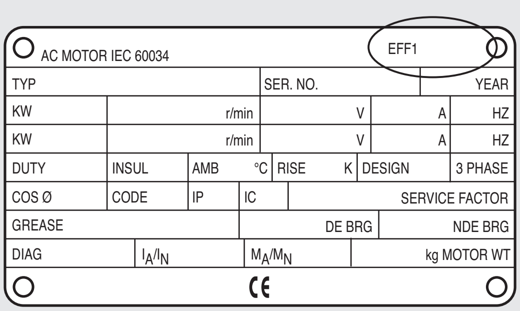
Reference: NEMA MG 1-1998 (Rev. 3), Table 12-10.

TABLE 2-17: IEC 60034-1, 1998 EFFICIENCY LEVELS

Nominal efficiency	Minimum efficiency <50 kW (15% loss difference)	Minimum efficiency >50 kW (20% loss difference)
94.1	93.3	93.5
93.6	92.7	93.0
93.0	92.0	92.3
92.4	91.3	91.6
91.7	90.5	90.9
91.0	89.7	90.1
90.2	88.7	89.2
89.5	87.9	88.5
88.5	86.2	87.4
87.5	85.9	86.3

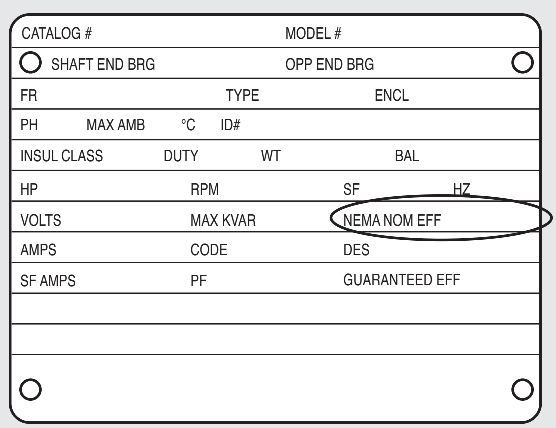
Reference: IEC 60034-1, Table 18. Nominal and minimum efficiencies for IEC motors measured by summation of loss method.

FIGURE 2-39



Typical IEC motor nameplate.

FIGURE 2-40



Typical NEMA motor nameplate.

Group D One medium-voltage motor [300 hp (225 kW/3.3 kV)] with formed stator coils rewound once. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Efficiency change of -0.2%. The behavior of this motor was similar to the low-voltage machines rewound with specific controls.

Table 2-18 through Table 2-21 show the full-load performance figures for each group calculated in accordance with IEEE 112B. Each motor is identified by a code number (far left column). In some cases, more than one motor was made by the same manufacturer.

Each motor was initially tested and then dismantled, stripped of its stator windings, rewound, reassembled and retested. To minimize performance changes due to factors other than normal rewind procedures, rotor assemblies were not changed. In the case of 1A and 3C, the bearings were relubricated. This violated the test protocol but showed that overlubrication significantly increased friction and windage losses and decreased efficiency.

To stabilize the losses, a break-in heat run was performed prior to testing. The method of data collection was all computerized and recorded on IEEE112-1996 Form B.

Also included in this section are the results of the round robin testing of a single motor, as well as a sample file of test data in accordance with IEEE 112B.

SIGNIFICANCE OF TESTS RESULTS

The test results for each contolled group falls within the range of the deviation of the round robin tests, indicating that test procedures were in accordance with approved industry practice (see "Round Robin Testing and Test Protocol" on Page 2-103).

The average efficiency change for each controlled group also falls within the range of accuracy for the test method (± 0.2%), showing that motors repaired/rewound following good practices maintained their original efficiency, and that in several instances efficiency actually improved (see sidebar "Explanation of Nameplate Efficiency").

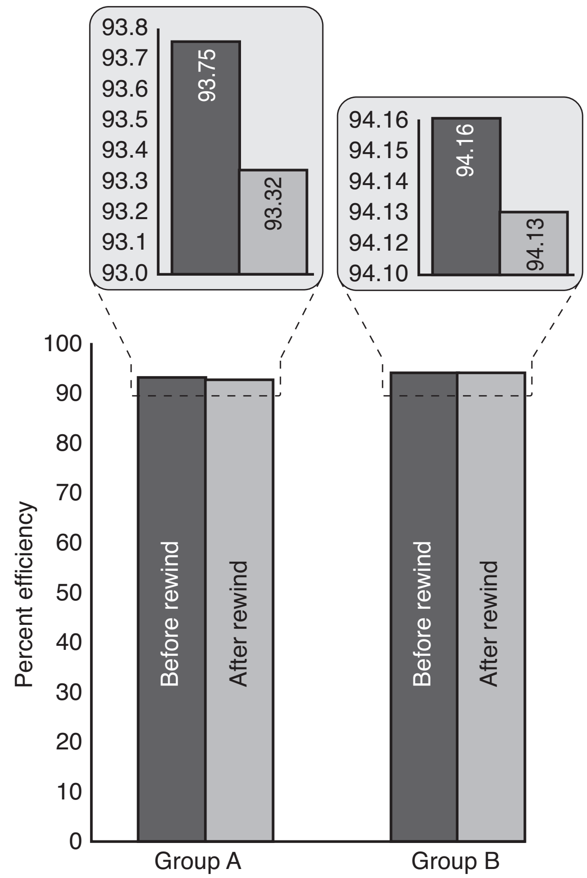
All motors were burned out at controlled temperatures. Other specific controls applied to motors (except those in Group A) included control of core cleaning methods and rewind details such as turns/coil, mean length of turn, and conductor cross sectional area. The benefits of these controls, which are clearly shown in Figure 2-41, form the basis of the *Good Practice Guide to Maintain Motor Efficiency* (Part 2).

CONCLUSION

This report is the work of a team of leading international personnel from industry and academia. It provides a full account of the details of the study, as well as actual test data. It also explains how motor losses were calculated for this study in accordance with IEEE 112 Method B, widely recognized as one of the most accurate test standards currently in use.

In addition, this report summarizes the main differences between the IEC test standard (BS EN 60034-2) and IEEE 112-1996 and compares the motor efficiencies measured for this project but calculated by the two different methods. Finally, it demonstrates that tests commonly used by service centers are effective in determining if repair processes (particularly winding burnout and removal) have affected motor efficiency.

FIGURE 2-41



Average efficiency.

The results of the study clearly demonstrate that motor efficiency can be maintained provided repairers use the methods outlined in the *Good Practice Guide to Maintain Motor Efficiency* [ref. 7].

ADDITIONAL INFORMATION INCLUDED WITH THE EASA/AEMT REWIND STUDY REPORT

- ***Good Practice Guide to Maintain Motor Efficiency* (Part 2).** Intended primarily for service center personnel, this outlines the good practice repair methods used to achieve the results given in this study. It can be used as a stand-alone document. It also contains repair tips, relevant motor terminology, and information about sources of losses in induction motors that affect efficiency. Included, too, is a useful analysis of stray load loss, which is currently treated differently in IEC and IEEE motor test standards.
- **Appendix 4: Electrical Steels.** The type of electrical steel and interlaminar insulation chosen for the stator and ro-

tor laminations are very important in determining motor performance and efficiency. Improper repair processes, however, can alter the qualities of the steel core and its interlaminar insulation. This appendix reviews the various types of electrical steel used throughout the world and explains in greater detail the reasons for some of the good practices suggested in Part 2.

- **Appendix 5: Repair or Replace?** This often difficult question is covered comprehensively here. Replacing a motor with a new one of higher efficiency is often the best financial option. At other times, repairing the existing motor will yield better results. Key factors include annual running hours, the availability of a suitable high efficiency replacement motor, downtime, and reliability. This chapter also contains charts that can help both users and repairers make the best choice.

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TABLE 2-18: GROUP A–LOW-VOLTAGE MOTORS REWOUND WITH NO SPECIFIC CONTROL ON STRIPPING OR REWIND

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	Percent load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction (watts)	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
1A 100 hp, 2 pole	Before	0.0580	45.00	0.0538	102.5	1458.1	834.0	1163.8	526.0	805.0	94.1		
	After	0.0591	45.45	0.0548	99.9	1313.1	773.9	1298.7	1152.0	977.3	93.1	-1.0	
	After	0.0601	47.85	0.0552	100.1	1323.1	774.2	1251.5	993.5	976.9	93.3	-0.8	DE bearing cleaned
	After	0.0601	47.85	0.0552	99.9	1323.1	770.9	1257.3	857	969.6	93.5	-0.6	Both bearings cleaned
	After	0.0601	47.85	0.0552	100.0	1323.1	770.5	1298.7	755.5	959.3	93.6	-0.5	Bearings replaced
2B 100 hp, 4 pole	Before	0.0933	37.10	0.0892	102.3	2640.8	1608.5	499.7	386.0	655.5	92.9		
	After	0.0927	34.08	0.0896	99.9	2536.6	1661.2	526.3	360.6	1043.4	92.4	-0.5	
3C 100 hp, 2 pole	Before	0.0448	36.70	0.0429	100.4	1423.2	714.0	632.8	609.8	944.1	94.5		
	After	0.0496	54.00	0.0446	99.5	1560.5	726.0	659.6	1151.1	1076.1	93.5	-1.0	
	After	0.0484	41.47	0.0455	99.5	1591.7	722.2	656.3	730.8	1047.3	94.0	-0.5	DE bearing cleaned
	After	0.0484	41.47	0.0455	99.0	1590.3	718.1	656.8	679.6	1050.1	94.1	-0.5	Both bearings cleaned
4D 100 hp, 2 pole	Before	0.0385	38.90	0.0366	99.2	852.0	752.4	705.4	1161.4	440.6	95.0		
	After	0.0415	36.93	0.0397	100.2	930.7	774.7	752.0	1137.4	719.0	94.5	-0.5	
5E 150 hp, 2 pole	Before	0.0611	32.90	0.0593	100.5	3436.2	1593.2	1906.9	1689.7	715.7	92.3		
	After	0.0652	34.65	0.0628	99.7	3486.2	1621.5	2300.1	1639.8	717.5	92.0	-0.3	
7B 150 hp, 2 pole	Before	0.0268	49.70	0.0245	99.8	1247.6	1381.6	1179.2	2781.6	942.1	93.7		
	After	0.0268	43.90	0.0250	99.9	1255.2	1439.9	1256.0	3077.0	1051.1	93.3	-0.4	

TABLE 2-19: GROUP B–LOW-VOLTAGE MOTORS REWOUND ONCE WITH CONTROLLED REWIND PROCESS

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	Percent load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
6F 150 hp, 2 pole	Before	0.0359	31.60	0.0350	100.4	1661.9	1637.1	988.5	1586.4	743.0	94.4		
	After	0.0390	30.63	0.0382	99.8	1729.8	1624.2	1058.2	1624.8	662.5	94.3	-0.1	
9E 60 hp, 2 pole	Before	0.1308	45.57	0.1212	99.8	1055.4	1124.2	647.7	1674.7	392.5	90.1		
	After	0.1266	43.17	0.1183	100.1	1026.0	1206.0	679.8	1645.0	497.8	89.9	-0.2	
10D 125 hp, 4 pole	Before	0.0347	28.95	0.0341	100.0	1317.9	931.1	785.3	986.8	602.1	95.4		
	After	0.0360	36.67	0.0344	100.1	1286.9	964.3	847.5	936.4	750.6	95.2	-0.2	
11F 200 hp, 2 pole	Before	0.0203	50.48	0.0185	99.8	1721.1	1020.7	1333.3	1439.7	113.8	96.4		
	After	0.0208	47.47	0.0192	100.1	1799.3	1250.9	1291.6	1291.1	114.3	96.3	-0.1	
14H 50 Hz, 55 kW, 4 pole	Before	0.0675	47.42	0.0621	100.0	1577.0	1215.7	1650.2	664.9	1069.7	89.9		
	After	0.0600	47.30	0.0553	99.9	1405.2	1165.3	2447.6	750.7	882.7	89.2	-0.7	Faulty core iron
16H 50 Hz 150 kW, 4 pole	Before	0.0196	45.75	0.0182	99.0	2304.3	1053.0	2122.9	740.1	904.8	95.4		
	After	0.0171	36.85	0.0163	100.1	1981.1	1017.6	2075.1	772.9	1112.0	95.6	+0.2	
18G 50 Hz 55 kW, 4 pole	Before	0.0775	48.70	0.0711	99.2	1334.6	803.1	733.2	219.6	277.6	94.2		
	After	0.0710	34.75	0.0685	100.0	1310.9	824.6	737.5	229.3	303.3	94.2	0	
19H 50 Hz 132 kW, 2 pole	Before	0.0296	43.97	0.0276	99.6	2537.6	1704.8	1925.3	3434.0	475.1	93.0		
	After	0.0259	36.15	0.0248	99.7	2167.1	1684.8	1863.0	3722.7	403.9	93.0	0	
20H 50 Hz 45 kW, 2 pole	Before	0.0773	41.53	0.0727	101.0	801.8	697.0	722.1	386.4	363.1	93.9		
	After	0.0712	39.03	0.0676	100.3	707.9	669.6	664.1	451.2	427.3	93.9	0	
21J 50 Hz 75 kW, 2 pole	Before	0.0468	44.55	0.0435	99.6	1319.6	870.0	1146.0	566.2	1087.9	93.7		
	After	0.0435	40.38	0.0411	99.9	1239.9	856.7	1126.8	510.4	1093.2	93.9	+0.2	
24E 100 hp, 4 pole	Before	0.0951	39.58	0.0900	100.4	1389.4	759.4	876.9	389.2	415.7	95.1		
	After	0.0936	34.99	0.0902	100.0	1465.7	775.3	1032.6	420.0	274.5	95.0	-0.1	

TABLE 2-20: GROUP C–LOW-VOLTAGE MOTORS REWOUND MORE THAN ONCE WITH CONTROLLED PROCESSES

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resis-tance (ohms)	% load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction (watts)	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
4D 100 hp, 2 pole	Before	0.0385	38.9	0.0366	99.2	852.0	752.4	705.4	1161.4	440.6	95.0		
	After	0.0415	36.93	0.0397	100.2	930.7	774.7	752.0	1137.4	719.0	94.5	-0.5	1st rewind
	After	0.4083	36.13	0.0391	100.2	895.1	745	686.2	1159.9	562.2	94.9	-0.1	2nd rewind
	After	0.4087	37.78	0.0389	100.5	896.4	744.9	693.0	1140.7	596.2	94.8	-0.2	3rd rewind
12F 150 hp, 2 pole	Before	0.0276	51.32	0.0250	99.9	1326.8	795.7	1123.0	1394.8	163.2	95.9		
	After	0.0272	50.33	0.0248	100.0	1280.2	852.8	1108.8	1296.7	282.1	95.9	0.0	1st rewind
	After	0.0259	43.43	0.0241	100.0	1243.1	830.9	1050.0	1307.2	380.1	95.9	0.0	2nd rewind
	After	0.0266	43.52	0.0248	100.1	1295.6	817.2	1093.6	1427.8	216.4	95.8	-0.1	3rd rewind
15J 50 Hz 75 kW, 4 pole	Before	0.0465	43.37	0.0435	100.3	1805.3	1204.2	1093.7	319.7	1280.7	93.0		
	After	0.0404	34.92	0.0389	100.2	1546.0	1102.9	1078.3	272.4	1117.3	93.6	+0.6	1st rewind
	After	0.0402	34.6	0.0387	100.2	1523.1	1098.0	1078.7	309.3	1138.6	93.6	0.0	2nd rewind
	After	0.0397	33.35	0.0385	100.3	1489.3	1059.7	1131.9	297.6	1094.6	93.7	0.1	3rd rewind
8C 200 hp, 4 pole	Before	0.0217	43.73	0.0202	99.2	1922.6	1129.1	1459.6	448.1	851.0	96.2		Fan blade broken[1]
	After	0.0194	38.33	0.0185	99.1	1775.5	1238.4	1612.1	358.2	1632.4	95.7	-0.5	Winding pattern changed
	Before	0.0217	43.73	0.0202	99.0	1922.6	1129.1	1459.6	761.3	851.0	96.0	-0.2	Effect of new fan fitted
	After	0.0199	30.68	0.0195	99.8	1772.1	1121.0	1618.8	671.4	1621.3	95.6	-0.4	2nd rewind, new fan
13G 50 Hz 110 kW, 4 pole	Before	0.0228	29.0	0.0224	99.4	1647.6	915.9	1453.9	856.9	1087.3	94.8		
	After	0.0236	39.37	0.0224	99.9	1662.7	932.0	1576.3	912.6	1250	94.6	-0.2	1st rewind
	After	0.0248	41.82	0.0233	99.9	1702.2	897.6	1388.9	1008.3	1217.4	94.6	0	2nd rewind
17H 50 Hz 5.5 kW, 4 pole	Before	1.8100	39.28	1.7156	100.5	411.2	212.9	131.5	22.5	72.8	86.7		
	After	1.6324	36.13	1.5653	99.1	365.6	177.9	153.5	69.2	53.7	86.9	+0.2	
22H 50 Hz 5.5 kW, 4 pole	Before	2.1991	42.83	2.0577	99.1	578.1	229.1	196.6	40.6	56.3	83.2		
	After	1.9681	51.15	1.7879	98.9	557.6	194.5	214.0	42.7	25.7	83.6	+0.4	

1 This value was not used in the final calculations because the motor had a broken fan blade when it was tested. The data was normalized using the friction and windage losses obtained after a new fan was installed.

TABLE 2-21: GROUP D–MEDIUM-VOLTAGE MOTOR REWOUND ONCE WITH CONTROLLED REWIND PROCESS

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	Percent load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction (watts)	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
23K 50 Hz 225 kW, 4 pole 3300V	Before	0.6899	34.40	0.6657	99.5	2687.3	2379.8	1928.9	1702.5	1269.4	95.7		See notes below.
	After	0.6766	37.88	0.6446	100.0	2750.3	2561.0	2484.7	855.3	1011.7	95.9	+0.2	See notes below.

Notes for 23K

The friction and windage (F&W) losses were 50% lower on the test after rewinding. This could just have been an error on the separation of core and F&W losses. When the two are added together, the difference is not as significant as 3631.4 before and 3340 after (i.e., a 10% reduction).

This machine was used and had been in storage for some time before testing. It was run at no load before it was sent to Nottingham. The bearing lubrication was not changed during rewinding.

Motor efficiency testing: Differences between IEEE Std. 112 and IEC Std. 60034-2-1

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Note: This article provides an update on the differences between the motor efficiency test standards that were current when the *EASA/AEMT Rewind Study* was conducted in 2003 and the latest versions of those standards.

For many years the USA and Europe have had different methods of determining induction motor efficiency. In the USA, for instance, motor efficiency is determined indirectly by measuring input-output with loss segregation as prescribed by IEEE Std. 112 Method B. In use since 1996 and revised in 2004, this standard became the norm for measuring motor efficiency under EPAct legislation.

When efficiency requirements were initially introduced in Europe by the European Commission and the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP), the EFF1, EFF2 and EFF3 requirements were based on efficiency testing using IEC Std. 60034-2:1996. Since this method of efficiency testing did not measure the additional load losses (stray losses) but instead allocated a fixed 0.5%, it was not as accurate as the IEEE 112 Method B. A new, more accurate method of determining motor efficiency was introduced in 2007 with IEC Std. 60034-2-1.

Under this new standard, for example, an 11 kW, 4-pole IE2 motor with 89.8% efficiency is identical to an EFF1 motor with 91.0% efficiency as tested under IEC Std. 60034-2:1996. The motor has not physically changed, but the efficiency has been determined by two different methods.

When The European Commission introduced new regulations in 2009 (EU 640/2009) implementing Directive 2005/32/EC for Electric Motors, the method of determining efficiency was changed to IEC Std. 60034-2-1. Directive 2005/32/EU is a framework directive relating to the "eco-design of energy using products" that covers all household and industrial products.

New EU efficiency bands IE1, IE2 and IE3 were introduced in 2009 for squirrel cage induction motors with voltage <1000V and 2 - 6 poles where:

- IE1 (Standard) efficiencies were equivalent to the earlier EFF2 efficiencies, albeit with a more accurate method of determining efficiency. Product with this efficiency level was available until June 15, 2015.
- IE2 (High) efficiencies are equivalent to the earlier EFF1 and EPAct efficiencies in USA. This was the minimum efficiency level for new product from June 16, 2011, to January 1, 2015, for motors between 7.5 kW - 375 kW, (10 hp - 500 hp).
- IE3 (Premium) efficiencies are equivalent to NEMA Premium®. This became the minimum efficiency requirement for new product starting January 1, 2015, for motors between 7.5 kW - 375 kW (10 hp - 500 hp).
- IE3 (Premium) efficiencies are equivalent to NEMA Premium®. This will be the minimum efficiency requirement for new product from January 1, 2017, for motors between 0.75 kW - 375 kW (1 hp - 500 hp).
- IE2 (High) efficient product can only be sold when used with variable-frequency drives.

Although regulation EU 640/2009 details the specific efficiencies of machines from 0.75 kW - 375 kW, these are also specified in IEC Std. 60034-30:2008. This standard specifies IE2 and IE3 efficiencies for squirrel cage induction machines for 50 Hz and 60 Hz operation and requires efficiency to be determined by IEC Std. 6034-2-1. This has been adopted as a European Norm (EN standard).

IEC Std. 60034-2-1 is similar to IEEE Std. 112 Method B with additional load losses (PLL) determined from residual loss (similar to PSL stray losses in IEEE Std. 112 Method B). Both standards limit direct efficiency measurement to machines with ratings of less than 1 kW (1.34 hp) and specify the separation of losses method.

IEEE Std. 112 Method B requires direct measurement of input and output power using watt meters, torque sensors and a tachometer to determine the total losses, from which all the known losses are subtracted to get the stray load losses (PSL). This standard, however, is specifically for polyphase induction motors and generators

IEC Std. 60034-2-1 clause 8.2 uses methodology similar to that of IEEE Std. 112 Method B to determine the efficiency of induction machines, with some minor variations in the detail procedures but identical requirements for instrumentation accuracy. The IEC standard, however, caters to a wider range of machine efficiency testing, since it includes DC machines and synchronous machines as well as induction machines.

IEC Std. 60034-2-1 also introduces a consideration of the uncertainty of measurement accuracy, specifying that only methods of testing with low uncertainty be used when determining the IE efficiency class as detailed in Tables 1-3 of that standard.

Although both standards permit load testing up to 150% rated load, motor testing guidance for IEC Std. 60034-2-1 proposes that load testing at 100%, 75%, 50% and 25% be used when determining additional load losses. This is to reduce uncertainty in instrumentation when changing ranges and measuring over a wide range of loads.

IEC Std. 60034-2-1 also identifies measurement of slip as an area with uncertainty. Since calculated rotor losses are directly proportional to slip, any error in slip contributes to a corresponding error in rotor losses.

Both IEEE Std. 112 and IEC Std. 60034-2-1 specify that speed measurement should be within 0.1% or 1 rpm,whichever gives the lowest error. However, speed can be measured to a higher degree of accuracy.

As an example, for a 45 kW (60 hp) 6 pole 50 Hz motor with a designed full-load speed of 990 rpm, the 1 rpm uncertainty permitted within the standards could give a 10% uncertainty in slip that would be reflected in the determination of rotor losses. This is further complicated by uncertainty in supply frequency measurement.

One method of overcoming these uncertainties is to use high-resolution shaft encoders on the test motor and the motor-generator set supplying the test motor.

Round-robin testing conducted in the USA and Europe for the 2003 EASA/AEMT Rewind Study identified significant variation in the determined efficiencies of motors evaluated at different test facilities. While the causes of these differences are still being investigated, the test preparation and procedures followed in each facility, the test site facilities for loading the machines and switching to hot running on no-load, the accuracy of the power supply sine wave and phase voltages, and the calibration and accuracy of the test instrumentation can have a significant effect on measured efficiency.

We know from the 2003 EASA/AEMT Rewind Study that Nottingham University's test facility was able to determine efficiency to within 0.2%, which was half that of most industrial test facilities, but the round-robin testing found a variance of 0.9% among test facilities. Therefore, although each test facility may be capable of consistently determining efficiency within acceptable tolerances, the absolute accuracy of specified efficiencies is still questionable.

The cause and analysis of stator and rotor failures in AC induction machines

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ABSTRACT

The squirrel cage induction motor is the work horse of industry because of its toughness and versatility. However, it has its limitations, which, if exceeded, will result in premature failure of the stator or rotor.

The purpose of this paper is to identify the various causes of stator and rotor failures. A specific methodology is proposed to facilitate an accurate analysis of these failures. Although this paper focuses on three-phase squirrel cage induction motors, much of this material applies to other types on AC induction machines.

Since the turn-to-turn insulation on the magnet wire is usually affected in most winding failures regardless of the cause, specific attention will be devoted to this area.

This paper is an update and an abridgement of numerous previous papers written by the author, which are referenced in the bibliography for a more detailed presentation on the subject matter.

INTRODUCTION

The majority of all rotor and stator failures are caused by a combination of various stresses which act upon these two components.

For the stator, these stresses can be grouped as follows:

A. Thermal
1. Aging
2. Overloading
3. Cycling
4. Transients

B. Electrical
1. Dielectric
2. Tracking
3. Corona

C. Mechanical
1. Coil movement
2. Rotor strike
3. Miscellaneous

D. Environmental
1. Moisture
2. Chemical
3. Abrasion
4. Foreign objects

For the rotor, these stresses have been identified in an expanded grouping. The stresses are:

A. Thermal
B. Electromagnetic
C. Residual
D. Dynamic
E. Mechanical
F. Environmental

These rotor stresses are the result of the following forces and conditions.

1. Working torque
2. Unbalanced dynamic force
3. Torsional vibration and transient torques
4. Residual forces from casting, welding, machining and fits (radial, axial, other)
5. Magnetic force caused by slot leakage flux, vibrating at twice the frequency of rotor current
6. Magnetic force caused by air gap eccentricity
7. Centrifugal force
8. Thermal stress caused by end ring heating
9. Thermal stress caused by temperature differential in bar during start (skin effect)
10. Thermal stress caused by axial bar growth
11. Axial force caused by skewing the rotor bar

It may be argued that the classification of the stresses is not 100% accurate, and the authors admit it was done for convenience of explanation.

If a motor is designed, manufactured, applied, installed, operated and maintained properly, these stresses remain under control and the motor will function as intended for many years. However, as each of these elements (from design through maintenance) varies from user to user, so does the anticipated life of each motor.

Information about stator failures begins on Page 2-120.
Information about rotor failures begins on Page 2-128.

The cause and analysis of stator failures

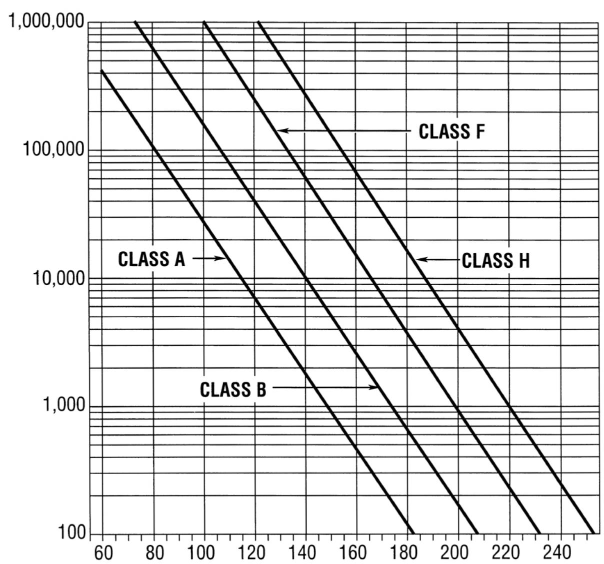
This section discusses the relationship between the various stresses and how they affect the life of the stator and contribute to premature failures.

THERMAL STRESSES

A. Thermal aging

IEEE 117 and IEEE 275 test procedures can be used to determine the effects of temperature on the winding insulation system. This method establishes a minimum insulation life of 20,000 hours for the test samples, namely, a motorette or scale model of a stator coil winding, under the prescribed test conditions. (See Figure 2-42.) As a rule of thumb, for every 10°C increase in temperature, the insulation thermal life is halved. The following graph indicates the relationship between the various classes of insulation and operating temperatures.

FIGURE 2-42



Temperature vs. life curves for insulation systems. Assumes life doubles for a 10°C decrease in temperature.

Unless the operating temperature is extremely high, the normal effect of thermal aging is to render the insulation system vulnerable to other influencing factors or stresses which actually produce the failure. Once the insulation system has lost its physical integrity, it will no longer resist the normal dielectric, mechanical and environmental stresses. It should be pointed out that if any of the stresses become severe enough, a winding failure will occur regardless of the amount of thermal aging. In reviewing this effect of temperature on thermal aging, there are two obvious approaches to insure longer thermal life. Either reduce the operating temperature or increase the class of insulation materials used.

As an example: If a motor were to operate at Class B temperatures (130°C max.) and use Class F insulation materials, the thermal life would increase to approximately 100,000 hours. (See Figure 2-42.)

B. Thermal overloading

1. Voltage variations

In recent years motor manufacturers have been designing more and more horsepower on a given frame size. The result is that motors are far more susceptible to damage from voltage variations. These variations affect the motor performance and the winding temperature.

Motors are designed in accordance with NEMA Stds. MG 1, 12.44 to operate satisfactorily with ± 10% voltage variation. To operate outside of this range could greatly reduce the motor's life.

2. Unbalanced phase voltage

A small amount of voltage unbalance will cause an increase in the winding temperature an excessive amount. As a rule of thumb, for every 3-1/2% voltage unbalance per phase, the winding temperature will increase 25% in the phase with the highest current. For this reason, every effort should be made to maintain a balanced three-phase voltage supply.

3. Cycling

During starting, a motor will draw anywhere from five to eight times the normal current required to run under full-load conditions. If a motor is subjected to repeated starts within a short period of time, the winding temperature will rapidly increase. Depending on the specific application, each motor has its own limitations. For example, take two identical motors, use one on a high inertia flywheel and the other on a centrifugal water pump. The motor used to drive the pump could be started many more times per hour than the one driving the flywheel and still operate within safe limits. If there is some question as to how many starts can be safely made, check with the motor manufacturer. To save time, be sure to supply him with the physicals of the load (inertia, weight, starting load speed torque curve, starting cycle, etc.).

An additional weakening effect of this cycling is to cause expansion and contraction of the insulation system. Over an extended period of time, the insulation materials will tend to become brittle and crack. The insulation designer must be sure the materials are flexible enough to withstand this movement without cracking, and yet not so flexible as to cause a failure due to mechanical forces. (See discussion under Mechanical Stresses.)

4. Overloading

Motor manufacturers normally design a certain amount of margin into their motors. This is usually done by designing the motor to operate below the normal limits for a specific insulation system, or using an insulation system with a rating well above the operating temperature. On the latest NEMA re-rates, this was usually accomplished by using a Class F insulation system with Class B operating temperatures. Within certain limits, it can be estimated that the winding temperature rise will increase as the square of the load (T µ L^2). By using this in conjunction with Figure 1 for temperature vs. life, it is possible to estimate the effect of loading on winding life. As an example: A 100 hp motor with a temperature rise of 64°C at full load will operate at 85°C rise at a 15% overload. (Assume an ambient of 40°C at both loads.) Thus, the thermal life drops from 1,000,000 hours to 160,000 hours.

5. Obstructed Ventilation

Heat generated in the rotor and stator are dissipated by conduction, convection and radiation. Anything which will obstruct the flow of air through or over the motor, or that will impede the radiation of heat from the motor parts, will cause an increase in winding temperatures. Therefore, it is important to keep the motor clean inside and outside and to assure that the flow of air is not restricted. As a useful hint, if for some reason it is necessary to operate an overheated motor, consider the possibility of additional cooling by increasing the "air over" the motor. This can be accomplished with a portable fan or blower. Be sure to direct the air in the direction that will aid and not oppose the normal ventilation of the motor. If it is not practical to keep the motor clean, then this should be taken into account during the design stage. Again, this can be accomplished by restricting the winding temperature and upgrading the insulation system.

6. Ambient Temperature

NEMA Stds. MG 1, 12.43 calls for standard motors to be designed to operate in a maximum of 40°C ambient. Table 2-22 indicates the effects that exceeding this limit can have on the insulation life, assuming the motor is operating at rated load when designed to operate at Class B temperatures with Class F insulation materials.

TABLE 2-22: AMBIENT TEMPERATURE VS. INSULATION LIFE

Ambient °C	Insulation life - hours
30	250,000
40	125,000
50	60,000
60	30,000

ELECTRICAL STRESSES

When discussing winding failures caused by electrical stresses in any depth, it is essential to have a basic knowledge of insulation materials and their properties. Space does not permit the establishment of this background; therefore, this discussion will cover only the highlights and indicate areas where possible problems may occur.

A. Dielectric

There is a definite relationship between insulation life and the voltage stresses applied to the insulating materials. It is also apparent that some materials have greater voltage endurance capabilities than others. These stresses can be broken down into three groups.

1. Phase-to-phase
2. Turn-to-turn
3. Turn-to-ground

It is the responsibility of the designer to understand the motor application and to select materials and establish coil designs that will assure adequate design life.

B. Tracking

Particularly in motors with operating voltages more than 600 volts, a phenomenon known as "tracking" can occur in the winding if the insulation system is not sealed from the environment. The failure mechanism is as follows:

1. A small pin hole or leak occurs between the copper wire and the open environment.
2. A combination of moisture and foreign material build a high-resistance bridge between the wire and ground.
3. Due to the potential difference, a small current discharges to ground causing small burn spots in the insulation system. As this condition progresses, the insulation to ground deteriorates to the point where a ground failure occurs. A common industry practice to minimize this condition is to keep the motor clean and dry. Where this is not practical, many users are calling for the motor manufacturer to provide a winding whose insulation system is capable of passing the sealed motor immersion test as called out in NEMA Stds. MG 1, 20.18 and IEEE 429. Applying this test to production units is not recommended.

Corona can become a serious problem particularly on windings operating above the 5 kV range or on an inverter power supply. Corona is a localized discharge resulting from transient gaseous ionization in an insulation system where the voltage stress has exceeded a critical value. There are three basic types of discharge:

1. Internal discharges occurring in cavities of the dielectric
2. Surface discharges occurring on the surface of the coils
3. Point discharges occurring in a strong electrical field around a sharp point or edge

Factors affecting corona discharge are: frequency, dielectric thickness, material, voids, voltage stress, geometry, humidity, mechanical stress and temperature. The failure mechanism is heating, eroding or causing a chemical reaction that deteriorates the winding insulation. It is the basic responsibility of the manufacturer to keep corona discharge within the bounds which will assure adequate motor life. However, the user can also help by keeping the motor clean and cool when practical. The user should also learn to identify this type of failure.

D. Transient voltage conditions

During recent years, substantial evidence has come to light that a significant number of motors are exposed to transient voltage conditions, or steep wave-front voltage supplies, which result in reduced winding life or premature failures (either turn-to-turn or turn-to-ground). These transient voltages can be caused by any of the following:

1. Line-to-line, line-to-ground, multi-phase line-to-ground and 3-phase faults which cause over voltages that can reach 3-1/2 times their normal peak values with extremely short

rise times.

2. Repetitive restriking—where the system is ungrounded and an intermittent ground on the circuit occurs causing high voltage oscillations and multiplication.
3. Current limiting fuses—where current interruption occurs, when stored magnetic field energy in the circuit inductance is not zero, causing voltage oscillations or resonance.
4. Rapid bus transfers—after transfer, a motor winding can see the vector difference between the reserve bus voltage and the decaying generated voltage. The net voltage will depend upon the phase angle between the bus voltage and motor voltage at the instant of reclosure. The maximum RMS voltage obtained can be 200%. The phase angle between the rotor and the reserve bus is continually changing as the frequency between the de-energized motor drops off as it slows down.
5. Opening and closing of circuit breakers—this starting surge is continually present. An impulse wave can be produced that will travel in a circuit at a specific rate when, upon closure of a breaker contact, arcing occurs due to a potential difference at the breaker contacts. This arc will influence the voltage wave entering the motor circuit. Surges can also occur when the breaker contacts do not engage simultaneously and will bounce or vibrate, causing an irregular voltage wave of a surge variety. (Similar to repetitive restriking.) Use of high-speed motor control devices, such as vacuum contactors, cause steep surges when "current chopping" is produced by the opening of the contacts in a vacuum with no arc to sustain the current.
6. Capacitor switching—where capacitors are used for power factor improvement, surges can develop when they are switched off and on. The surges occur on the half-cycle after interruption, when the opening contacts of the switch have twice normal line-to-neutral crest voltages across them.

   As the capacitor voltage holds firm during the first instant, the system voltage will jump (snap) over the capacitor voltage and then a high frequency oscillation will start.

   Extremely high voltage surges can occur during instances where a motor and capacitor are switched off together disconnecting them from the power source. Magnitudes of the surge are dependent on the value of the capacitance. Capacitors switched with the motor are a source of excitation at the motor terminals and high voltages are induced. This problem is usually great on high inertia drives where speed reduction is a factor for continued excitation.
7. Insulation failure–when a breakdown or puncture of the insulation on a power system occurs at points other than at the motor, impulse surges can develop. Such a breakdown, in high-voltage designs, can cause surge voltages that will exceed 3 times normal line-to-ground voltages in a system that is not solidly grounded.
8. Lightning–voltage surges can be caused by lightning through direct contact of a lightning stroke or by induction by a nearby stroke. These voltage waves propagate along the line with the magnitudes of the crest a function of the lightning current and rise times dependent upon the surge impedance of the system.
9. Variable frequency drives–depending on the specific design, it is possible during starting/stopping or even during the switching of each half-cycle, to introduce voltage spikes. (For more information on the recommended waveform for such applications, see "Application Considerations of Pulse-Width Modulated Inverters and AC Induction Motors to a Total System," in Section 5 of this manual, and EASA's *Root Cause Failure Analysis* manual.)

Estimates of the magnitude of these various surges normally range from two to five times the normal line-to-neutral crest voltage with rise times ranging from .1 to 1 microsecond. Winding failures caused by these transients usually appear as turn-to-turn faults or turn-to-ground faults. Frequently the cause is confused with some other mode of failure.

The motor manufacturer normally does not have sufficient application information available to determine when to include surge and lightning protection on the motor. However, he can determine the surge limits which the motor can withstand and still give satisfactory life.

These limits are generally established as follows:

- The maximum magnitude of the surge voltage shall not exceed 1.25 x the crest voltage of the standard 1 minute 60 Hz hipot test.

$$\text{i.e.,}\quad V_m = 1.25\sqrt{2}\left(2V_L + 1000\right)$$

- The rate of rise of the surge voltage (V_m) should not exceed a rate based on reaching V_m in less than 10 microseconds.

$$\text{i.e.,}\quad \frac{V_m}{10} = \text{Volts per } \mu \text{ second}$$

It is the responsibility of the engineer who is designing the power distribution system to insure that appropriate steps are taken to keep these transient voltages within safe limits. Motor manufacturers will vary somewhat in their recommendations for acceptable limits.

Table 2 provides fairly typical values among manufacturers.

For applications where the values in Table 2-23 are

TABLE 2-23: TYPICAL TRANSIENT VOLTAGE LIMITS

Nameplate voltage	Max. withstand voltage (V_m in kV)	Max. rate of rise in kV/μ s section
600	3.9	.6
2400	10	1.0
4160	16	1.6
4800	19	1.9
6600	25	2.5
6900	26	2.6

exceeded, it is recommended that a special insulation system with increased turn and/or ground dielectric strength be used, or that surge capacitors and/or surge arrestors be utilized. The latter is usually the most economical.

Surge arresters limit the magnitude of the transient voltage spike. This is achieved by the arrester conducting to ground when the voltage reaches a given value. The purpose of the surge capacitors is to limit the rate of rise of the voltage or turn-to-turn stresses. This is achieved by the capacitor momentarily absorbing the initial energy, thereby slowing down or sloping the steep wave front.

MECHANICAL STRESSES

A. Coil movement

The current in the stator winding produces a force on the coils which is proportional to the square of the current ($F \mu I^2$).

This force is at its maximum during the starting cycle, causing the coils to vibrate at twice line frequency with movement both in the radial and tangential direction. This movement can cause severe damage to the coil insulation, loosen the topsticks, and cause damage to the copper conductors. Large, high-speed machines generally suffer more from coil movement than small, low-speed machines. The longer the coil extensions, the greater the problem. Also, the greater the frequency of starts, and the longer the acceleration time, the greater the opportunity to weaken the insulation system.

B. Rotor strikes

There are a number of reasons why the rotor will strike the stator. Some of the most common ones are:

1. Bearing failures
2. Shaft deflection
3. Rotor-to-stator misalignment

When this contact between the rotor and stator occurs, several things can happen. If the strike only happens during starting, the force of the rotor can eventually cause the stator laminations to puncture the coil insulation, resulting in a grounded coil. Sometimes motors will operate for years with this condition, depending upon the frequency of starts and the amount of contact between the rotor and the stator. If the contact is made while the motor is running at full speed, the result is usually a very premature grounding of the coil in the stator slot caused by excessive heat generated at the point of contact.

C. Miscellaneous

Some of the most common miscellaneous mechanical causes of winding failures include:

1. Rotor balancing weights coming loose and striking the stator.
2. Rotor fan blades coming loose and striking the stator.
3. Loose nuts and bolts striking the stator.
4. Foreign particles entering the motor through the ventilation system and striking the stator.
5. A defective rotor (usually open rotor bars) can cause the stator to overheat and fail.
6. Poor lead lugging of connections from the motor leads to the incoming line leads, causes overheating and failure.
7. Broken lamination teeth striking the stator due to fatigue.

ENVIRONMENTAL STRESSES

Another term for environmental stresses is contamination. One of the most important things a motor user can do to ensure longer, trouble-free motor operation is to keep the unit clean and dry, both internally and externally. The presence of foreign material can have the following effects on the motor:

1. Reduction in heat dissipation, which will increase operating temperature, thereby reducing insulation life.
2. Premature bearing failure due to high localized stresses.
3. Breakdown of the insulation system, causing shorts and grounds.

If it is not practical to keep the motor clean and dry, the alternative is to select the enclosure and/or an insulation system that will give the greatest protection against the contaminants which are present. Once the application has been properly analyzed, it is usually possible to select a motor that will give reasonable life.

Much time could be devoted to the effects of moisture, chemicals and foreign particles on winding life. It is sufficient to say that every effort should be made to minimize these conditions and communicate to the motor designer any abnormal conditions that might have adverse effects on the materials and designs normally used.

One common problem worth mentioning is condensation developing on the stator winding. When this condition becomes acute, it will usually cause the stator winding to ground out in the slot. A common preventative step is to dry out the winding by use of space heaters or trickle heating during the off cycle. Prolonged idle periods or long-term storage aggravate condensation-related problems.

ANALYSIS OF WINDING FAILURES

This section identifies the various kinds of failure modes and patterns and relates them to the probable specific cause of the failure.

Key areas to analyze

Five key areas should be considered and related to one another in order to accurately diagnose the cause of a winding failure. They are:

1. Failure mode
2. Failure pattern
3. Appearance
4. Application
5. Maintenance history

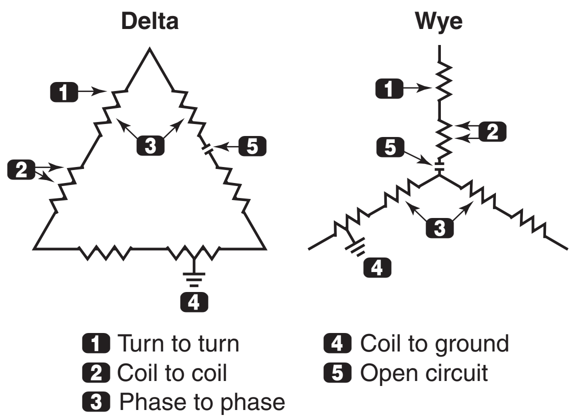
The following is a brief discussion of each of these areas.

A. Failure modes

Regardless of the cause of failure, the actual mode of failure can be broken down into the following five groups, as shown in Figure 2-43.

In analyzing winding failures, it is difficult to determine which of the above conditions was the initial problem and which was the result of the problem. A simple example will illustrate this point.

FIGURE 2-43



Possible failure modes in delta and wye stators. Note: It is possible to have any combination of these failure modes.

A random-wound motor is started frequently and due to excessive coil movement sustains a minor turn-to-turn short within one coil. As this condition progresses, excessive heating is generated within the shorted coil resulting in insulation deterioration and eventually in a partial ground through the slot liner. Depending upon the type of motor protection, the motor may continue to run. More and more heat would then be generated in the damaged area until the phase or ground insulation is destroyed. At this point a direct phase-to-phase fault or ground fault occurs, and the motor is quickly dropped off the line.

Inspection could reveal all five modes of failure, but the turn-to-turn condition was the initial problem, and the others were the result of the problem. A turn-to-turn failure is usually very difficult to recognize due to the destructive nature of the final fault conditions.

B. Failure patterns

Closely related to the mode of failure, but to be considered separately, is the pattern of failure, which can be classified into the following four groups.

1. Symmetrical
2. Single phasing
3. Non-symmetrical with grounding
4. Miscellaneous non-symmetrical excluding grounding

Combining the mode and patterns of failure can provide clues as to the cause of failure. The examples in Figures 3 Figure 2-44 through Figure 2-48 are of units burned out under controlled conditions at a U.S. Electrical Motors Test Facility.

In each case, the defect was deliberately inflected. The stator was then energized, and the failure was observed and recorded on film.

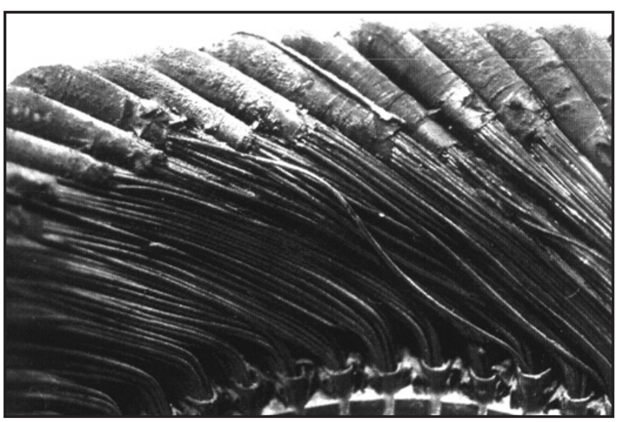
The key point to remember is that it is absolutely necessary to tie the mode and pattern of failure together in order to make an accurate diagnosis. In each of the above cases, the mode of failure was turn-to-turn, but the cause of failure was different. It was the pattern of failure which more indicatively pointed to the cause of failure.

C. Appearance

When coupled with the mode and pattern of failure, the general appearance of the motor usually gives a clue as to the possible cause of failure. The following checklist will be useful.

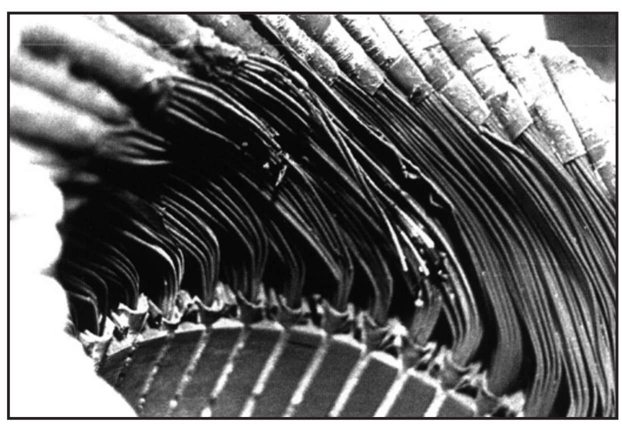
1. Is the winding clean?
2. What foreign materials are present?

FIGURE 2-44



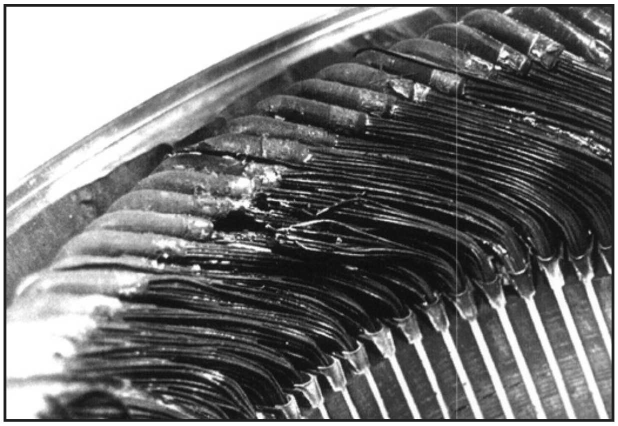
This failure pattern is symmetrical; each coil of each phase has been overheated. The failure mode is a multiple turn-to-turn shorting. The cause of failure was excessive overheating caused by an overload condition.

FIGURE 2-45



This failure pattern is single-phasing; one complete phase has over heated and failed due to turn-to-turn shorting. The cause of failure was single-phasing.

FIGURE 2-46



This failure pattern is non-symmetrical without grounding; several groups of coils have been overheated. The failure mode is also multiple turn-to-turn shorting. The cause of failure was damaged wire.

3. Are there signs of moisture?
4. Has there been rotor rub or pullover?
5. What is the condition of the rotor? Does it show signs of overheating? Are there any signs of stall or locking of the rotor?
6. Does the rotor appear to have been turning when the failure occurred?
7. Are the topsticks, coils or coil bracing loose?
8. Are the bearings free to rotate? Are there signs of moisture contamination in the frame or bearing housings?
9. Are any mechanical parts missing that could have hit the winding, such as nuts, washers, bolts or balancing weights? Are the rotor cooling fins or fans intact?
10. Are the motor cooling passages free and clear of clogging debris? Is it on the connection end or opposite connection? If the motor is mounted horizontally, where is the failure with respect to the clock? Which phase or phases failed? Which group of coils failed? Was the failure in the first turn or first coil?

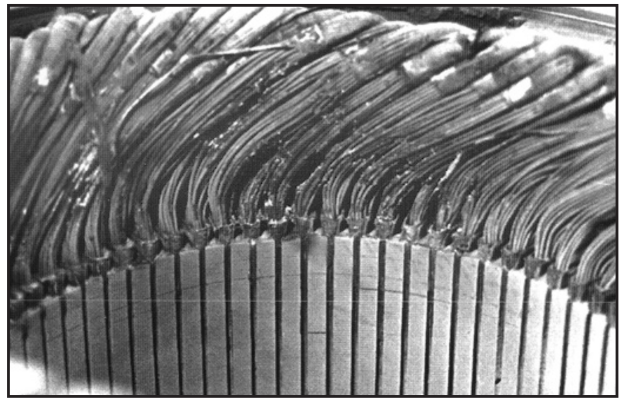
When analyzing winding failures, it is helpful to draw a sketch of the winding and indicate the point where the failure occurred.

D. Application considerations

Usually, it is difficult to reconstruct the actual operating conditions at the time of failure. However, a knowledge of the general operating conditions will be helpful. The following items should be considered.

1. What is the load characteristic of the driven equipment?
2. Were there cycling or pulsating loads?
3. Any chance of stallout?
4. What was the voltage? Was it balanced?
5. Was the motor powered by a variable-frequency drive?
6. Any signs of transient voltage conditions past or present?

FIGURE 2-47



This failure pattern is non-symmetrical with grounding; one coil is grounded, and there is multiple turn-to-turn shorting. The cause of failure was damaged cell wall.

FIGURE 2-48

This photograph is the same stator shown in Figure 6. The actual ground fault can be seen. Note that the turn-to-turn shorting occurred 180° opposite of the grounded coil.

7. Have other motors failed on this application? If so, how?
8. How long had the motor been running, or did it fail on startup?
9. What was the acceleration time?
10. Does the motor start across-the-line, at reduced voltage or on part-time winding? What was the starter timer set at?
11. What was the condition of the motor controller?
12. What kind of motor protection is in the system, and what tripped?

13. What is the environment? Is the motor indoors or out in the weather?
14. Was there rain, snow or lightning just prior to the failure?
15. What was the ambient temperature?

E. Maintenance history

An understanding of the past performance of the motor can give a good indication of the cause of the problem. Again a checklist may be helpful.

1. How long has the motor been in service? If it failed on initial startup, such things as contamination, transients, coil movement and thermal aging can usually be eliminated as a potential cause.
2. During the early or initial operation of the motor, were any unusual phenomena observed? Did the load accelerate properly? Did the motor carry the load at normal speed and thermal characteristics?
3. Was the winding resistance and current balanced?
4. Do past maintenance records indicate any weaknesses, such as cracking or aging of the insulation system?
5. Is there a past history of insulation megger readings or previous problems with moisture and contaminates?

METHODOLOGY

The following summary groups the various causes of winding failures in accordance with burnout patterns:

A. Symmetrical burnout pattern with all phases overheated

In each case an excessive amount of heat was generated symmetrically throughout the winding. The heat was either caused by too much current or the inability of the motor to dissipate the normal heat generated.

1. Possible Cause

a. Low or high voltage
b. Excessive loading
c. Excessive number of starts
d. Lack of proper ventilation
e. High ambient condition
f. Defective rotor
g. Complete bearing failure, causing stall

2. Winding appearance (pattern)

In general, each coil group will show signs of overheating evidenced by discoloration and insulation breakdown, depending on the amount of heat.

3. Mode of failure

The actual failure usually occurs due to a combination of shorts and opens. The winding may also be grounded due to extreme heating in the stator slot or motor lead.

B. Single-phased burnout pattern (symmetrical)

These failures are usually the easiest of all to identify because of their unique patterns. Figure 2-44 is a typical example.

1. Possible cause

a. Single phased controls or power supply
b. Open winding lead or wire
c. Improper connection
d. Unbalanced voltage source

2. Winding appearance (pattern)

Depending on whether wye or delta connected, either one or two phases may overheat and usually fail due to turn-to-turn shorting within the overheated phases.

3. Mode of failure

If the cause is internal to the winding, the unheated phase or phases will have an open circuit. There will usually be signs of multiple turn-to-turn shorting. Note: The motor controls and protection equipment, or some other element of the power distribution system, may also show signs of single-phasing.

C. Non-symmetrical burnout patterns where the winding is grounded

Depending upon the type of motor protection used, a ground failure can be the most destructive type of failure. Not only is the winding destroyed, but in some cases the lamination is badly damaged due to large fault currents.

This type of failure also has the greatest potential for electrical shock and hazard to operating personnel.

1. Possible causes

a. Rotor rub against stator lamination; during starting or running condition.
b. Damaged insulations; slot end turns or leads.
c. Transient voltage; switching surges or lightning strokes.
d. Contamination; moisture, chemicals or foreign materials.
e. Low-voltage tracking or corona deterioration on insulation.
f. Overheating in the stator slot due to excessive current or poor heat dissipation.
g. Coil movement in the slot or end turns.

2. Winding appearance (pattern)

The winding failure is usually limited to specific spots in the stator slot and, with the exception of Item (f), does not give the appearance of a general overheating condition.

3. Mode of failure

The primary failure mode is coil-to-ground. However, there can be signs of turn-to-turn and phase-to-phase shorting.

D. Miscellaneous non-symmetrical burnout patterns (excluding grounds)

Many of those items listed above, which are responsible for ground failures, can also cause a turn-to-turn failure. The determining factor is directly related to the strength and weakness of the insulation system. For example, if a stator is exposed to an extreme moisture condition, it will fail at the weakest point in the insulation system of that particular machine. If there has been previous coil movement in the end turns resulting in some damage, the mode of failure would be turn-to-turn. If the stator slot insulation was weakened more by the same coil movement, then the failure mode would be coil-to -ground. The failure mode can also be phase-to-phase or coil-to-coil. Most of these types of failures are isolated to specific areas of the winding without any definite pattern, except for those caused by transient or steep wave-fronted voltages. In these cases, the failure is usually at the beginning or the end of a phase.

1. Possible cause

Same as for grounded stator, except for the rotor rub condition.

2. Winding appearance (mode & pattern)

Will generally be evidenced by isolated turn-to-turn shorts and opens, normally without the overall heating appearance. However, there will be signs of excessive heating adjacent to the failed area, and frequently, a phase-to-phase fault occurs when the motor is shut off.

This section discusses the relationships of the various stresses and how they affect the life of the rotor and contribute to premature failures.

The cause and analysis of rotor failures

THERMAL STRESSES

A. Thermal overload

Thermal overloading can occur during acceleration, running or stall conditions. Keep in mind that from a thermal standpoint, some motors are "stator limited" and others are "rotor limited." While running at full-load speeds, most motors are stator limited. The stall condition poses the greatest potential for rotor damage in the shortest time, and is the most difficult to protect against when relying on thermal protection. Most thermal sensing devices are installed in the stator. By the time they sense the heat generated in the rotor, it may be too late.

Safe stall times range from a few seconds to a few minutes, depending on the design. It is a good practice to know this information when planning for motor protection against overload conditions. Even though it is desirable to have safe stall times longer than acceleration times, this is not always possible nor necessary. The best way to protect the rotor from thermal overloading is to rely on current-sensing devices, which will sense the high currents associated with the starting and stall conditions. Zero-speed switches have also been used to allow protection against the stall condition when the acceleration time exceeds the safe stall time. The most common causes of thermal overload failures are:

1. An abnormal number of consecutive starts, causing excessive bar or end ring temperature.
2. Rotor stalling due to high break-away loading.
3. Failure to accelerate to full speed due to intersect between the load and motor speed torque curve.
4. The rotor rubbing the stator due to a bearing failure, rotor pullover or abnormally high vibration.
5. Broken rotor bars due to fatigue caused by bar motion or end ring thermal growth.
6. Insufficient ventilation due to plugged filters or duct passages.
7. Unbalanced phase voltages and corresponding negative sequence currents with associated rotor surface heating.

Rotor failures due to thermal overloading can be detected by inspection of the rotor cage (bars and end ring). Often there will be signs of overheating, even to the extent that the cage material may melt. Frequently, the stator will also be damaged from the molten cage or brazing material.

B. Thermal unbalance

Thermal unbalances can be caused by either the effect of starting or running conditions. Unbalances can also be inherently designed or manufactured into the rotor, or can occur due to operation outside of its design limits. The most common causes of thermal unbalance failures are:

1. Frequent starts, causing temperature differential in the rotor bars due to the phenomenon of skin effect.
2. Unequal heat transfer between the rotor bars and the rotor core.
3. The rotor bowing due to unequal changing of stacking pressures associated with thermal cycling.
4. Loss of fit between the rotor core and the shaft due to thermal expansion during startup, causing unstable vibration.
5. Hot spots on the surface of the rotor due to smeared lamination or rotor rubs.
6. Temperature gradients due to unequal circulating currents. These can be generated by either broken and/or varying isolation or shorting of the rotor bars.

These conditions are more common in high-speed machines with large rotor length-to-diameter ratios. The problem is compounded by the fact that the vibration can be acceptable during no-load testing and not manifest itself until start-up cycling under load conditions. For this reason, some manufacturers load test high-speed machines as a part of their quality procedures. Correction of this problem is difficult since the hot unbalance is not always repeatable. That means refine balancing the machine while it is hot may not correct the situation. Over the years, manufacturers have tried a number of cures for this condition, including heat treating, cold shocking, remachining and stress relieving of the core.

Note that there are other causes of thermal unbalances, or at least that there are a number of different theories as to the causes.

Therefore, while it is relatively easy to identify machines with vibration problems that are temperature sensitive, it is very difficult to identify the exact cause. When problems of this nature occur, it is best to consult the motor manufacturer because he usually is the most knowledgeable about proclivities of his product and, more important, the most likely fixes.

C. Hot spots and excessive losses

A number of variables during the manufacture, design, or repair of the rotor can cause unpredictable losses and hot spots.

Some of the common variables causing these conditions are:

1. Smearing of lamination in the slot or on the rotor surface.
2. Irregular shorting of rotor bars to laminations in the slot area.
3. Poor stacking of lamination: too loose, excessive burr, or lack of symmetry.
4. Varying tightness of fit between rotor bar and lamination.
5. Nonuniform loss distribution in the lamination caused by improper annealing or insufficient control during lamination processing.
6. Improper lamination design.
7. Bad bar-to-end ring connections.

The motor manufacturers, through normal quality control inspection procedures and testing, are able to detect most of these problems. Once the motor is in the field, detection is more difficult. However, there are a number of tests which are useful, such as:

1. Growler test.

2. Single-phase rotational test.
3. No-load saturation test.
4. Running test for open or broken bars.
5. Temperature-sensitive paints.
6. Ultrasonic testing.
7. Current monitoring with high-speed equipment.

Of course, monitoring under load such items as noise, vibration, temperature, current, watts and slip can help verify that the rotor is free from defect.

D. Rotor sparking

There are several potential causes of rotor sparking on fabricated rotors. Some are of a nondestructive nature, and some can lead to rotor failure.

Nondestructive sparking can and probably does occur during normal motor operation. This sparking is normally not observed due to its low intensity and/or because the motor enclosure prohibits its observation. Normal operation is defined as conditions during which any motor could be subjected to voltage dips, load fluctuation, switching disturbances and so forth.

There are a couple of other reasons why sparking is usually not observed during normal running at full load. The centrifugal force at full-load speed is usually greater than the electromagnetic forces acting on the bar due to rated load current. It also tends to displace and hold the bar radially in the slot. Furthermore, the frequency within the rotor circuit is very low (equal to the slip frequency). This low frequency corresponds to a low impedance of the rotor cage circuit, essentially confining all rotor current to the cage itself. Therefore, while possible, no sparking is normally observed during operation at full load and speed.

However, during across-the-line starting, the current in the rotor cage is five to eight times normal. This high current combined with the higher cage impedance (due to the frequency of the rotor current initially varying from line frequency at standstill) will cause a voltage drop along the length of the bar in excess of eight times the normal running value. It is this voltage that tends to send current through the laminations. In short, during startup, there are actually two parallel circuits—one through the rotor bar, and the other through the laminations.

The magnetic forces created by the high current flow during startup cause the rotor bars to vibrate at a decaying frequency, starting at 60 Hz, which produces a force of 120 vibrations per second. This primarily radial vibration within the confines of the rotor slot causes intermittent interruptions of the current flow between the bars and various portions of the laminations, with resultant visible arcing.

The design and manufacturing processes for rotors include measures intended to reduce sparking. However, material and manufacturing tolerances, together with the effects of differential thermal expansion and thermal cycling, preclude any motor from "sparkless" operation. Even identical or duplicate motors can and will exhibit various levels of spark intensity, since all component parts have tolerances and are thermally cycled during operation.

The sparks observed in the air gap are actually very small particles of bar and/or core iron, heated to incandescence by current passing through the iron-bar boundary. Initial punching burrs and/or particles of bar material removed during installation can generally be expected to decrease after several starts. However, particles generated by intermittent sparking will not decrease during the life of the motor.

The brief period of intensified sparking that can occur during starting is not detrimental to motor life. Motors with more than 20 years of this operation have been disassembled to reveal only a slight etching of the rotor bars at areas of contact with the core iron.

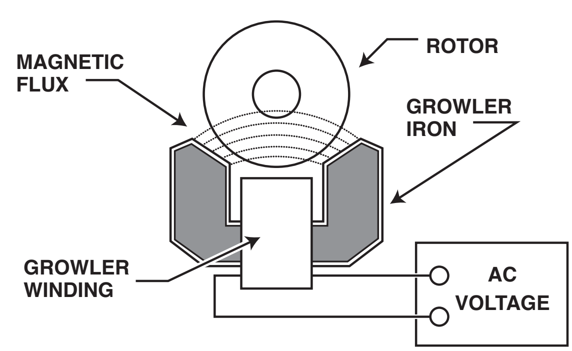
However, destructive sparking can occur under several circumstances, the most common being a broken bar or defective bar-to-end ring connection.

The usual point of bar breakage occurs at the area close to where the bar connects to the end ring. Breakage is preceded by radial cracks starting either in the top or bottom of the bar. While sparking caused by fatigue failure of the rotor bar is usually greater in intensity than that previously mentioned, it is still difficult to detect visually since the majority of motor enclosures prevent "line of sight" observation of the air gap.

The more common methods of determining whether sparking is caused by broken bars or end ring connections are:

1. Inspection of the rotor assembly, looking for blued lamination, etc.
2. Tapping the bars with a mallet. Loose or broken bars have a distinct sound.
3. Current pulsation when unit is under load.
4. Growler test (Figure 2-49).

FIGURE 2-49

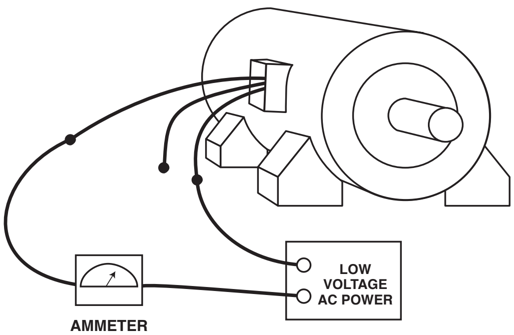


THE GROWLER

5. Single-phase rotor test (Figure 2-50).
6. Phase angle displacement test.
7. Observed noise (rattling sound) during starting cycle.

Prevention of advanced levels of rotor sparking is the result of proper design, manufacture and operation of the motor.

FIGURE 2-50



SINGLE-PHASE ROTOR TEST

MAGNETIC STRESSES

A. Electromagnetic effect

The action of the slot leakage flux, resulting from bar current, generates electrodynamic forces. These forces are proportional to rotor current squared (I^2), and are unidirectional. They tend to displace the bar radially between the top and bottom of the slot. These forces vibrate the bar at twice the frequency of the rotor current. Hence, they produce deflection or a bending stress in the bar. If the deflection is high enough, a fatigue failure in the bar will result. It can be shown that the radial force acting on the rotor bar will cause a deflection during starting that would be greater than that allowed by the normal slot confinement. It is theorized that the bar actually flattens out in the center of the slot, so that the stress at the end connector to bar joint is higher than that allowed by simple slot-constrained bar motion.

If it is assumed that the current remains constant during an acceleration, and the acceleration time at full voltage is approximately 11 seconds, then using the worst case above, the average motor is suitable for approximately 4,000 starts prior to failure. This figure appears to be confirmed by documented motors in service where no provision has been made to confine bar motion in the rotor slot.

Motors utilizing cast rotors, fitted bars, or swaged rotor bars to prevent this motion have been shown to be capable of 50,000 to 100,000 starts with no reported failures.

B. Unbalanced magnetic pull

Unbalanced magnetic pull is a potential problem that can cause the rotor to bend and strike the stator winding. In the "ideal" motor, there would be no rotor deflection because the rotor would be centered in the air gap with the magnetic forces balanced in opposite directions. In the real world, rotors are not perfectly centered in the air gap. Such things as eccentricity, rotor weight, bearing wear, belt loading and machine alignment all affect how much off-center the rotor is located.

R.L. Nailen describes the pullover process as follows:

> When that happens, the air gap between rotor and stator decreases on one side while increasing on the other. In an alternating magnetic field, the result of a decreasing air gap is a greater force of attraction across that gap.
>
> That is, the "reluctance" of the magnetic flux path, its opposition to the passage of flux, is reduced. The same magnetizing current in the winding can generate more flux across the gap, leading to still greater pull. At the same time, the air gap is being increased on the opposite side of the machine. Reluctance becomes greater there, so that flux and magnetic side pull are reduced. Unbalanced forces now act upon the rotor. The greater pull on the side having the small gap will tend to move the rotor in that direction, making the gap still smaller. The process would continue until the gap becomes zero and the rotor comes into contact with the stator.
>
> If some rotor eccentricity is always expected, why doesn't this pullover occur more often? The answer is that the rotor movement is restrained by the stiffness of the shaft. The greater the movement, the more the shaft resists being bent.

Motor designers attack this problem by limiting the minimum air gap and setting limits on the acceptable amount of air gap eccentricity. This is usually in the range of 10-20% of the air gap, depending upon the size of machine. In conjunction with this, the shaft size is selected, based on its ability to resist these bending forces (shaft stiffness). The potential for rotor pullover can be described as a function of the air gap, concentricity, stack length, air-gap flux density, and stator winding circuitry.

The chance of rotor pullover is usually greatest during the starting cycle when the ampere-turns are also greatest. When the rotor strikes the stator, it can usually be heard. Depending on the amount of contact, it may or may not result in damage to the rotor and/or stator parts. Inspection of the parts is the best way to confirm that this condition exists and evaluate how serious it is.

It has been demonstrated over the years that multi-parallel circuits have a positive influence on reducing the tendency for rotor pullover. On machines where pullover is a potential problem, single-circuit connections should be avoided.

C. Electromagnetic noise and vibration

In addition to pullover problems, air-gap eccentricity can cause noise and/or vibration problems. The radial force produced by the stator harmonics combine with those produced by the rotor harmonics and can create electromagnetic noise and/or vibration.

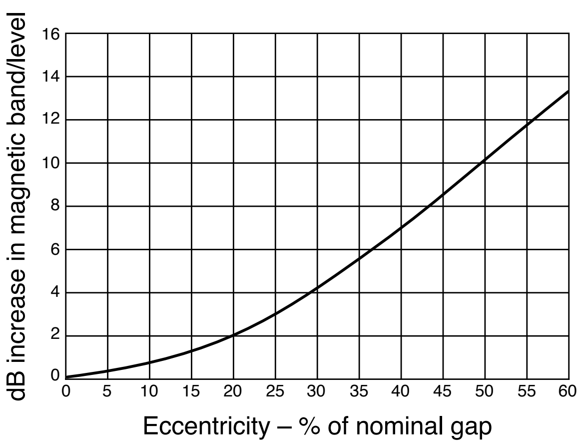
Five basic types of air-gap eccentricities can occur:

1. Rotor O.D. is eccentric to the axis of rotation.
2. Stator bore is eccentric.
3. Rotor and stator are round but do not have the same axis of rotation.
4. Rotor and shaft are round, but do not have the same axis.
5. Any combination of the above conditions.

These conditions may or may not cause a significant amount of electromagnetic noise or vibration. The noise at full load is usually higher than that occurring at no load.

Vibration due to eccentricities will usually vary as a function of terminal voltage. In his paper "Effect of Air-Gap Eccentricity on Motor Sound Level," John Courtin developed the curve in Figure 2-51 to indicate the relationship between air gap eccentricity and noise based on a series of tests on NEMA size open dripproof motors.

FIGURE 2-51



Percent eccentricity vs. increase in dB level (magnetic band).

Although the finite numbers might not be totally representative of all motors, they do indicate the magnitude of the problem and suggest a possible cure for motors that have electromagnetic noise. Experience shows that motors with severe air-gap eccentricity (over 25%) will contribute 2 to 3 dBA to the overall noise level of the machine.

RESIDUAL STRESSES

Residual stresses can be present in any plane (i.e., radial or axial), and are normally not harmful to the rotor as long as they do not cause any significant change in the rotor geometry. Some of the more common residual stresses are the result of casting, brazing, welding, stacking and machining operations. On larger motors, it is common practice to stress relieve the rotor shaft prior to final machining.

Some manufacturers have even tried stress relieving to reduce the rotor cage residual stress. If any of these stresses do result in a change in the rotor geometry, they usually take place during the transition between idle and full load thermal conditions and can cause vibration problems that might not be noticed when running at no load. On high-speed machines, most manufacturers provide a means for refine balancing that would also allow for hot balancing, if necessary.

As in the case of thermal stress, problems of this nature should be referred to the motor manufacturer.

DYNAMIC STRESSES

Some of the more common dynamic stresses associated with rotor design are listed below. Many of these stresses are a function of operating procedure and can be outside of normal design limits.

A. Shaft torques

The rotor shaft is designed to handle torques in excess of those normally associated with motor full-load or breakdown torque. Any torque above these levels is usually of short duration and referred to as a transient torque. Transient torques commonly occur upon starting, bus transfers, or out-of-phase reclosures. They can also be generated by shock loading from driven equipment or by operation on an inverter power supply.

For example, it is possible to generate shaft torques that are 20 times the motor full-load torque through an out-of-phase bus transfer. It is important that the manufacturer is consulted when any transfers will be made before the motor open circuit time constant has elapsed. Applications involving shock loading, such as shredders, also should be identified so that adequate margin can be designed into the rotor.

High shaft torques can also exist under normal operating conditions if a torsional resonance occurs. This is especially true of high-speed rotors. Motors can normally accelerate quite satisfactorily through the first system critical, but will require additional analysis if operated on an inverter where sustained operation at varying speeds would be possible.

B. Centrifugal forces

Normally, a rotor is designed to be capable of being oversped within NEMA design limits (20% for 2 poles and 25% for slower speeds).

Even up to these speeds, caution is necessary if the unit is energized during this condition. Examples of this condition would include inverter operation or wind generators. The reason for this caution is that component parts such as the rotor core to shaft interference fit are now required to handle both centrifugal as well as thermal stresses. Should this fit be lost, high vibration with corresponding destructive results might occur. Of course, centrifugal forces beyond the overspeed limits also need to be checked for causing possible problems associated with end ring or lamination stresses and/or retention of fan blades or balance weights.

One example of this might be a failed or stuck check valve in a pipeline or deep well pump, where the head of liquid causes the pump to turbine backwards and overspeed the rotor.

C. Cyclic stress

The motor shaft can be subjected to cyclic stress that may lead to an eventual fatigue failure. Cyclic stress can be caused by the application, such as misalignment between drives equipment, overtightened belts or incorrect sheave size for overhung loads. Cyclic loads of this nature should be analyzed to make certain safe operating limits are maintained. Any stress raiser, such as a change in shaft diameter, should be analyzed to minimize stress concentrations. Stress relieving of the shaft assembly may be necessary to assure that welding or machining stresses are within acceptable limits.

ENVIRONMENTAL STRESSES

For convenience, any environmental condition affecting the life of the rotor has been defined as a stress. Foreign materials, which can cause abrasion or clog the ventilation paths, could constitute a stress, as could chemicals or moisture, which can attack and breakdown the basic rotor materials. A good example would be the high concentration of a very caustic solution that would etch away an aluminum rotor cage or sulphur fumes, which could cause deterioration of the rotor brazing alloy. Motors with small gaps [.010” - .040” (.25 - 1 mm)] have actually had rotors rust to the stator lamination when a large amount of moisture was present. Corrosion has also caused balance weights to come loose and “sling” into the stator winding with destructive results. Where harsh environmental conditions exist, it is a good practice to alert the manufacturer of the type of environment to which the motor will be exposed. Some manufacturers actually coat the rotors to obtain additional protection.

MECHANICAL STRESSES

In addition to those failures associated with the previously mentioned stresses, there is another broad category of failures that can be grouped under the general heading of mechanical failures. Some of the more common ones are:

1. Casting porosity
2. Loose laminations
3. Broken or fatigued parts
4. Incorrect fit between shaft and core
5. Poor rotor/stator geometry
6. Loss of air gap
7. Bent rotor shaft
8. Bearing failure
9. Misalignment
10. Incorrect materials
11. Tooth resonance

ANALYSIS OF ROTOR FAILURES

Using the same methodology proposed for the stator, there are five key areas which must be considered and related to one another in order to accurately diagnose the cause of rotor failures. They are:

1. Failure class
2. Failure pattern
3. Appearance
4. Application
5. Maintenance history

The following is a brief description of each of these areas.

A. Failure classes

Regardless of the cause of failure, the actual classes of failure can be grouped as follows:

1. Shafting
2. Bearing
3. Lamination
4. Squirrel cage
5. Ventilation system
6. Stator
7. Any combination of the above

In analyzing rotor failures, it is difficult to determine which of these factors was the initial problem and which was the result.

A simple example will illustrate the point. A 3600 rpm, 500 hp (370 kW) motor has a bent shaft that causes severe vibration and damages the bearings. This results in the loss of the air gap while the motor is running. The rotor strikes the stator, overheating both the rotor and stator lamination along with the primary and secondary windings. The aluminum rotor bar melts and is slung out into the stator winding where it causes a line-to-line fault that shuts down the machine.

Although inspection could reveal six classes of failure, the faulty shaft was the initial problem; the others were the result of this problem. Unfortunately, due to the destructive nature of the failure, it is often difficult to separate the cause from the effect.

B. Failure patterns

Closely related to the class of failure, but considered separately, is the pattern of failure that can be classified according to the various stresses operating in the machine:

1. Thermal
2. Magnetic
3. Residual
4. Dynamic
5. Mechanical
6. Environmental

Combining the class and pattern of failure can provide clues to the cause of failure.

C. Appearance

When coupled with the class and pattern of failure, the general appearance of the motor usually gives a clue to the possible cause of failure. The following check list will be useful in evaluating assembly conditions.

1. Does the rotor exhibit any foreign material?
2. Are there any signs of blocked ventilation passages?
3. Are there signs of overheating exhibited by lamination, bars, painted surfaces, etc.?
4. Has the rotor lamination or shaft rubbed? Record all locations of rotor contact.
5. Are there any signs of a stalled or locked rotor?
6. Was the rotor turning during the failure?
7. What was the direction of rotation and does it agree with fan arrangement?
8. Are any mechanical parts missing, such as balance weights, bolts, rotor teeth, fan blades, etc., or has any contact occurred?
9. Are the bearings free to rotate as intended?
10. Are there any signs of moisture on the rotating assembly

or contamination of the bearing lubricant?

11. Are there any signs of movement between rotor core and shaft or bar and lamination?
12. Is the lubrication system as intended or has there been lubricant leakage?

When analyzing rotor failures, it is helpful to draw a sketch of the motor and indicate the point where the failure occurred, as well as the relationship of the failures to both the rotating and stationary parts, such as shaft keyway, etc.

D. Application considerations

Usually, it is difficult to reconstruct the actual operating conditions at the time of failure. However, a knowledge of the general operating conditions will be helpful. The following items should be considered.

1. What are the load characteristics of the driven equipment and the loading at time of failure?
2. What is the operating sequence during starting or process damage?
3. Does the load cycle or pulsate?
4. What is the voltage during starting and operation?
5. How long does it take for the unit to accelerate to speed?
6. Have any other motors or equipment failed on this application?
7. How many other units are successfully operating?
8. How long has the unit been in service?
9. Did the unit fail on starting or while operating?
10. How often is the unit started and is this a manual or automatic operation?
11. What type of protection is provided?
12. What removed or tripped the unit from the line?
13. Where is the unit located, and what are the normal environmental conditions?
14. What was the ambient temperature at time of failure?
15. What were the environmental conditions at time of failure?
16. Is the mounting base correct for proper support to the motor?
17. Was power supplied by a variable-frequency drive?

E. Maintenance history

An understanding of the past performance of the motor can give a good indication as to the cause of the problem. Again a checklist may be helpful.

1. How long has the motor been in service?
2. Have any other motor failures been recorded, and what was the nature of the failures?
3. What failures of the driven equipment have occurred?
4. When was the last time any service was performed?
5. What operating levels (temperature, vibration, noise, etc.) were observed prior to the failure?
6. What comments were received from the equipment operator regarding the failure?
7. How long was the unit in storage or sitting idle prior to starting?
8. What were the storage conditions? Were space heaters energized?
9. How often is the unit started?
10. Was unit meggered prior to putting in service?
11. Were correct lubrication procedures utilized?

METHODOLOGY

The following discussion provides a means for identifying the specific cause of rotor failure based on failure patterns: thermal failure, magnetic failure, dynamic failure, mechanical failure and environmental failure. Note that remaining failures are grouped with miscellaneous failures, rather than being discussed as separate items. For a summary of typical failures and telltale rotor appearances, refer to Appendix I of the author's PCIC-87-2 paper.

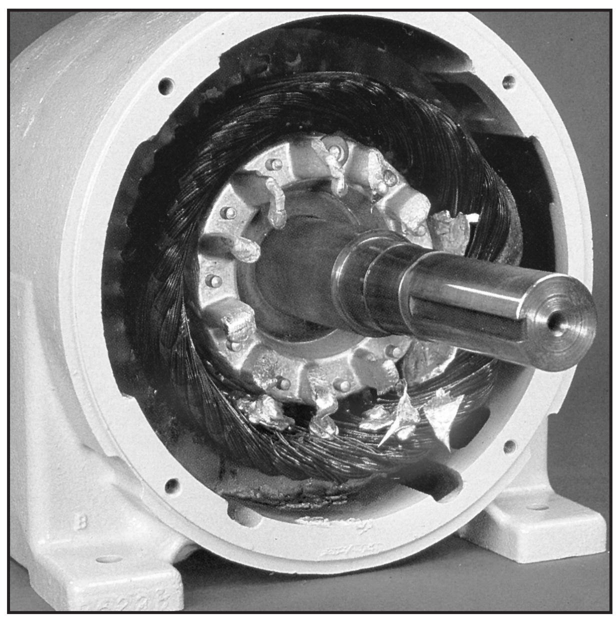
A. Thermal failure

Thermal failures are generally easy to identify because of the appearance of the rotor. The ultimate cause of the failure, however, can be quite difficult to pinpoint.

1. Possible cause

a. Thermal overload
b. Thermal unbalance
c. Excessive rotor loss
d. Hot spots
e. Incorrect direction of rotation
f. Locked rotor (Figure 2-52.)

FIGURE 2-52



Severe thermal deterioration of the insulation in all phases of the motor normally is caused by very high currents in the stator winding due to a locked rotor condition. It may also occur as a result of excessive starts or reversals.

2. Rotor appearance

Evidence of extreme heating of the rotor will be visible. This can range from isolated bluing caused by hot spots to molten aluminum either on the rotor or slung into the winding. Many times, excessive temperature can be determined by observing the color of painted surfaces.

3. Class of failure

Most thermal failures will exhibit an uneven pattern over the entire rotor, which may be accompanied by molten aluminum from the slots or end ring. To narrow the options of possible causes, additional patterns must be noted. Locked rotors will typically have aluminum puddled at the bottom of the winding, while thermal overloads, excessive rotor losses and incorrect rotation will have aluminum spread around the winding or rotor surface.

For air-ducted rotors, bars melted in the air passages are indicative of overheating due to stalling, failure to accelerate or excessive starting frequency. Bars melted in the lamination pockets are indicative of overheating during running or operation. Hot spots and thermal unbalance typically exhibit uneven heating patterns on the rotor surface and can result in changes in the magnitude of vibration versus time between cold starting and hot running conditions.

In severe cases, rotors that have bowed due to thermal instability will often exhibit a rub on the rotor surface in one area with a corresponding 360° smear on the stator or on one side of the shaft and a 360° smear of the bearing cap or oil seal.

B. Magnetic failures

Magnetic failures may be obvious or extremely difficult to isolate. Because of secondary damage, careful observation is necessary to accurately identify the ultimate cause of failure.

1. Possible cause

a. Rotor pullover
b. Uneven magnetic pull
c. Lamination saturation
d. Circulating currents

2. Rotor appearance

Visual evidence of magnetic stresses is relatively limited. Rotor rubs may appear as a spot smear on the rotor O.D. and the stator I.D., or a spot smear on the stator I.D. along with a totally smeared rotor O.D. Failures due to magnetic stresses where the rotor did not physically strike the stator usually display no observable pattern. They can be detected only by measurements of associated parts (end brackets, frames, shafting, etc.) and analysis of magnetic forces under actual operating conditions (operating voltage, frequency, etc.).

Audible evidence of magnetic stress is more common. Loose rotor bars usually exhibit noise or sparking during starting. They can also result in localized hot spots or bar breakage, which can be readily observed after disassembly.

Broken rotor bars can be detected without disassembly by applying a single-phase voltage of 5-10 percent of rated voltage to two motor leads and slowly turning the rotor by hand while observing line current with a clip-on ammeter. A broken bar will cause a fluctuating current every time it passes under a pole pair. Variance in current readings of 3-5 percent or more is usually a sign of a broken bar (see Figure 2-50).

3. Class of failure

Rotor pullover may or may not be accompanied by physical contact with the stator. If contact does occur, the first evidence may be noise, vibration, or catastrophic winding failure. If contact does not occur, evidence may be limited to noise or vibration.

Prolonged, excessive pullover will result in high radial bearing loading with a corresponding reduction in bearing life. Any history of short bearing life or combination of bearing failures and rotor rubs should be looked at as a potential pullover problem. Rotor rubs due to eccentricity typically show heavy smearing in a small area of the rotor O.D. and around the entire stator bore. Uneven magnetic pull typically exhibits a rub in a small area of the stator and around the entire O.D. of the rotor. This is caused by the axis of rotation being different than the magnetic axis of the winding.

Careful measurements would be necessary to detect this condition. Saturation and circulating currents would result in poor performance of the motor and could be detected by the motor manufacturer, who is in the best possible position to isolate performance problems.

Magnetic failures not involving contact can manifest themselves in noise and/or vibration. Out-of-concentricity rotor cores (particularly 2 poles) will generally exhibit a pulsating beat at slip frequency, while slow-speed motors normally exhibit vibration. These magnetic forces are easily isolated because they cease immediately upon removal of voltage. Broken rotor bars can lead to vibration problems but more likely, in severe cases, the bar pounds its way out of the slot and makes contact with the stator core or winding. A rattling sound at startup or under load may indicate loose or broken rotor bars.

C. Dynamic failure

With a few exceptions, dynamic failures originate with forces external to the motor. Stresses of this nature must be identified and either corrected or accounted for in component/system design, if repeated failures are to be eliminated.

1. Possible cause	Origin
Vibration	External or internal
Loose rotor bars	Internal
Rotor rub	External or internal
Transient torque	External
Overspeed	External
Cyclic stress	External

2. Rotor appearance

Cyclical, vibration, and torque stresses generally result in broken shafts and/or failed bearings. Overspeed evidence typically consists of broken fan blades, shifted rotor core, high vibration, and damage or distortion of shaft-mounted parts (fans, coupling, etc.). Examination of failed parts many times can isolate the origin of failure. As an example, a shaft torsional failure indicates rotation opposite to the normal direction of rotation, and can point to an out-of-phase bus transfer or reclosure as the origin of failure. Dynamic failures often result in extensive damage to the entire motor. Bearing failures usually allow the rotor to contact the stator, with subsequent loss of the winding. Overspeeding can damage all parts of the motor.

3. Class of failure

It is often extremely difficult to reconstruct the exact sequence of events leading to the origin of the failure. Many dynamic failures originate with forces external to the motor that are not available for analysis after the motor has been removed. Close inspection of component parts, couplings, etc., is mandatory. Equally important may be an analysis of the past history or operating characteristics of the unit, as well as conversations with the operators on duty at the time of failure.

D. Mechanical failure

The exact cause of a mechanical failure is often very difficult to identify because the appearance of the failed part is very similar to failures due to other reasons (dynamic stresses, thermal failures, etc.). Careful analysis, however, will usually reveal physical evidence of a mechanical problem.

1. Possible cause

a. Casting variation (voids).
b. Loose lamination and/or bars.
c. Incorrect shaft-to-core fit.
d. Fatigue or part breakage.
e. Improper rotor and stator geometry.
f. Material deviations.
g. Improper mounting and/or shaft resonance.
h. Improper design or manufacturing practices.

2. Rotor appearance

The rotor can exhibit any of the patterns mentioned previously: hot spots, smearing, fractures, movement, etc. Some form of physical damage or movement is usually associated with this type of failure.

3. Class of failure

As with most failures, it is extremely important to inspect all parts of the motor, not just the rotor, to determine the failure class. Rotor core or shaft rubs are common due to rotor's axis of rotation being moved off magnetic center by improperly located or failed component motor parts and/or misalignment of overhung loads. Loose lamination or bars normally exhibit noise during starting or running. The movement of these parts can lead to fatigue failure, localized hot spots, shaft bending, rotor rubs and winding or bearing failure, etc. Fatigue failure of shafts or components should be analyzed to determine whether long- or short-term cyclic failure has occurred. Even the appearance of external components (e.g., grease on belt drives) may provide a clue to the origin of failure.

E. Environmental failures

Environmental failures are among the easiest to diagnose. It is especially important to observe maintenance records and operating site conditions to get the complete history surrounding the failure.

1. Possible cause

a. Contamination
b. Abrasion
c. Foreign particles
d. Restricted ventilation
e. Excessive ambient temperature
f. Unusual external forces

2. Rotor appearance

Restricted ventilation due to deposits in air passages or ducts or excessive ambient temperatures will exhibit an overall heating pattern on the rotor as well as component parts. Other patterns include etched rotor and/or aluminum surfaces, rust deposits, localized gouges in both rotor and stator surfaces, "sandblasted" surfaces, and foreign material lodged in the winding.

3. Class of failure

Environmental failures are most often the result of misapplication or improper maintenance. Dust or other materials can clog filters, ventilation passages or air ducts, causing general overheating. Enclosed motors can be coated with a blanket of material, preventing proper heat transfer and/or proper air flow. Chemicals or water can enter the motor and attack the rotor surfaces. On units with small air gaps (up to 0.040" or 1 mm), the rotor can be rusted solidly to the stator I.D. Foreign material can get into the rotor, breaking the fan blades or damaging the rotor surfaces.

Examination of the bearings and/or lubrication for thermal deterioration or contaminants can explain certain unexpected failures. For example, the addition of even a small percentage of moisture in the lubricant significantly reduces the fatigue capability of bearings. This can have dramatic effects on heavily loaded applications, as can the use of incompatible greases or oils, which reduce the oil film strength.

F. Miscellaneous failures

Failures in this category don't easily fall into clearly defined areas. They exhibit characteristics from each of the previously defined failures and must be examined carefully to isolate the ultimate cause of failure.

1. Possible cause

a. Stress concentration
b. Uneven bar stress
c. Misapplication
d. Poor design practice
e. Manufacturing variations
f. Inadequate maintenance
g. Improper operation
h. Improper mounting

2. Rotor appearance

All, part or none of the previously mentioned patterns may be present in this category. New patterns may also exist that could identify the failure origin.

3. Class of failure

Depending upon the specific cause, different classes of failure may have occurred. Inadequate, excessive or improper maintenance can lead to overheating or bearing failure. Misapplication and improper operation can result in thermal failures or broken parts. Poor system or motor design practice can result in any range of operation from poor performance to catastrophic failure.

For this analysis, it is necessary to document the exact operating sequence in an attempt to isolate the failure's origin.

One example of this analysis was a returned 3600 rpm motor that exhibited a failed winding, excessive rotor core and shaft rubs, failed bearings and a spun fan bore on the outboard end. This motor was located at an unattended remote pumping station and was removed from the line via ground fault protection. It had operated successfully for more than 9 months prior to failure. While almost all components had failed, the origin of the failure was found to be a faulty check valve. The following supports that conclusion. Analysis of the shaft in the location of the damaged fan, as well as the inboard fan location, revealed all parts to be in tolerance. Both fan blades exhibited slight bowing, which was duplicated by overspeeding a new fan to approximately 5000 rpm. Further investigation revealed that the plastic nipple in the air deflector used to pressurize the outboard bearing was smeared in the opposite direction of normal rotation.

The conclusion was that the pumping station check valve had malfunctioned, causing the unit to overspeed in the reverse direction while un-energized. This resulted in the outboard fan losing its fit, traveling down the shaft, and making contact with the air deflector nipple. When the unit was finally started, the fan bore smeared in the direction of rotation, causing local heating and ultimately bearing failure. The dropped rotor rubbed the stator, leading to the winding failure. To prevent reoccurrence, it was recommended that the check valve be repaired prior to motor replacement.

Note that no mention is made of the effects of thermal or residual aging on rotor failures. This can be explained as follows.

Unless the operating temperature is extremely high, the normal effect of thermal aging is to render the rotor materials vulnerable to other influencing factors or stresses that actually produce the failure. Once the rotor has lost its physical integrity, it will no longer resist the normal dynamic, magnetic, mechanical and environmental stresses.

Of course, if any of the basic stresses becomes severe enough, a failure will occur regardless of the amount of thermal aging. This type of failure is normally identified by slow, long-term changes in vibration and many times can be brought under control by thermally shocking the rotor.

CONCLUSIONS

Due to the destructive nature of most failures, it is not easy, and is sometimes impossible, to determine the primary cause of failure. By a process of elimination, one can usually be assured of properly identifying the most likely cause of the failure.

The key point in going through this process of elimination is to use the basic steps of analyzing the failure class and pattern, noting the general appearance of the motor, identifying the operating condition at the time of failure, and reviewing the past history of the motor and application.

Omitting any of these steps makes it easy to arrive at a false conclusion about the real cause of the failure. Hence, the required action might not be taken, and future failures of the same kind will undoubtedly occur.

ADDITIONAL RESOURCES

Refer to the Appendix of IEEE Paper PCIC 87-2 and PCIC 85-24 for detailed discussions of the following subjects.

1. Summary of typical rotor failures and telltale appearance.
2. Swaging of rotors to tighten bars.
3. Aluminum vs. copper bar construction.

These papers also contain a detailed bibliography on various rotor subjects, which may be helpful in failure analysis.

The bibliography of IEEE Papers PCIC 76-7, PCIC 77-4 and PCIC 78-2 may also be useful.

All six papers provided the material for the abridgement of this combined paper, as well as the opportunity to update the original papers based on current information.

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2.10 POWER FACTOR IMPROVEMENT

Power factor correction: Why it is important

By Richard Huber
BC Hydro
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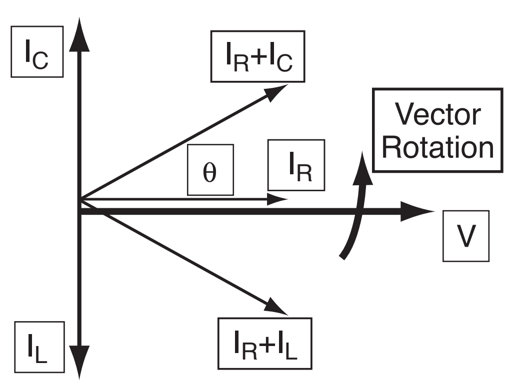
Power factor is the ratio of kW to kVA in an AC circuit. It can also be defined as the cosine of the phase angle between the current and the voltage. This angle is affected by the amount of inductance or capacitance in the circuit. If the circuit contains inductive elements only, the current (I_L) will lag the voltage by 90 degrees, as shown in Figure 1. If the circuit contains capacitive elements only, the current (I_C) will lead the voltage by 90 degrees. Combining resistive elements with either the inductive or capacitive elements will cause the angle between the current and voltage to be less than 90 degrees. (For a circuit that contains resistive elements only, the current (I_R) will be in phase with the voltage.) These phase relationships between voltage and current are shown in Figure 2-53. Power factor is defined mathematically as the cosine of angle θ, or cosine $\theta = I_R / I_{R+C}$

FIGURE 2-53



Vector relationships between current and voltage for various combinations of circuit elements.

As mentioned previously, the phase angle between voltage and current is most commonly the result of inductive or capacitive elements in the circuit. Examples of inductive elements are motors, transformers and lighting ballasts. Normal capacitive elements are capacitors and synchronous condensers (a synchronous motor operating unloaded, for power factor correction).

CORRECTIONS PAY OFF

In large office buildings or industrial settings, the power factor should be maintained close to unity. The benefits in doing so are as follows. First, the losses in the cables and other equipment can be reduced because the current flow through them is reduced. This, in turn, reduces heating, and hence aging. In addition, the requirements for circuit interrupting devices are less onerous, so smaller or less expensive ones can be used. Finally, energy costs can be reduced by eliminating or reducing utility surcharges. Note that not all utilities penalize the user for low power factor.

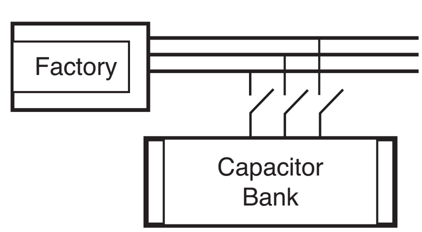
As demand for a utility's power approaches capacity, power factor penalties are often used to help manage usage. So even if a particular power company does not impose power factor penalties right now, that is no guarantee they won't do so in the future. One power company's surcharges are shown in Table 2-24.

TABLE 2-24: POWER FACTOR SURCHARGES

Power factor %	Surcharge %
90 to 100	0
88 to 89	2
87 to 85	4
80 to 84	9
75 to 79	16
70 to 74	24
65 to 69	34
60 to 64	44
55 to 59	57
50 to 54	72
Less than 50	80

To reduce or eliminate these charges, the power factor should be maintained closer to unity. To accomplish this, bulk or central power factor correction is often used. Capacitors are

FIGURE 2-54



Bulk capacitor bank power factor correction.

added to the power system where the supply enters the building or factory. The capacitors can be fixed, switched manually or switched by an automatic controller. A simple installation is shown schematically in Figure 2-54.

If the capacitors are fixed, the owner/operator has no control over the power factor if the factory load changes. Consequently, these capacitors are often installed so they can be switched manually. Alternatively, if the load and power factor are changing continually, the capacitors can be switched using an electronic controller. One or more transducers are used to determine the power factor. When it is outside a specified range, capacitors are added or removed from the circuit to adjust the power factor of the system.

Table 2-25 contains information that can be used to determine the correct capacitor size for static applications for a given load and power factor. This method of power factor correction improves the power factor of the building or factory up to the point at which the capacitors are located, but does nothing to change the power factor or the current drawn by loads beyond (downstream of) the capacitors.

TABLE 2-25: CAPACITOR KVAR RATING FOR POWER FACTOR IMPROVEMENT
CAPACITOR MULTIPLIERS FOR KILOWATT LOAD

Original power factor (%)	Desired power factor (%)				
	100	95	90	85	80
60	1.333	1.004	0.849	0.713	0.583
62	1.266	0.937	0.782	0.646	0.516
64	1.201	0.872	0.717	0.581	0.451
66	1.138	0.809	0.654	0.518	0.388
68	1.078	0.749	0.594	0.458	0.328
70	1.020	0.691	0.536	0.400	0.270
72	0.964	0.635	0.480	0.344	0.214
74	0.909	0.580	0.425	0.289	0.159
76	0.855	0.526	0.371	0.235	0.105
77	0.829	0.500	0.345	0.209	0.079
78	0.802	0.473	0.318	0.182	0.052
79	0.766	0.447	0.292	0.156	0.026
80	0.750	0.421	0.266	0.130	
81	0.724	0.395	0.240	0.104	
82	0.698	0.369	0.214	0.078	
83	0.672	0.343	0.188	0.052	
84	0.646	0.317	0.162	0.026	
85	0.620	0.291	0.136		
86	0.593	0.264	0.109		
87	0.567	0.238	0.083		
88	0.540	0.211	0.056		
89	0.512	0.183	0.028		
90	0.484	0.155			
91	0.456	0.127			
92	0.426	0.097			
93	0.395	0.066			
94	0.363	0.034			
95	0.329				
96	0.292				
97	0.251				
99	0.143				

Example: Assume total plant load is 100 kW at 60 percent power factor. Capacitor kVAR rating necessary to improve power factor to 80 percent is found by multiplying kW (100) by multiplier in table (0.583), which gives kVAR (58.3). Nearest standard rating (60 kVAR) should be recommended.

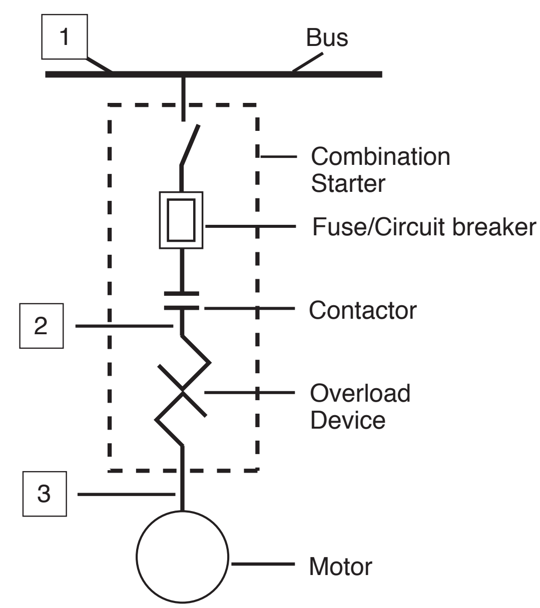
Power factor correction using switched capacitors can introduce switching transients into the supply or load circuits. If frequent switching is required and/or equipment is being damaged by voltage transients, a synchronous condenser might be a better alternative for bulk or central power factor correction. In this method, power factor is maintained by adjusting the excitation current of a synchronous motor, either driving a load or operating as a synchronous condenser.

Another method of power factor correction is to improve the power factor on the branch circuits within the building or factory. This method can be used on motor circuits and lighting circuits. Static or switched capacitors can be used for this purpose. Historically, static capacitors have been used for this application and are switched with the device being compensated (as discussed below). However, with the reduction in costs of the electronic controllers, transducers and capacitors, switched capacitor banks can now be applied to branch circuits.

LOCATIONS ARE IMPORTANT

Examples of locations where capacitors can be added directly to a motor circuit are shown in Figure 2-55.

FIGURE 2-55



Locations for power factor correction capacitors for an induction motor circuit.

Installing a capacitor at Location 1 will help correct the power factor, but it is little better than the bulk correction discussed earlier. The capacitor remains energized at all times, and if other motors or other inductive equipment are connected to the bus, it can lead to critical compensation or over compensation. In the case of critical compensation, the capacitors adjust the power factor to unity. Hence, the inductive reactance equals the capacitive reactance at 60 Hz. In the case of over compensation, the capacitor is too large and the inductive reactance and capacitive reactance are equal at a frequency less than 60 Hz. In either case, undesirable large current surges can occur, resulting in high voltages on the bus.

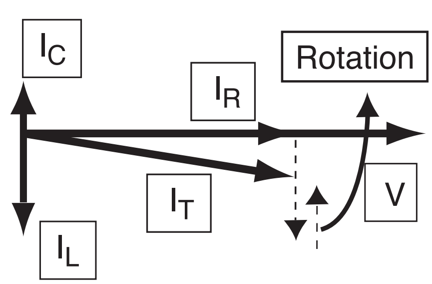
Locations 2 or 3 are better for capacitor installation. When the motor is offline, so are the capacitors. However, Location 3 introduces additional problems for motors where jogging or frequent switching occur, such as elevator motors, multispeed motors, or open transition autotransformer or wye-delta start or some (except the so-called extended- or double-delta) part winding start motors.

For these applications, a capacitor at Location 3 can introduce high amplitude switching transients or current surges into the motor. Location 1 is better for these applications. In addition, at Location 3, the overload protection devices will have to be downsized as the current through them has been reduced.

Location 2 is the best for installing power factor correction capacitors for motors. Table 2-25 can be used to select capacitors for this type of installation.

Now let's take a closer look at the vector relationships between voltage and current when a capacitor is added to the circuit. The general relationship between voltage and current is shown in Figure 2-53. The relationship between inductive current, resistive current, capacitive current and total current is shown in Figure 2-56.

FIGURE 2-56



Relationship between current vectors.

The vector relationship is:

$$I_T = I_R + I_L + I_C$$

Mathematically, the total current is calculated as follows:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

Assume the following: $I_R = 10$, $I_L = 4$, $I_C = 3$. Then

$$I_T = \sqrt{(10 \times 10) + (4 - 3) \times (4 - 3)}$$

$$I_T = \sqrt{100 + 1}$$

$$I_T = \sqrt{101} = 10.05$$

One can see that if these currents represented the motor in Figure 2-55, and the capacitor were placed at Location 2, the current drawn from the supply would be 10.05 amps. The motor current would still be the vector sum of $I_R + I_L$, or mathematically,

$$\sqrt{(10 \times 10) + (4 \times 4)} = 10.77 \text{ amps}$$

which is the same as before the capacitor was installed. Hence, the motor overload protection devices would not have to be changed. If, however, the capacitor were installed at Location 3, the current through the overload devices would be the 10.05 amps calculated above. Hence, they may have to be replaced with devices that are more suitable for the lower current.

The power factor (pf) for the circuit without the capacitor is:

$$pf = \frac{kW}{kVA}$$

$$pf = \frac{V \times I_R}{V \times I_T}$$

$$pf = \frac{I_R}{I_T}$$

$$pf = \frac{I_R}{\sqrt{I_R{}^2 + I_L{}^2}}$$

$$pf = \frac{10}{10.77} = 0.93$$

If the capacitor is added, the total current from the source becomes 10.05 amps as calculated previously. The new power factor is:

$$pf = \frac{10}{10.05} = 0.99$$

If I_R is the current in phase with the voltage at full load, one can see that the power factor even without compensation is reasonably good. If the load on the motor is reduced, and I_R decreases to 4 amps, the power factor is then:

$$pf = \frac{4}{\sqrt{(4 \times 4) + (4 \times 4)}}$$

$$pf = \frac{4}{5.66} = 0.707$$

Now add the capacitor and the power factor is:

$$pf = \frac{4}{\sqrt{(4 \times 4) + [(4 - 2) \times (4 - 2)]}}$$

$$pf = \frac{4}{\sqrt{16 + 4}}$$

$$pf = \frac{4}{4.47} = 0.895$$

So, at reduced or unloaded conditions the capacitor provides the compensation necessary to significantly improve the power factor.

One must exercise care when selecting the capacitor. If the capacitor is chosen so that $I_C = I_L$ the circuit is then considered to be critically compensated. That is, the circuit is resonant at line frequency. This generally is not a good condition because large currents can flow between the motor and the capacitor generating high voltages that can damage the motor and/or the capacitor.

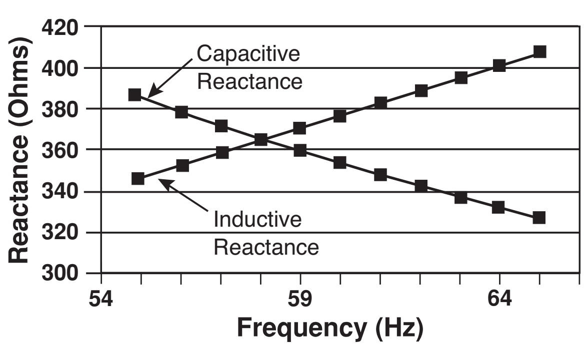
It is also important to avoid overcompensation where the capacitor value is too large. This can also lead to a resonant condition. Consider the following example:

For resonance $X_C = X_L$

$$\frac{1}{2}\pi pfC = 2\pi pfL$$

If the capacitor is oversized, the capacitive reactance at line frequency will be less than the inductive reactance and resonance will not occur during operation. However, when the supply to the motor is disconnected, and before the field in the rotor has collapsed, the frequency will decay. This will increase the capacitive reactance and decrease the inductive reactance, creating another resonant condition at about 58 Hz for a 60 Hz supply (Figure 2-57).

FIGURE 2-57



Reactance vs. frequency.

When selecting capacitors for power factor correction, it is advisable to select capacitors that will provide capacitive current equal to approximately 80% of the motor magnetizing current. If done in this manner, the change in power factor at low loads will be similar to that calculated in the example above, and resonant situations can be avoided.

For most practical situations, the magnetizing current for the motor can be assumed to be the no-load current (i.e., the motor is not connected to the load). The capacitor for power factor correction should be selected based on 80% of this value.

Caution: Motors can be driven by the load if there is a loss of power and a capacitor is connected.

CONSIDER ELECTRONIC EQUIPMENT

Now let's consider some of the electronic equipment one can find on a low-voltage distribution system.

The power factor for many variable-frequency drives is also low. However, correcting the power factor with capacitors in close proximity to the drive must be done with care and in many cases is not recommended. To connect capacitors adjacent to a variable-frequency drive unit can cause extensive resonant oscillations of the current and voltage. Voltage transients are also often present. They are produced because the current to the drive is continuously being switched. Each time it is switched, a voltage transient occurs, which causes voltage oscillations between the capacitor and the supply or the capacitor and the drive unit. In both cases this can damage or reduce the life of connected components. On small motors the large voltage transients that sometimes occur can result in broken shafts.

This subject is covered in more detail in the *NEMA Applications Guide* referenced in the bibliography.

If a capacitor is used to correct the power factor, it should be sufficiently far away from the switched current source that the impedance between the capacitor and any other connected object would diminish the voltage transients. Alternatively, a series reactor may be installed in the supply circuit to reduce the amplitude of the voltage transients.

The use of power factor correction capacitors with electronic soft starters should only be considered if the capacitors are connected through a separate contactor, or switch on after the voltage to the motor has reached its peak value.

Switched power supplies in computers and other electronic equipment can also affect the phase angle between voltage and current. This type of equipment behaves similar to an inductor, and the power factor can be as low as 0.6. In addition, these devices introduce large amounts of current harmonics into the supply system. To improve the power factor of this type of equipment requires the addition of special electronic circuits to shape the current wave, thus eliminating harmonics and reducing the angle between voltage and current. These "special" electronic circuits usually take the form of a DC converter where the power to the load is controlled by a pulse width modulator such that the increase in load current is in phase with the supply voltage.

When attempting to improve the power factor and reduce harmonics from switched power supplies, inverters or other electronic devices, obtain the assistance of someone who specializes in power quality issues.

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2.11 STARTING OF AC MOTORS

Determining starting capacitance for single-phase motors

The following trial-and-error method can be used to determine the proper capacitor size for a capacitor start motor. As Figure 2-58 shows, it requires two voltmeters: one connected across the starting winding measuring E_w; the other connected across the capacitor measuring E_c.

The sum of the magnitude of these voltages should *not* equal the applied voltage. The intent is to make the magnitude of the capacitive reactance slightly larger than that of the inductive reactance of the starting winding, essentially compensating for the inductive reactance of the starting winding.

With respect to the applied voltage, the phase angle of the current in the starting winding will then shift approximately 90 degrees (see Figure 2-59 and Figure 2-60) relative to the current in the running winding, allowing the motor to start.

As a guide for sizing starting capacitors, begin with about 400 microfarads (μF) per horsepower (540 μF per kW) for 115-volt motors, or about 100 μF per horsepower (135 μF per kW) for 230-volt motors. The actual size of the capacitors will vary, depending on motor size and design.

Connect the trial capacitor in series with the starting winding of the motor. Then connect the motor windings to an AC supply that is the same voltage as the rated voltage for the motor. Lock the rotor, briefly apply the rated voltage, and measure E_c and E_w. (**Caution:** Prolonged application of voltage may damage the motor.)

E_c should be 5 to 10 percent greater than E_w. If it is less, decrease the size of the capacitor. If it is more, increase the size of the capacitor. Repeat the test until a suitable capacitor size is obtained.

FIGURE 2-58

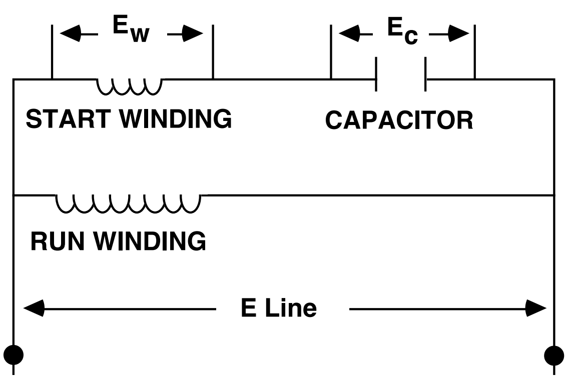
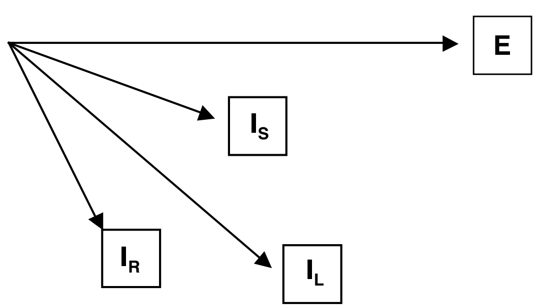
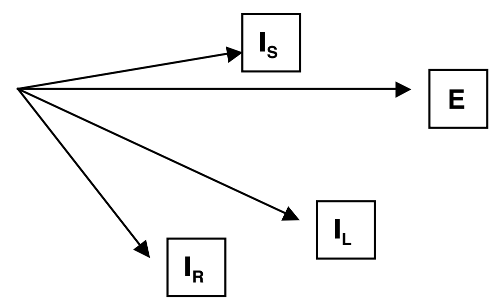


FIGURE 2-59



Approximate vector relationship between the currents in the starting winding (I_S), running winding (I_R) and the line current (I_L). The angle between the currents in the starting and running winding without the starting capacitor is approximately 30 degrees.

FIGURE 2-60



Approximate vector relationship between the currents in the starting winding (I_S), running winding (I_R) and the line current (I_L) with the starting capacitor added. Note that the angle between the currents in the starting and running winding is now approximately 90 degrees.

Methods of reducing the starting current of induction motors

By EASA Technical Services Committee

The locked-rotor current of typical induction motors, started across-the-line, is approximately six times full-load current. A current of that magnitude causes increased heating of the winding, undesirable voltage dips on the power line, and undue mechanical stresses on gears, couplings and other parts of the equipment.

> **Caution:** Some of these starting methods leave one end of each phase energized.

Through methods described in this article, the inrush current for an induction motor may be reduced to an acceptable level, thereby assuring satisfactory operation of the motor. Before choosing a starting method, however, consider these factors:

- Compatibility of motor winding with starting method;
- Torque requirements of the driven equipment;
- Motor starting characteristics;
- Overload protection of motor and control;
- Initial cost (which varies considerably).

There are three methods for limiting the current and torque when starting induction motors:

- Reduction of terminal voltage by use of an autotransformer, resistors, reactors; or electronic soft starter.
- Reconnection of the stator winding using the series-parallel, wye-delta or part-winding method.
- Reduction in voltage and frequency by variable-frequency drive.

AUTOTRANSFORMER STARTING

An autotransformer lowers the motor current in proportion to the motor voltage and reduces the line current proportionally to the square of the motor voltage.

Autotransformers are normally designed to apply 50, 65 or 80 percent of line voltage to the motor terminals. With an 80-percent tap setting on the transformer, both the secondary voltage and the secondary current supplied to the motor terminals are reduced to 80 percent of their across-the-line values. The primary (line) current, however, is reduced to 64 percent (.8 x .8) of its across-the-line value.

The starting torque is also reduced in proportion to the square of the motor terminal voltage or to 64 percent of maximum starting torque.

PRIMARY RESISTOR STARTING

The use of resistors in series with the stator winding reduces the starting current, the terminal voltage, and the starting torque of the motor.

As the speed of the motor increases from standstill, the line current decreases. This raises the terminal voltage and the torque. The resistors are then gradually cut out, and when the line current has decreased to a value low enough to permit full line voltage to be applied to the motor terminals, the resistors are short-circuited. This starting procedure can be performed either manually or by the use of timers.

Resistor starting, normally used for voltages less than 600 volts, is more economical than the autotransformer method. For a given value of line current, however, the starting torque is lower than if an autotransformer had been used. The energy wasted in the resistors is equal to the I^2R loss.

PRIMARY REACTOR STARTING

Reactor starting, which is based on the same principles as resistor starting, increases the voltage at the motor terminals faster than if resistors are used. This is due to the rapid decrease of motor reactance during acceleration.

Reactors lower the power factor and consume less power than resistors, so they are normally used for starting large machines and for voltages above 600.

SERIES-PARALLEL STARTING

The series-parallel starting method can be used for both single- and dual-voltage motors. Single-voltage motors must be designed for operation with an even number of winding circuits. Dual-voltage motors can be started as long as the final connection has parallel circuits. In both cases the winding is series connected for starting and parallel connected for running.

The series-parallel method must be used only where light loads are to be started. This method develops only 25 percent of normal starting torque and draws 25 percent of full-voltage starting current.

WYE-DELTA STARTING

The use of wye-delta starting requires that the motor be designed for operation with a delta-connected winding. The winding is connected wye for starting, which reduces both starting current and torque to 33 percent of their across-the-line values. The connection is changed to delta for the running operation.

Wye-delta started motors are built with six leads for single voltage operation and with 12 leads for dual voltage operation.

PART-WINDING STARTING

Part-winding start motors have special internal connections and are usually designed with an even number of winding circuits. Whether single- or dual-voltage, the motors are started in two or three steps. Dual-voltage motors can only be part-winding started on the high voltage when the high-voltage connection has parallel circuits.

For two-step starting, one-half of the motor winding is energized first. Two or three seconds later the other half of the winding is energized by connecting both winding sections in parallel. Sometimes the motor will not start until both halves of the winding have been energized. Since only two or three seconds elapse between the first and second step, the motor is not damaged and line disturbances are minimal.

For high-speed motors (2-12 poles), the starting current is about 70 percent and the starting torque about 50 percent of their across-the-line values.

For three-step starting, as in two-step starting, one-half of the winding is energized first. Two or three seconds later, in step two, a portion of the other half of the winding is energized, followed by the remaining portion in step three.

Three-step starting can also be used in conjunction with impedance starting. The impedance is usually connected in series with the portion of the winding to be energized first. The impedance is short-circuited during step two, and in the third step the remaining portion of the winding is energized.

Most motors with two-step, part-winding starting are noisy when initially energized, and during this time they will not accelerate to full speed. For example, a four-pole motor will only accelerate to one-half or two-thirds of rated rpm, depending on the internal connection. When the second step is initiated, however, the motor attains full speed.

A part-winding start motor connected internally for alternate pole (1 to 7) performs more quietly on the first step than a motor connected adjacent pole (1 to 4) internally. The reason is that the alternate pole machine is better balanced magnetically than the adjacent pole machine.

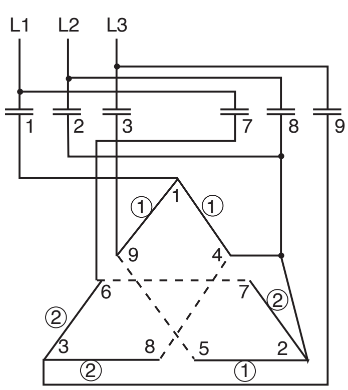
The alternate pole connection will sometimes produce locking torques on the first step, thus preventing the motor from rotating until the second step is energized. Because of this the adjacent pole connection is preferred.

Various arrangements of two- and three-step part-winding starting with 2-, 3-, and 4-pole contactors are shown.

Figure 2-61 shows a two-step starting arrangement for a nine-lead, delta-connected winding with equal current flow in the six contacts.

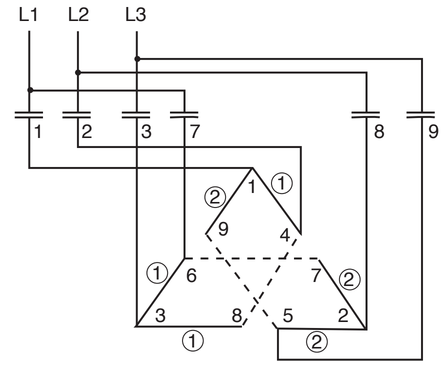
Motor Lead 1 is connected to Terminal 1 on the controller. Motor Leads 2, 4, and 8 are connected to controller Terminals 2 and 8. Motor Leads 5 and 9 are connected to controller Terminal 3. Motor Leads 6 and 7 are connected to controller Terminal 7. Motor Lead 3 is connected to controller Terminal 9. Half the winding is energized on the first step (1), and the other half on the second step (2). In Figure 2-61 through Figure 2-65 the sequence in which the coil groups are energized is indicated by the circled numbers.

FIGURE 2-61



9 lead delta-connected winding
2-step starting (1/2—1/2)
Two 3-pole contactors

FIGURE 2-62

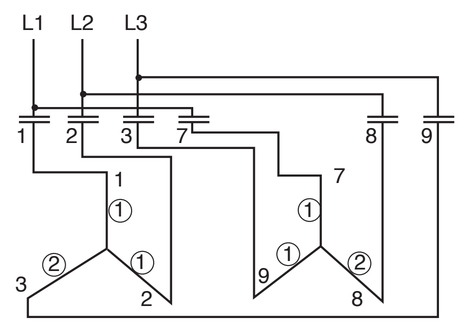


9 lead delta-connected winding
2-step starting (1/2—1/2)
4- and 2-pole contactors

Figure 2-62 shows a four- and two-pole contactor arrangement for a nine-lead delta connected motor. Again, half the winding is energized on the first step (1), and the other half on the second step (2).

This connection gives smooth acceleration with low starting currents and low torque. It is suitable for light loads, such as fans, pumps, and so forth.

FIGURE 2-63

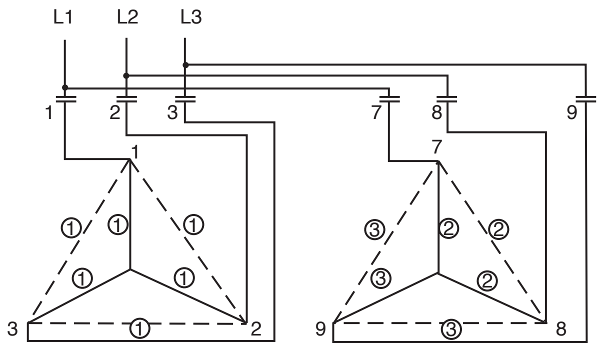


6 lead wye-connected winding
2-step starting (2/3—1/3)
4- and 2-pole contactors

Figure 2-63 shows a four- and two-pole contactor which energizes two-thirds of the wye-connected winding on the first step. The line current on the first step will be unbalanced, averaging approximately 65 percent of full winding starting current and producing about 40 percent locked torque.

Figure 2-64 shows a six-lead, wye connection with three-step starting, which is suitable for large motors with low torque requirements. The first contactor energizes half of the winding. After the second contactor closes, five-sixths of the winding is

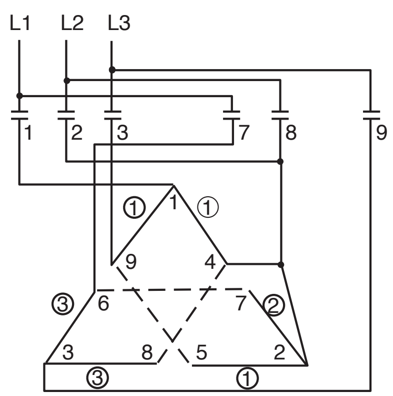
FIGURE 2-64



6 lead wye- or delta-connected winding
3-step starting (1/2—1/3—1/6) wye connected
(1/2—1/6—1/3) delta connected
3-, 2- and 1-pole contactors

energized. Starting current on the first step is about 40 percent; current on the last step is about 30 percent. A six-lead delta connection is shown by the dash lines.

FIGURE 2-65



9 lead delta-connected winding
3-step starting (1/2—1/6—1/3)
3-, 2- and 1-pole contactors

Figure 2-65 shows a nine-lead delta connection with the same three-step starting arrangement as in Figure 2-64. After the second contactor is activated, two-thirds of the winding is energized.

ELECTRONIC SOFT START

Solid-state soft starters are phase-controlled, and basically "turn off" the power for part of each cycle. By varying the conduction angle of the switches, the voltage delivered to the motor can be varied. The conduction angle is increased to raise the voltage. This is an effective way to reduce starting current as long as the voltage delivered is high enough to meet starting torque requirements.

Switching elements are generally rated at least 3 times the line voltage for reasons of reliability. This means a 460 volt motor requires switches rated over 1200 volts. This is accomplished using either an SCR-SCR or SCR-diode method. SCR-diode soft starters are more likely to produce harmonics, but they are considerably less expensive and can therefore still be found in use.

Ramp time is adjustable, allowing the operator to meet the torque and acceleration required by the load. No special winding connection is required, so the soft starter can be used with any three-phase motor.

VARIABLE-FREQUENCY DRIVES

The use of variable-frequency drives (VFD) allows the operator to define the ramp rate and starting torque and even establish the desired speed-torque curve. By keeping the volts-per-hertz ratio constant, the motor can be gently accelerated from standstill to (and even past) full speed. Unlike other methods of soft starting, the VFD also permits the motor to operate at any speed continuously, as long as the ventilation system is capable of removing the heat from the motor. (For more information on the use of VFDs, see "Application Considerations of Pulse-Width Modulated Inverters and AC Induction Motors to a Total System," in Section 5 of this manual.)

TABLE 2-26: STARTING CHARACTERISTICS OF INDUCTION MOTORS IN PERCENT OF FULL-VOLTAGE VALUE

Starting method	Voltage at motor	Line current	Motor torque
Full-voltage value	100	100	100
Autotransformer			
80% tap	80	64*	64
65% tap	65	42*	42
50% tap	50	25*	25
Primary resistor			
Typical rating	80	80	64
Primary reactor			
80% tap	80	80	64
65% tap	65	65	42
50% tap	50	50	25
Series-parallel	100	25	25
Wye-delta	100	33	33
Part-winding (1/2-1/2)			
2 to 12 poles	100	70	50
14 and more poles	100	50	50
Solid-state soft start	Variable	Variable	Variable
Variable-frequency drive	v/Hz adjustable	Variable	Variable

*Autotransformer magnetizing current not included. Magnetizing current is usually less than 25 percent of motor full-load current.

CONCLUSION

When selecting the starting method for a specific motor, consideration must be given to compatibility of motor and starting method, torque requirements, cost of equipment, and so forth. The various starting methods described in this article and summarized below and in Table 2-26 are meant to be a guide for determining the best starting method for your motor.

- Autotransformer starting enables the motor to produce a comparatively high starting torque for a given value of line current.
- Resistor and reactor starting are more economical than the use of an autotransformer, but the starting torque is less for a given value of line current.
- Series-parallel starting produces the least torque of all the methods described and is only suitable for starting light loads.
- Wye-delta starting, which requires a special winding design, is the prevelant starting method in Europe.
- Part-winding starting is widely used to reduce lighting flicker and shaft stress in pumps.
- The electronic soft start reduces starting voltage and torque.
- A variable-frequency drive permits starting torque and acceleration to be controlled.

Secondary resistors for wound-rotor motors

Prepared by the Technical Services Committee

The effect of secondary resistance on wound-rotor motor operation

Wound-rotor motors are used primarily for either speed control or adjustable torques. Either of these are accomplished by means of adjusting the resistance in the rotor circuit, commonly referred to as secondary resistance. This is done through the use of slip rings, a bank of resistors, and a switching device–either manual or automatic.

One of the greatest problems in using this type of motor is in the selection of resistors to use in the secondary to give the desired characteristics. When this is done, the ohmic resistance, as well as the current-carrying capacity, must be considered.

The best way to understand a polyphase slip-ring motor is to first visualize it as a variable-voltage transformer. Once the stator winding is energized, a rotating magnetic field is established that revolves about the inside of the stator at synchronous speed. Counter voltages will therefore be induced in both the rotor and stator windings.

Assuming the rotor as being held stationary, this induced rotor voltage will be directly proportional to the turns ratio of the stator and rotor windings. Under this same condition, the frequency of the rotor voltage will be the same as that of the stator voltage. However, once the rotor is left free to rotate, it will accelerate to a speed just slightly less than the rotating stator field. A proportionally lower voltage at a proportionally lower frequency will then be induced in the rotor because the direction of rotation is the same as that on the magnetic field. Consequently, at half speed, the voltage and frequency of the rotor will both be one-half of what they would be under locked-rotor conditions.

Rotor slip is the variation in speed between synchronous speed and the speed of the rotor. It is expressed as follows:

$$(1)\ \%\ \text{slip} = \frac{(\text{Synchronous rpm} - \text{Running rpm}) \times 100}{\text{Synchronous rpm}}$$

Therefore, at 75% speed, the slip is 25%, the voltage is 25% and the secondary frequency is 25%. Or under a purely hypothetical case, if speed is 100%, or synchronous speed, then slip is zero, voltage is zero, and frequency is zero. It is therefore apparent that every induction motor must operate with some slip.

Torque is produced in an induction motor by the in-phase current flow in the secondary winding reacting on the stator rotating magnetic field. In-phase current is that portion of the total current in phase with the voltage. To get this current flow, however, there must be sufficient voltage induced to overcome the impedance of the circuit. This can be verified by:

$$(2)\ I_2 = \frac{V}{Z_t}$$

Where:

I_2 = Rotor current in amperes per phase
V = Secondary voltage per phase
Z_t = Total impedance per phase
$= \sqrt{R^2 + X^2}$
R = Internal and external resistance per phase
X = Reactance per phase

You can see that either an increase in voltage or decrease in resistance will cause higher current to flow. If the resistance is greater than the reactance, the in-phase current will also increase and more torque will be produced. If this greater torque is not required by the load, the motor will speed up. The increased speed will cause the slip to decrease and, therefore, the voltage is also decreased. This will cause the current to be reduced. The slip, current, and voltage finally reach a balance point for a given load.

Maximum speed of a wound-rotor motor is obtained when all external resistance is removed from the secondary and the slip rings are shorted out. Any insertion of resistance in the secondary circuit or any application of load to the motor shaft will cause a corresponding reduction in motor speed. The more resistance there is in the secondary circuit the greater the speed change will be for a given change in load.

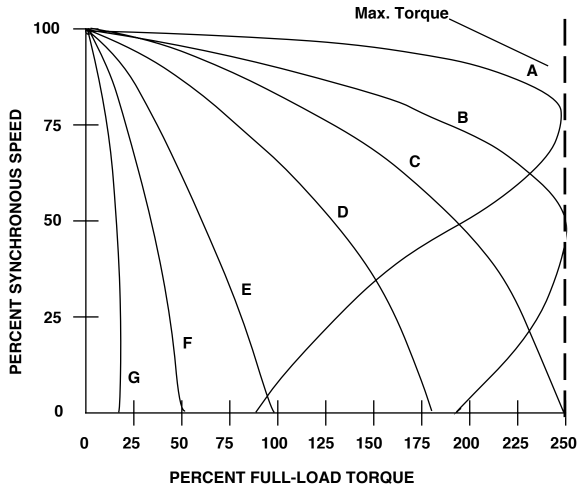
One of the outstanding features of a wound-rotor motor is its ability to limit the line currents drawn upon starting. Imagine for a moment a locked-rotor condition with the motor energized, the load connected, and a very high resistance in the rotor circuit. The voltage would therefore be at maximum, but the current would be quite low, as you can see from the equation $I = E/R$. The current flow in the stator would also be low because the rotor currents are reflected into the stator circuit by transformer action. As the rotor resistance gradually is reduced, the current is increased. The increased current causes increased torque, until maximum torque is reached, which eventually starts turning the load. The speed may be increased further by removing additional resistance from the secondary circuit.

Maximum torque with the rotor locked occurs when the resistance of the rotor circuit equals the reactance. Further reduction in resistance decreases the locked torque, but the line current continues to increase because the impedance continues to decrease. As the resistance decreases, the reactance becomes more effective. This reduces the power factor. When the power factor decreases at a faster rate than the impedance, the in-phase current decreases and less torque is produced.

Now let us illustrate through the use of curves how a wound-rotor motor functions.

In Figure 2-66 Curve G shows an infinitely high rotor

FIGURE 2-66



resistance which produces practically zero torque. On the other hand, Curve A shows no external resistance, so maximum speed for a given load will be obtained. Starting the motor with different resistance values will give the family of torque curves shown in Figure 2-66. Reducing the resistance with respect to Curve G causes increased locked-rotor torque up to Curve C. Further reduction of resistance causes decreased locked-rotor torques; however, maximum torque remains the same but occurs at a higher speed.

Where rotor resistance is high compared with reactance, rotor currents are directly proportional to torque; therefore, current will vary in a manner similar to the torque for Curves D, E, F and G in Figure 2-66. Reactance equals resistance for Curve C and becomes larger than the resistance for Curves A and B. The current will therefore continue to rise while the torque decreases.

It is also important to remember that the rotor current is reflected into the stator winding, which means that any reduction in secondary current will also reduce primary starting current.

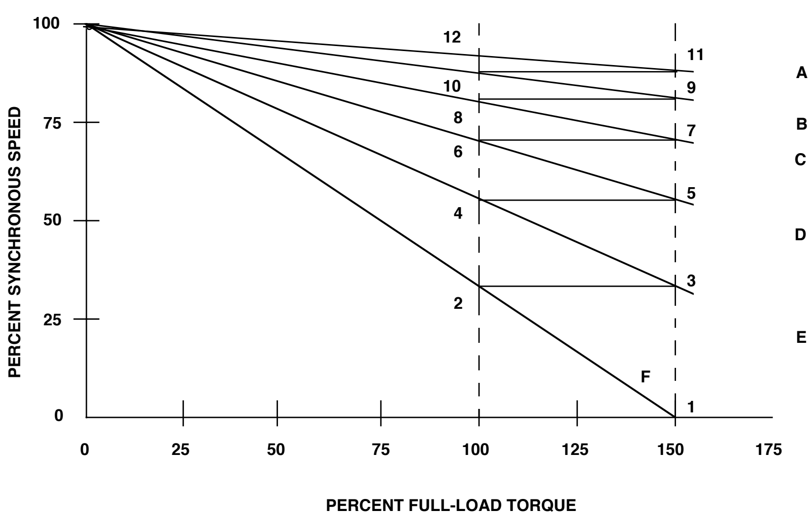
A generally accepted rule for limits of speed reduction can be very easily illustrated in Figure 2-66. Notice the difference in steepness between Curve A and Curve E. You can see that a given change in the load torque will cause wide variations of speed on Curve E, as compared with Curve A. Therefore, wound-rotor motors are not normally used for continuous duty service at speeds less than 1/2 rated synchronous speed.

Starting a wound-rotor motor with the slip rings shorted has the disadvantages of causing undue mechanical stress on the motor windings and possible line disturbances. Besides this, it defeats one of the main purposes of using a slip-ring motor. Proper starting through the use of variable resistance is illustrated in Figure 2-67.

Assume that a slip ring motor has an external resistance connected in the secondary circuit, the value of which will give a characteristic shown by Curve F of Figure 2-67. This curve indicates that the motor will have 150% starting torque. Should this motor be started under full load (100% torque) it will therefore accelerate to Point 2 of Curve F. The motor will operate at that reduced speed so long as the load or resistance are not changed. However, if the secondary resistance is decreased by one step, so that it now operates on the characteristic curve shown by E, then the torque and current immediately change to Point 3 at the instant the resistance change takes place. Point 3 will now develop more torque than is required by the load so the motor then accelerates to Point 4. This resistance change and acceleration continues until the full-load speed reaches Point 12, with all secondary resistance shorted out. The greater the number of steps, the smoother the acceleration and the lower the line surge currents.

The curves in Figure 2-67 are shown as straight lines for ease of calculation. This will introduce some error but for practical purposes should be satisfactory. If an application is very critical, you must use the actual characteristic curves of the specific motor.

FIGURE 2-67



Secondary resistor selection for wound-rotor motors

Wound rotor motors, as opposed to AC induction motors, generate the same torque in both forward and reverse. They are commonly used on fans, pumps, conveyors and crane systems. The motors are rated according to their primary and secondary windings. The primary ratings are given in volts and power (kilowatts), while the secondary ratings are specified in terms of voltage and current (the secondary current is defined by the locked rotor output, verified during testing of the motor).

RESISTANCE CALCULATION

To calculate the total resistance per phase, the following information is required:

1. Secondary voltage
2. Secondary current
3. The number of speeds/steps required for the application. The number of steps is the actual number of resistor stages to be switched through, whereas the number of speeds is the number of steps plus one (the "extra" speed being no resistors at all in the circuit).
4. Duty class, according to NEMA.
5. Starting torque (which can also be specified as the last digit of the classification number).

FORMULA FOR TOTAL RESISTANCE

$$R_{tot} = \frac{\text{Secondary voltage}}{(\text{Secondary current x 1.713 x \% Starting torque})}$$

The total resistance is then divided into the requisite number of steps. The size is not uniform to allow for smooth transitions of motor speed as the load's inertia changes. The most common breakdowns are given below, with the first step being that closest to the secondary AC power source and then moving progressively toward the motor.

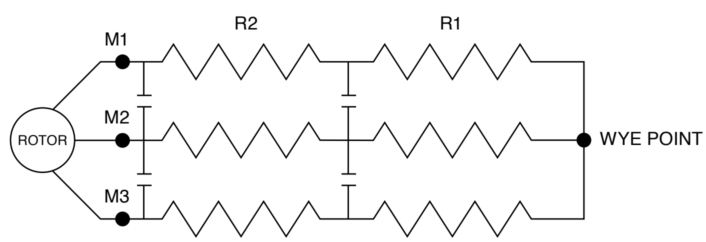
The amperage associated with each step is determined by the amount of current seen by the individual steps, as dictated by how long they are left in the circuit and by the duty class of the motor. These values listed below are percentages of the rated secondary current. As a general rule, pumps, fans and conveyor systems are Class 130, while crane systems can be Class 160, 170 or 190.

One note concerning the secondary current: if the starting torque is greater than 100%, remember to also use this factor in sizing the individual resistor steps. For example, if the starting torque is 150% of nominal, the amperage used for designing the resistor sizes will be 1.5 times the rated secondary current of the motor.

Table 2-27 is for selecting the NEMA class for an application in relation to starting torque and duty cycle. Table 2-28 shows applicable NEMA standards for various applications.

Note: Information and graphics for secondary resistor selection provided by Post Glover, Erlanger, KY.

FIGURE 2-68



2 STEP / 3 SPEED

TABLE 2-27: NEMA CLASSIFICATION OF RESISTORS

Approximate percent of full-load current on first point starting @ rest	Class numbers applying to duty cycles							
	30 sec. on out of each 15 min.	5 sec. on out of each 80 sec.	10 sec. on out of each 80 sec.	15 sec. on out of each 90 sec.	15 sec. on out of each 60 sec.	15 sec. on out of each 45 sec.	15 sec. on out of each 30 sec.	Continuous duty
25	101	111	131	141	151	161	171	91
50	102	112	132	142	152	162	172	92
70	103	113	133	143	153	163	173	93
100	104	114	134	144	154	164	174	94
150	105	115	135	145	155	165	175	95
200 or over	106	116	136	146	156	166	176	96

TABLE 2-28: NEMA RESISTOR APPLICATION STANDARDS

APPLICATION	NEMA CLASS
Blowers	
Centrifugal	133-93
Constant pressure	135-95
Brick plants	
Augers, conveyors, dry plans, pug mills	135
By-product coke plants	
Door machine, leveler ram, pusher bar, valve reversing machines	153
Cement mills	
Conveyors	135
Crushers	145
Elevators	135
Rotary dryers	145-95
Grinders and pulverizers	135
Kilns	135-95
Coal and ore bridges	
Bridge	153
Closing, holding	162
Trolley	162 or 163
Coal mines	
Car hauls	162
Conveyors	135 or 155
Cutters	135
Crushers	145
Fans	134 or 95
Hoists	
Slope	172
Vertical	162
Jigs, picking tables	135
Rotary car dumpers	153
Shaker screens	135
Compressors	
Constant speed	135
Varying speed	
Centrifugal	93
Plunger type	95
Concrete mixers	135
Cranes–general purpose	
Hoist	153-163
Bridge or trolley with	
Sleeve bearings	153-163
Roller bearings	152-162
Flour mills	
Line shafting	135
Food plants	
Butter churns, dough mixer	135
Hoists	
Winch	153
Mine slope	172
Mine vertical	162
Contractor's hoists	152
Larry cars	153
Lift bridges	152
Machine tools	
Bending rolls	163 or 164
Boring mills	135
Bulldozers	135
Drills, gear cutters	115
Grinders	135
Hobbing machines, lathes	115
Milling machines	
Presses, punches	135
Saws, shapers	115
Metal mining	
Ball, rod and tube mills	135
Car dumpers–rotary	153
Converters–copper	154
Crushers	145
Conveyors	135
Tilting furnace	153
Paper mills	
Beaters	135
Calenders	154-92
Chippers	145
Pipeworking	
Cutting and threading	135
Expanding and flanging	135-95
Power plants	
Clinker grinders	135
Coal crushers	135
Conveyors	
Belt, screw	135
Pulverized fuel feeders	135
Pulverizers	
Ball type	135
Centrifugal	134
Stokers	135-93
Pumps	
Centrifugal	134-93
Plunger	135-95
Rubber mills	
Banbury, crackers	135
Calenders	155
Mixing mills, washers	135
Steel mills	
Accummulators	153
Casting machines–pig	153
Charging machines	
Bridge	153 or 163
Peel	153 or 163
Trolley	153 or 163
Coiling machines	135
Converters–metal	154
Conveyors	135-155
Crushers	145
Furnace door, gas valves	155
Gas washers	
Hot metal mixers	163
Ingot buggy, kickoff	153
Levelers	
Manipulator fingers	153 or 163
Pickling machine	153
Pilars–slab, racks	
Reelers	135
Saws–hot or cold	155
Screw downs	153 or 163
Shears, shuffle bars	155
Side guards	153 or 163
Sizing rolls, slab buggy,	155
Soaking pit covers	
Straighteners	153
Tables	
Approach	153
Lift	153 or 163
Main roll	153 or 163
Roll	153
Shear approach	153 or 163
Transfer	153
Tilting furnace	153
Wire stranding machine	153
Woodworking plants	
Boring machines, lathe, mortiser, moulder, planers, power trimmer and mitre, sanders, saws, shapers, shingle machine	115

2.12 NON-STANDARD WINDING CONNECTIONS

Interspersed windings: What are they?

By Chuck Yung, EASA Senior Technical Support Specialist

INTRODUCTION

Interspersed windings have been in use for many years, primarily on 2-pole machines. Sometimes called "cyclic shift" windings, they were used by only a handful of motor manufacturers (only one still does), so information about them was closely held.

While interspersed windings are not new, they are rare enough that many winders lack a clear understanding of their purpose or overlook the interspersion when taking data. That can lead to problems. Failure to duplicate an interspersed connection, for example, can result in a motor that cannot accelerate its load. With a large motor, the effect may be so severe that it cannot even accelerate to speed uncoupled.

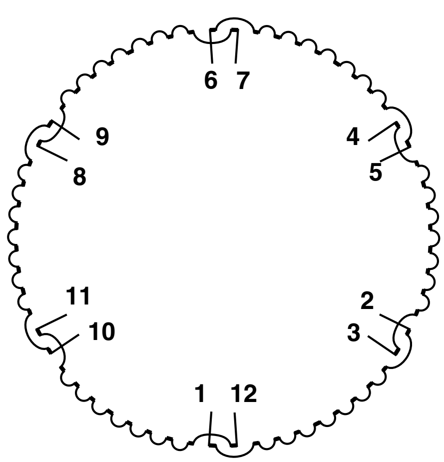
This paper explains what interspersed windings are and how they work. Its purpose is to help repair technicians correctly identify and properly repair machines having these unusual windings. "Diagrams for Interspersed Connections" on Page 2-158 includes templates and connection diagrams.

BACKGROUND

What they are. The interspersed winding gets its name from the way the coils of adjacent groups intermingle. Lay your hands palm-down and overlap your thumbs. That is how the first and last coils of each pole group look in a single-interspersed winding (see Figure 2-69).

What they do. Interspersed windings help solve a significant design problem associated with 2-pole machines. They make it possible to manipulate other design variables (e.g., chord factor and distribution factor) in ways that reduce the adverse effects of harmonic waveforms on the performance of these machines.

FIGURE 2-69



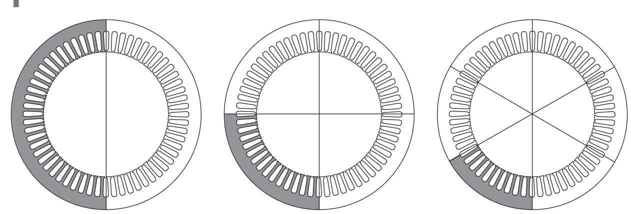
Example of 2-pole interspersed winding—60 slots.

To understand how interspersed windings work, it helps to review the design variables that they can affect.

Poles, frequency and speed. The speed of an AC machine is determined by the number of magnetic poles it has and the frequency of supplied power. At 60 Hz, for example, 7200 cycle reverses occur per minute, so the magnetic field of a 2-pole machine rotates at 3600 rpm (7200/2 = 3600 rpm). Similarly, 4-pole machines have a synchronous speed of 1800 rpm (7200/4 = 1800); and 6-pole machines run at 1200 rpm (7200/6 = 1200).

Coil pitch. Coil pitch describes the number of stator slots that a coil (or a pole group) spans in a given winding. The shaded areas shown in Figure 2-70, for example, represent the full coil pitch for 2-, 4- and 6-pole windings.

FIGURE 2-70



To find the full coil pitch for a given winding, multiply (1/poles) times the number of stator slots. A 60-slot motor with a 6-pole winding, for instance, would have a full pitch of 10 teeth:

(1/6) x 60 = 10 Teeth (coil sides lie in Slots 1 and 11)

The same 60-slot motor with a 4-pole winding would have a full pitch of 15, with coil sides in Slots 1 and 16. A 2-pole winding, on the other hand, would have full pitch of 30—i.e., halfway around the stator—with the coil sides in Slots 1 and 31. Winding this could be impossible.

Effective turns per coil. The strength of a winding is determined by the effective turns of each coil. Effective turns, which depend on the coil pitch and the grouping arrangement, equal actual turns only when a full-pitch winding is used. The narrower the coil pitch, the less effective each turn becomes. For a full-pitch winding, the chord factor (K_c, sometimes referred to as K_p) equals 1.

Chord factor. Chord factor is the ratio of the effective turns of a coil to the actual turns. In other words, effective turns equal actual turns times chord factor.

Chord factor (K_c) depends on the relationship of the total slots, poles and coil pitch. The narrower the coil pitch, the lower the chord factor and the less effective each turn becomes. This relationship is described by the formula:

$$\text{Chord factor} = \text{Sin}\left(90 \times \left(\frac{\text{Teeth spanned}}{\text{Slots per pole}}\right)\right)$$

For a 60-slot, 2-pole motor with a 1 - 20 pitch:

Teeth spanned = 19

$$\text{Chord factor} = \text{Sin}\left(90 \times \left(\frac{19}{30}\right)\right)$$

Sin 57° = 0.839

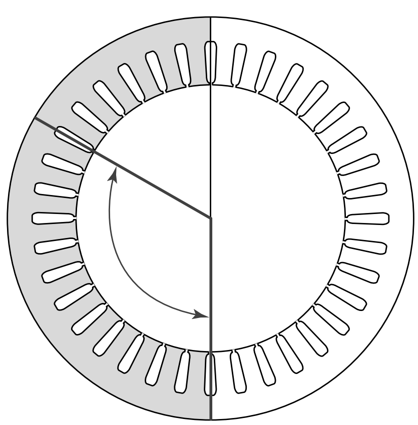
The chord factor remains constant unless the coil pitch is changed.

In the optimum electric motor, a coil spanned to a chord factor (K_c) of 0.966 best eliminates the harmonics that distort the normal AC sine wave. This exact pitch is not possible with all slot/pole combinations, so motors with 4 or more poles are usually pitched to a chord factor between .900 and .996.

The 2-pole motor is an exception. Using a 60-slot motor as an example, the desired pitch for a full-strength winding would be between 1 - 27 and 1 - 29. But in that case a cross-section of the coil extension would contain 28 to 30 coils–the sheer bulk of which could make the motor impossible to wind.

To overcome this, most lap-wound 2-pole machines have shorter (narrower) coil pitches, resulting in chord factors between 0.707 and 0.866 (Figure 2-71). These chord factors fall outside of the desirable range (0.900 to 0.966), so the turns are less effective. Harmonics may also pose problems.

FIGURE 2-71

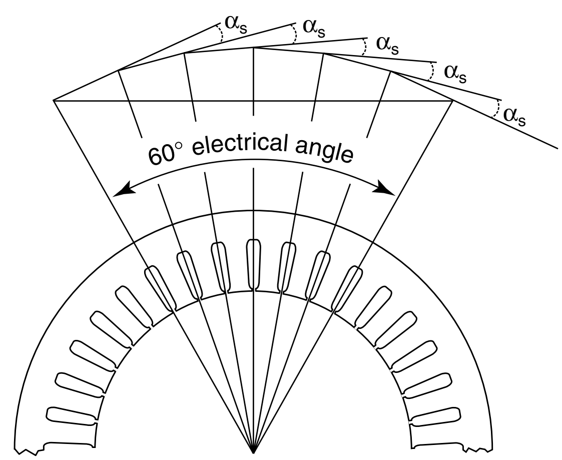


Full pitch for a 2-pole winding would be halfway around the stator bore. For practical reasons, the coil pitch normally used is approximately as shown.

Distribution factor. The distribution factor (K_d) is a mathematical description of the way in which the pole groups and coils are distributed around the stator. It is derived by dividing the sum of the cosines of the electrical angles for each coil in a pole group by the number of coils per group. Consequently, it can be altered by changing the placement of the coils within each group. The interspersed connection offers a way to accomplish this.

$$K_d = \frac{\text{Sum of cosines}}{\text{Coils per group}}$$

FIGURE 2-72



As Figure 2-72 shows, the electrical angle from the center of a group to the center of each coil within that group increases according to the placement of each coil of the group.

With an interspersed winding, an additional factor comes into play: placement of the interspersed coils of the pole group in slots not immediately adjacent to the rest of the group. This "jump slot" interspersion (represented by your thumbs in the earlier example) means the electrical angle from the center of the pole group to each of the interspersed coils is greater than that of the corresponding coil in a standard winding.

Because the distribution factor is derived from the cosines of these angles, it will change if the layout of the interspersed coils changes. Figure 2-73 compares the cosine angles and resulting distribution factors for a 36-slot motor with standard grouping with those of single- and double-interspersed schemes. (See "Diagrams for Interspersed Connections" on Page 2-158 for comparison of other slot numbers.)

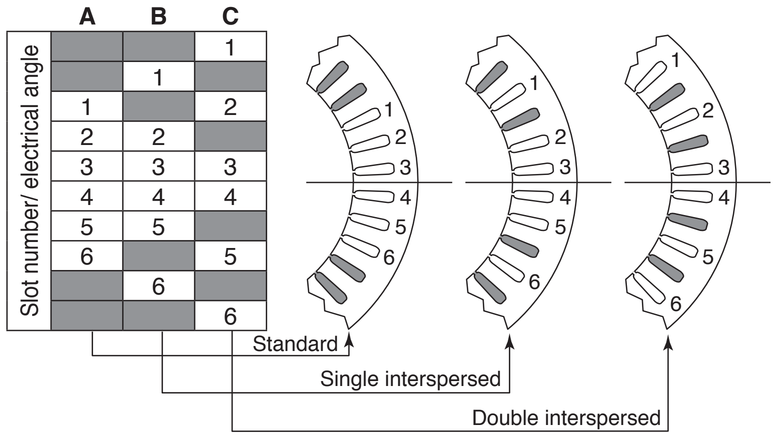
The distribution factor is lower for the interspersed schemes, so each turn is less effective. Consequently, more actual turns are needed for an interspersed winding than for a standard winding.

FIGURE 2-73

EXAMPLE OF THE DISTRIBUTION FACTOR FOR A 36-SLOT MOTOR

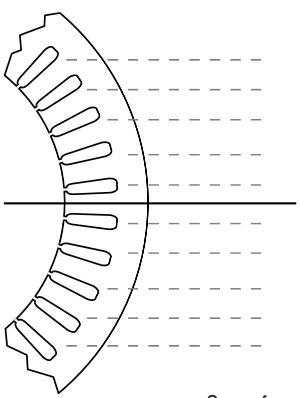
KEY

- Column A shows the coil placement for a standard lap winding.
- Column B shows the coil placement for a group, single-interspersed winding.
- Column C shows the coil placement for a double-interspersed winding.
- Shaded cells indicate slots not occupied by coils of this group. The values in the remaining cells are the cosine of the electrical angle for that coil side.
- To calculate the distribution factor for various harmonics, multiply the ratio of the harmonic times the angle for each coil.



$$\text{The distribution factor } (K_d) \text{ for the coil group} = \frac{\text{Sum of the cosines of the group of coils}}{\text{Coils per group}}$$

36 SLOTS—6 COILS PER GROUP



	Fundamental				5th harmonic				7th harmonic		
45			0.707	225			-0.707	315			0.707
35		0.819		175		-0.966		245		-0.423	
25	0.909		0.909	125	-0.574		-0.574	175	-0.996		-0.996
15	0.966	0.966		75	0.259	0.259		105	-0.259	-0.259	
5	0.996	0.996	0.996	25	0.906	0.906	0.906	35	0.819	0.819	0.819
5	0.996	0.996	0.996	25	0.906	0.906	0.906	35	0.819	0.819	0.819
15	0.966	0.966		75	0.259	0.259		105	-0.259	-0.259	
25	0.909		0.909	125	-0.574		-0.574	175	-0.996		-0.996
35		0.819		175		-0.996		245		-0.423	
45			0.773	225			-0.707	315			0.707
Sum of cosines	5.736	5.562	5.218		1.182	0.388	0.750		0.872	0.274	1.060
Distribution factor	0.956	0.927	0.870		0.197	0.056	0.125		0.145	0.046	0.177

$$\text{Actual turns} = \frac{\text{Effective turns}}{(K_d \times K_c)}$$

Although the chord factor for a 2-pole motor may be as low as 0.707, the slightly lower distribution factor requires only a small increase in turns per coil. At the same time, the dramatic reduction in the 5th and 7th harmonics means that the intersperse can significantly improve motor performance.

HARMONICS

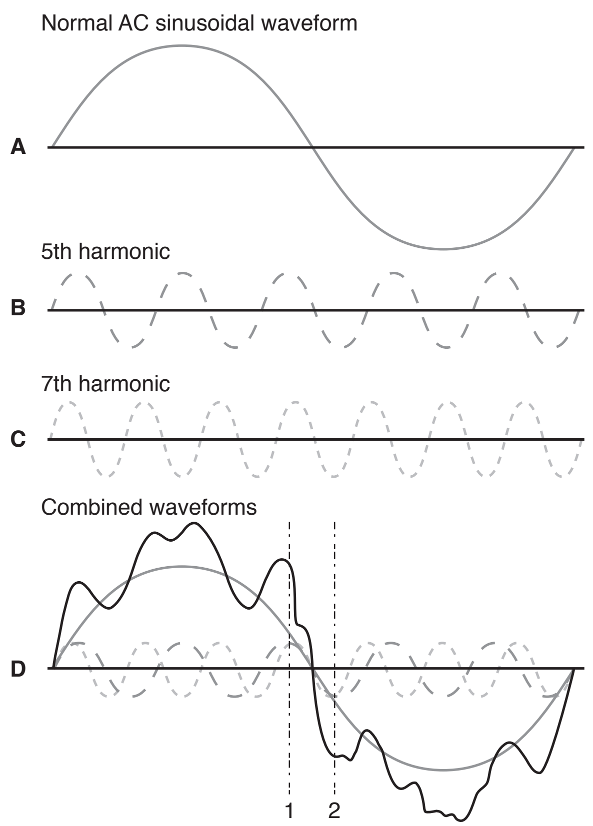
Harmonics are multiples of the fundamental (or line) electrical frequency. In the case of 60 Hz power, for example, the fundamental frequency completes 60 cycles per second, producing the normal AC sinusoidal waveform (see Figure 2-74 A).

If harmonic frequencies were present, they would simultaneously (though independently) complete their own cycles, each with its own waveform. The 5th harmonic, for instance, would complete 300 cycles per second, while the 7th harmonic would cycle 420 times (see Figure 2-74 B and Figure 2-74 C). Other harmonics exist as well, but the 5th and 7th impact the operation of three-phase electric motors the most.

The effect of each unique harmonic depends on its magnitude and on the shape of the resulting waveform when it combines with the fundamental waveform.

As Figure 2-74 D shows, the 5th and 7th harmonics affect the fundamental frequency most when the sum total is at the greatest deviation from zero (near points 1 and 2). That is because the different waveform values are additive at each

FIGURE 2-74



point in time (represented by the horizontal axis). The dark line shows how the combined effects of the 5th and 7th harmonics distort the fundamental AC sinusoidal waveform.

HOW DO HARMONICS AFFECT THE OPERATION OF A MOTOR?

Negative torque. One problem introduced by harmonics is that alternate odd harmonics (except for multiples of 3) "buck" the line frequency waveform, producing a negative torque when rotor speed is above the synchronous speed for that harmonic. These negative-sequence harmonics (including the 5th, 11th and 17th) try to rotate the induction motor in the opposite direction (see Table 2-29). The negative torque has a subtractive effect on output torque.

TABLE 2-29: HARMONIC FREQUENCIES AND THEIR RESPECTIVE SEQUENCES (+ OR -)

Harmonic	1	3	5	7	9	11	13	15	17
Sequence	+	0	-	+	0	-	+	0	-
Frequency	60	180	300	420	540	660	780	900	1020

Eddy current losses. Another concern with harmonics has to do with eddy current losses. Since they are a function of the square of the frequency, eddy current losses associated with the 5th harmonic on 60 Hz power theoretically could be 25 times those of the fundamental frequency, while those for the 7th harmonic could be 49 times as great. (This would only be true if the magnitudes of the fundamental and harmonic frequencies were the same.) Fortunately, the magnitude of harmonics is determined by this equation:

$$\frac{1}{n} \times K_p \times K_d \times \text{Fundamental frequency}$$

Where:

n = Harmonic order
K_c = Coil pitch
K_d = Distribution factor for the harmonic

On motors with 4 or more poles, spanning a winding to a chord factor of 0.900 to 0.996 minimizes the effects of negative torque and eddy current losses due to 5th and 7th harmonics. The smaller span needed for lap-wound 2-pole, however, may permit harmonics of sufficient magnitude to reduce net torque drastically. One solution is to strengthen the design enough to overcome the negative torque, so that net torque is sufficient to meet demand.

WHAT THE INTERSPERSE DOES

The interspersed connection changes the distribution factor of each pole group. It also affects each frequency differently– i.e., the line frequency and the various harmonic frequencies. Variables include the number of coils per group, the number of stator slots, coil pitch and the interspersion scheme used (single or double). By selecting the interspersion scheme that best reduces the effects of disruptive harmonics, it is possible to improve motor performance.

HOW INTERSPERSION HELPS

The line frequency distribution factor for each interspersed scheme is slightly lower than that of the standard grouping, but for the 5th and 7th harmonics it is dramatically lower. A slight decrease in the effective turns is more than offset by the reduction in harmonic distortion.

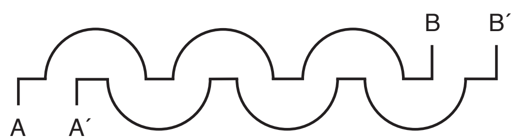
Note also that the benefits of the interspersion depend on the number of coils per pole group, or (since these are unique to 2-poles) the number of stator slots. For groups of 6 coils (36 slots), the single interspersion yields a lower distribution factor for both the 5th and 7th harmonics. With a 54-slot winding (9 coils/group), the benefit of the double-interspersed scheme is considerably greater than that of the single-interspersed (see "Coil Placement and Distribution Factors for Interspersed Connections" on Page 2-162).

Other considerations include copper savings resulting from the narrower coil pitch. For a manufacturer producing thousands of 2-pole machines annually, the savings may be significant. Offsetting this is the additional complexity of the connection. With a random-wound stator, the additional connection time may offset the savings on materials.

INTERLEAVED COILS

An unusual aspect of some interspersed windings is interleaved coils. With this design, each pole group is divided to form two parallel paths. The two parallel paths within each group allow use of a 4-circuit connection on a 2-pole motor. The electrical angle of each coil in the group–and therefore the distribution factor of the group–does not change. Interleaving the coils is a means of doubling the circuits. When a random-wound motor has the interleaved connection shown in Figure 2-75, it is best to wind the coils individually and essential to duplicate the connection exactly.

FIGURE 2-75

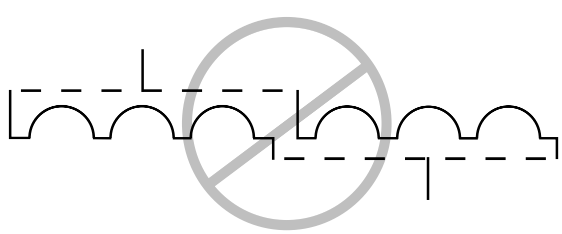


Correct method of interleaving and interspersing coils.

Method of interleaving and interspersing coils. Looping individual coils is usually the best way to accomplish this, although it is possible to extend the crossovers when looping the coils in order to save labor (see Figure 2-75).

When rewinding a motor that has a large number of parallel wires and very few turns, it may help to double the number of circuits. To use twice the normal maximum circuits, the interleave method shown in Figure 2-75 must be used. Attempting to simplify this by splitting the group in two and paralleling them results in the two halves being out of phase by 32.36° (see Figure 2-76). This would produce harmful circulating currents.

FIGURE 2-76



Incorrect method of interleaving and interspersing coils.

CONCLUSION

The role of the interspersed connection is to reduce distortion of the sinusoidal waveform of 2-pole machines. Electric motors originally designed with an interspersed connection should have the intersperse duplicated when repairs include a stator rewind. A motor designed with an intersperse will lose a significant amount of torque if the intersperse connection is ignored. The intersperse also offers a means of improving the efficiency of a 2-pole motor, by reducing the counter-torque that results from the use of less effective coil pitches necessary for 2-pole windings.

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Richard Nailen, "The Meaning of Distribution Factor," *Electrical Apparatus*, Aug. 1988.

Ray Waggoner, "Six-Pulse Conversion and Harmonics," *Electrical Construction & Maintenance*, Dec. 1993 and Jan. 1994.

Note: This article was originally published as *EASA Tech Note 37* (December 2000); it was reviewed and updated as necessary in August 2016.

TIME-SAVING METHOD FOR MAKING COILS FOR AN INTERSPERSED WINDING

When making coils for an interspersed winding, instead of looping individual coils, try this time-saving idea.

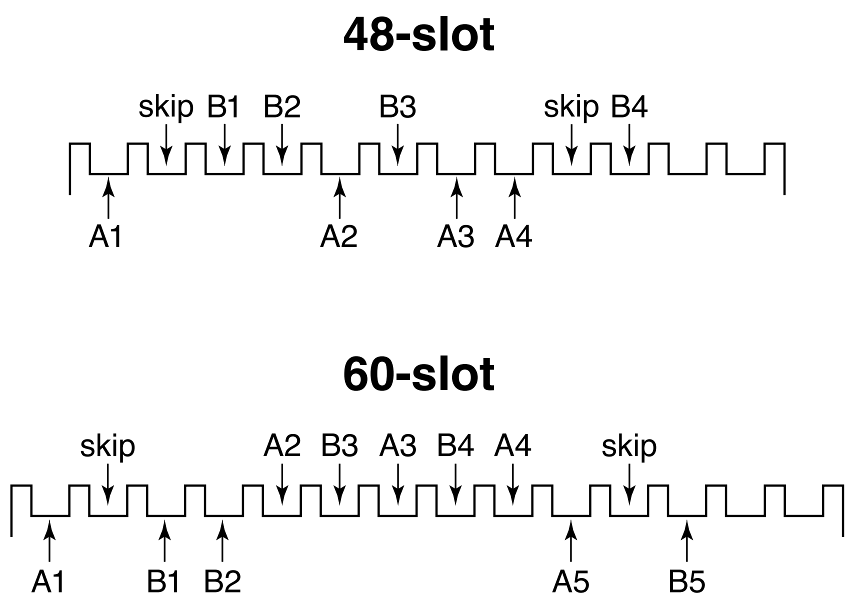
Visualize the coil positions for each sub-group on the coil machine head, and then loop the first sub-group in the correct slot positions on the coil head (in Figure 2-77 and Figure 2-78, those are A1-A2-A3-A4), skipping the spaces reserved for the other half of the "interleaved" sub-group. Tie off the completed sub-group but leave it in place.

Next, loop the second sub-group in the correct positions (B1-B2-B3-B4).

Tie the coils as usual, then remove the entire group from the coil head and insert it into the stator just as you would a conventional winding.

Note: To manage the higher voltage stresses of an interleaved and interspersed winding, use sleeving or tape to insulate the cross-overs within the group.

FIGURE 2-77



Time-saving method for making coils for an interspersed winding.

FIGURE 2-78

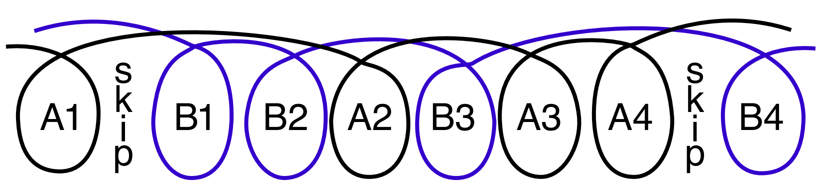


Illustration of 48-slot coil sub-group result.

DIAGRAMS FOR INTERSPERSED CONNECTIONS

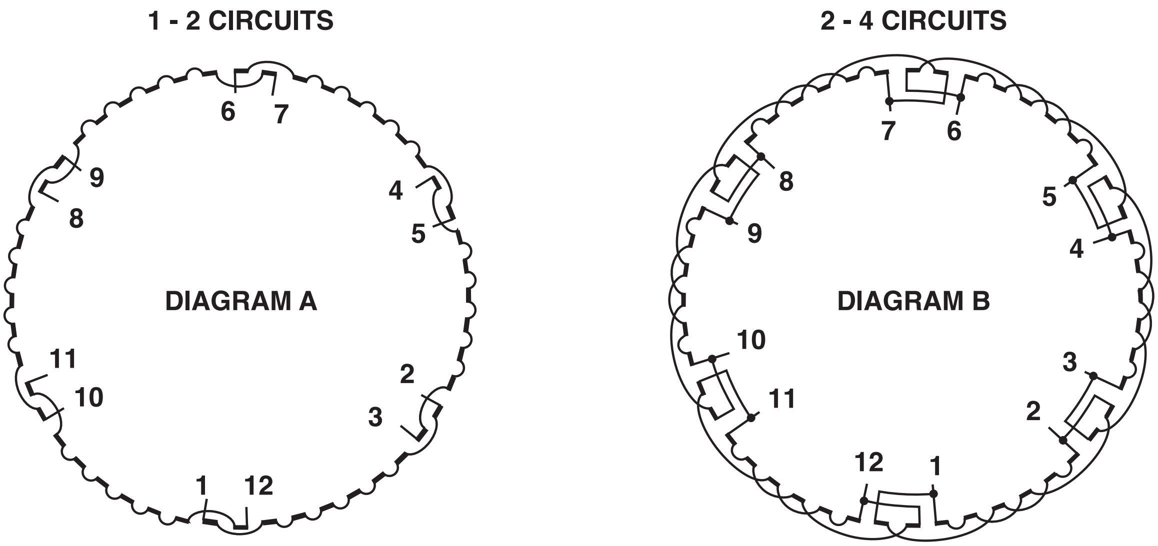
Diagrams showing the interconnections of the coils and the numbering of the coil ends of the pole-phase groups are shown in Figure 2-79 and Figure 2-80.

Diagrams marked A are for windings having one or two winding circuits.

Diagrams marked B are for windings having the coils of each pole-phase group connected in two parallel circuits, permitting the winding to be connected two or four circuits.

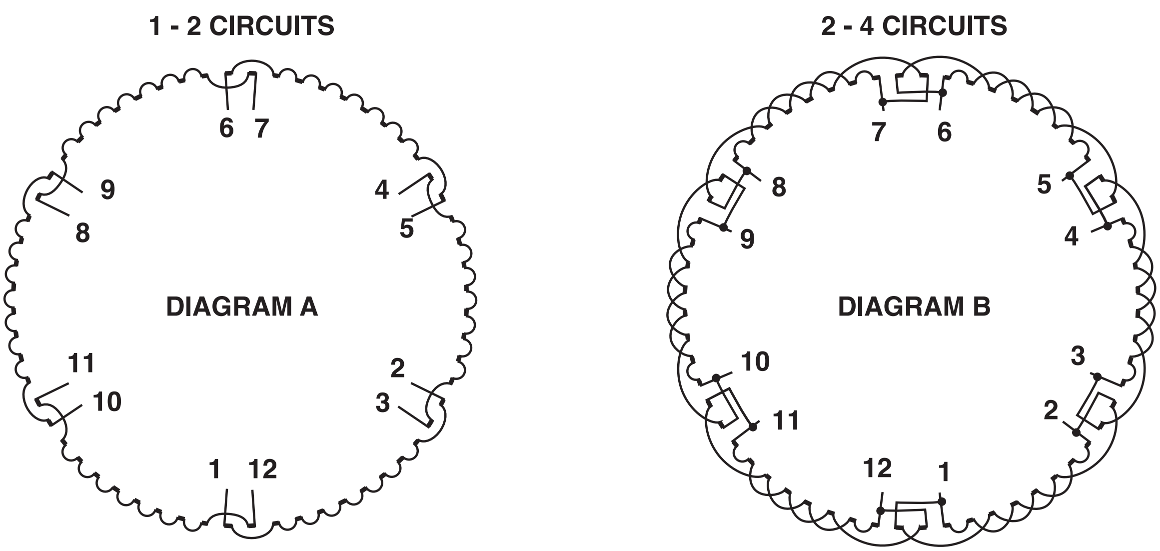
Pole and lead connections for these diagrams are shown in Table 2-30 to Table 2-34. The tables indicate connections common to both types of windings with identical terminal connections but with a different number of winding circuits. The number of circuits for both Diagram A and Diagram B is indicated in each table.

FIGURE 2-79



Numbering system for 2-pole interspersed windings—48 slots.

FIGURE 2-80



Numbering system for 2-pole interspersed windings—60 slots.

Note: For 2-pole, 4-circuit connections see Section 11 of EASA's *Internal Connection Diagrams*.

TABLE 2-30: 2 POLE—WYE CONNECTED

Diagram A	Lead number	Group end number	Pole connection	Diagram B
1 circuit	1 2 3 Neutral	1 4 5 7, 10, 11	2-8, 3-9, 6-12	2 circuits
2 circuits	1 2 3 Neutral	1, 8 4, 9 5, 12 2, 3, 6, 7, 10, 11		4 circuits
1 & 2 circuits	1 4 5 2 3 6 7 8 9 Neutral	1 2 3 4 5 6 8 9 12 7, 10, 11		2 & 4 ciruits

TABLE 2-31: 2 POLE—DELTA CONNECTED

Diagram A	Lead number	Group end number	Pole connection	Diagram B
1 circuit	1 2 3	1, 11 4, 7 5, 10	2-8, 3-9, 6-12	2 circuits
2 circuits	1 2 3	1, 6, 8, 11 2, 4, 7, 9 3, 5, 10, 12		4 circuits
1 & 2 circuits	1 4 5 2 3 6 7 8 9	1, 11 2 3 4, 7 5, 10 6 8 9 12		2 & 4 circuits

Note: For 2-pole, 4-circuit connections see Section 11 of EASA's *Internal Connection Diagrams*.

TABLE 2-32: 2 POLE—PART WINDING, WYE CONNECTED

Diagram A	Lead number	Group end number	Diagram B
2 circuits	1 2 3 7 8 9 Neutral	1 4 5 8 9 12 2, 3, 6 / 7, 10, 11	4 circuits
1 & 2 circuits	1 4 5 2 3 6 7 8 9 Neutral	1 2 3 4 5 6 8 9 12 7, 10, 11	2 & 4 circuits

TABLE 2-33: 2 POLE—PART WINDING, DELTA CONNECTED

Diagram A	Lead number	Group end number	Diagram B
2 circuits	1 2 3 8 7 9	1, 6 2, 4 3, 5 7, 9 8, 11 10, 12	4 circuits
1 & 2 circuits	1 4 5 2 3 6 7 8 9	1, 11 2 3 4, 7 5, 10 6 8 9 12	2 & 4 circuits

Note: For 2-pole, 4-circuit connections see Section 11 of EASA's *Internal Connection Diagrams*.

TABLE 2-34: 2 POLE—WYE-DELTA CONNECTED

Diagram A	Lead number	Group end number	Pole connections	Diagram B
1 circuit	1 2 3 4 5 6	1 4 5 7 10 11	2-8, 3-9, 6-12	2 circuits
2 circuits	1 4 5 2 3 6	1, 8 2, 7 3, 10 4, 9 5, 12 6, 11		4 circuits
1 & 2 circuits	1 4 5 2 3 6 10 7 8 11 12 9	1 2 3 4 5 6 7 8 9 10 11 12		2 & 4 circuits

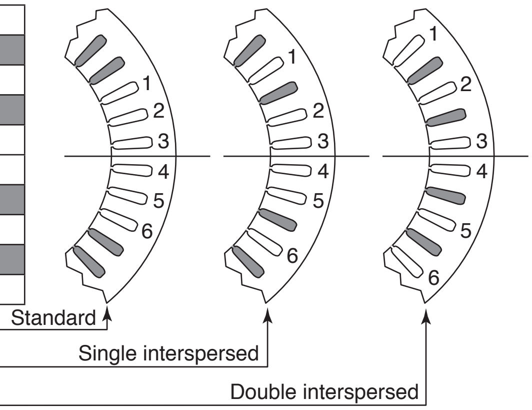
COIL PLACEMENT AND DISTRIBUTION FACTOR FOR INTERSPERSED CONNECTIONS

KEY

- Column A shows the coil placement for a standard lap winding.
- Column B shows the coil placement for a group, single-interspersed winding.
- Column C shows the coil placement for a double-interspersed winding.
- Shaded cells indicate slots not occupied by coils of this group. The values in the remaining cells are the cosine of the electrical angle for that coil side.
- To calculate the distribution factor for various harmonics, multiply the ratio of the harmonic times the angle for each coil.

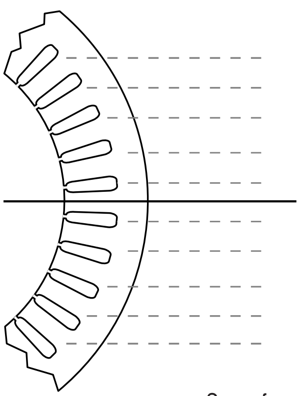
Slot number/ electrical angle

A	B	C
		1
	1	
1		2
2	2	
3	3	3
4	4	4
5	5	
6		5
	6	
		6



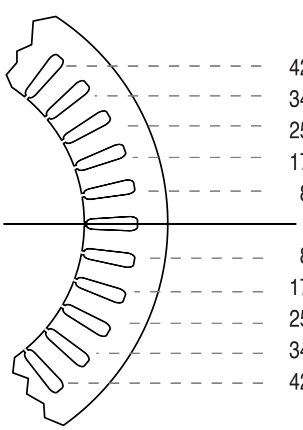
$$\text{The distribution factor } (K_d) \text{ for the coil group} = \frac{\text{Sum of the cosines of the group of coil}}{\text{Coils per group}}$$

36 SLOTS—6 COILS PER GROUP



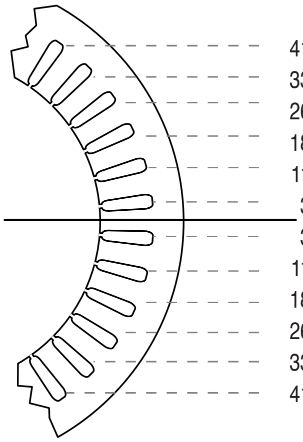
Fundamental	A	B	C	5th harmonic	A	B	C	7th harmonic	A	B	C
45			0.707	225			-0.707	315			0.707
35		0.819		175		-0.966		245		-0.423	
25	0.909		0.909	125	-0.574		-0.574	175	-0.996		-0.996
15	0.966	0.966		75	0.259	0.259		105	-0.259	-0.259	
5	0.996	0.996	0.996	25	0.906	0.906	0.906	35	0.819	0.819	0.819
5	0.996	0.996	0.996	25	0.906	0.906	0.906	35	0.819	0.819	0.819
15	0.966	0.966		75	0.259	0.259		105	-0.259	-0.259	
25	0.909		0.909	125	-0.574		-0.574	175	-0.996		-0.996
35		0.819		175		-0.996		245		-0.423	
45			0.773	225			-0.707	315			0.707
Sum of cosines	5.736	5.562	5.218		1.182	0.388	0.750		0.872	0.274	1.060
Distribution factor	0.956	0.927	0.870		0.197	0.056	0.125		0.145	0.046	0.177

42 SLOTS—7 COILS PER GROUP



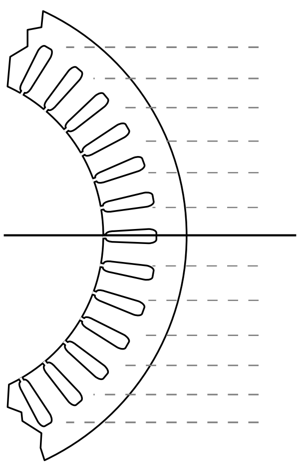
Fundamental	A	B	C	5th harmonic	A	B	C	7th harmonic	A	B	C
42.85			0.733	214			-0.829	300			0.500
34.28		0.826		171		-0.988		240		-0.500	
25.71	0.901		0.901	129	-0.629		-0.629	180	-1.000		-1.000
17.14	0.956	0.956		86	0.070	0.070		120	-0.500	-0.500	
8.57	0.989	0.989	0.989	43	0.731	0.731	0.731	60	0.500	0.500	0.500
0	1.000	1.000	1.000	0	1.000	1.000	1.000	0	1.000	1.000	1.000
8.57	0.989	0.989	0.989	43	0.731	0.731	0.731	60	0.500	0.500	0.500
17.14	0.956	0.956		86	0.070	0.070		120	-0.500	-0.500	
25.71	0.901		0.901	129	-0.629		-0.629	180	-1.000		-1.000
34.28		0.826		171		-0988		240		-0.500	
42.85			0.733	214			-0.829	300			0.500
Sum of cosines	6.692	6.542	6.246		1.134	0.626	0.454		1.000	0.000	1.000
Distribution factor	0.956	0.935	0.892		0.192	0.089	0.065		0.143	0.000	0.143

48 SLOTS—8 COILS PER GROUP



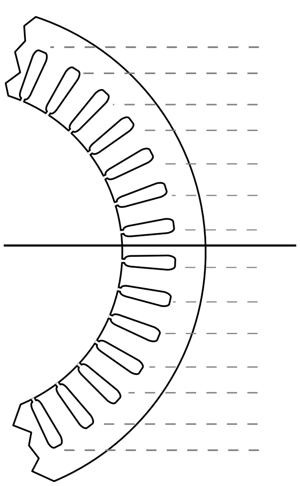
	Fundamental				5th harmonic				7th harmonic		
41.25			0.752	206			-0.899	289			0.326
33.75		0.832		169		-0.982		236		-0.559	
26.25	0.897		0.897	131	-0.656		-0.656	184	-0.998		-0.998
18.75	0.947	0.947		94	-0.070	-0.070		131	-0.656	-0.656	
11.25	0.981	0.981	0.981	56	0.559	0.559	0.559	79	0.191	0.191	0.191
3.75	0.998	0.998	0.998	19	0.946	0.946	0.946	26	0.899	0.899	0.899
3.75	0.998	0.998	0.998	19	0.946	0.946	0.946	26	0.899	0.899	0.899
11.25	0.981	0.981	0.981	56	0.559	0.559	0.559	79	0.191	0.191	0.191
18.75	0.947	0.947		94	-0.070	-0.070		131	-0.656	-0.656	
26.25	0.897		0.897	131	-0.656		-0.656	184	-0.998		-0.998
33.75		0.832		169		-0.982		236		-0.559	
41.25			0.752	206			-0.899	289			0.326
Sum of cosines	7.646	7.516	7.256		1.588	0.906	0.100		1.128	0.250	0.836
Distribution factor	0.956	0.940	0.907		0.1948	0.113	0.0125		0.141	0.0313	0.1045

54 SLOTS—9 COILS PER GROUP



	Fundamental				5th harmonic				7th harmonic		
40			0.766	200			-0.940	280			0.174
33		0.835		167		-0.974		233		-0.602	
26	0.894		0.894	133	-0.682		-0.682	187	-0.993		-0.993
20	0.940	0.940		100	-0.174	-0.174		140	-0.766	-0.766	
13	0.973	0.973	0.973	67	0.391	0.391	0.391	93	-0.052	-0.052	-0.052
6.7	0.993	0.993	0.993	33	0.839	0.839	0.839	47	0.682	0.682	0.682
0	1.000	1.000	1.000	0	1.000	1.000	1.000	0	1.000	1.000	1.000
6.7	0.993	0.993	0.993	33	0.839	0.839	0.839	47	0.682	0.682	0.682
13	0.973	0.973	0.973	67	0.391	0.391	0.391	93	-0.052	-0.052	-0.052
20	0.940	0.940		100	-0.174	-0.174		140	-0.766	-0.766	
26	0.984		0.894	133	-0.682		-0.682	187	-0.993		-0.993
33		0.835		167		-0.974		233		-0.602	
40			0.766	200			-0.940	280			0.174
Sum of cosines	8.600	8.482	8.252		1.748	1.164	0.216		1.258	0.476	0.622
Distribution factor	0.956	0.942	0.917		0.1942	0.129	0.024		0.140	0.0529	0.0691

60 SLOTS—10 COILS PER GROUP



	Fundamental				5th harmonic				7th harmonic		
39			0.777	195			-0.966	273			0.052
33		0.839		165		-0.966		231		-0.629	
27	0.891		0.891	135	-0.707		-0.707	189	-0.988		-0.988
21	0.934	0.934		105	-0.259	-0.259		147	-0.839	-0.839	
15	0.966	0.966	0.966	75	0.259	0.259	0.259	105	-0.259	-0.259	-0.259
9	0.988	0.988	0.988	45	0.707	0.707	0.707	63	0.454	0.454	0.454
3	0.999	0.999	0.999	15	0.966	0.966	0.966	21	0.934	0.934	0.934
3	0.999	0.999	0.999	15	0.966	0.966	0.966	21	0.934	0.934	0.934
9	0.988	0.988	0.988	45	0.707	0.707	0.707	63	0.454	0.454	0.454
15	0.966	0.966	0.966	75	0.259	0.259	0.259	105	-0.259	-0.259	-0.259
21	0.934	0.934		105	-0.259	-0.259		147	-0.839	-0.839	
27	0.891		0.891	135	-0.707		-0.707	189	-0.988		-0.988
33		0.839		165		-0.966		231		-0.629	
39			0.777	195			-0.966	273			0.052
Sum of cosines	9.566	9.452	9.242		1.932	1.414	0.518		1.396	0.678	0.386
Distribution factor	0.956	0.945	0.924		0.193	0.141	0.052		0.140	0.068	0.039

Winding connections for multi-mode, three-phase motors

By Preben Christensen, EASA Staff Engineer (retired)

Multi-mode motors are used in services demanding efficient operation of the drive at more than one torque level. Such motors, designed for two or more torque (hp) ratings, are single-speed, squirrel cage induction motors that operate at a fixed voltage.

The multi-mode, three-phase motor has one stator winding and either 9 or 12 motor leads that can be reconnected externally to provide the various torque ratings.

It is not always easy to distinguish a multi-mode winding from an ordinary three-phase stator winding because of the similarity between the two. The winding information, however, and the nameplate data can help you determine if a motor has a multi-mode winding.

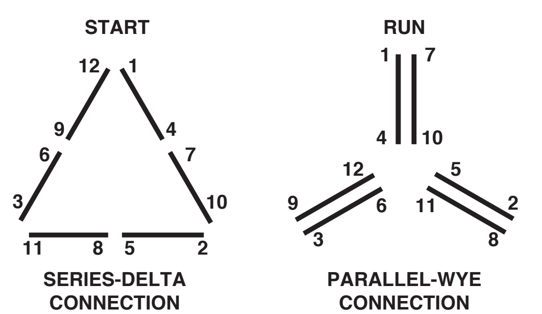
The surest way to find out what type of winding used in the motor is by carefully noting the interconnection of coils and motor leads when stripping the motor. Terminal connection information, as well as the nameplate data, however, can also alert the technician that the motor contains a multi-mode winding.

This article describes internal winding connections for dual-, triple- and quadruple-rated, three-phase motors. Because it is sometimes difficult to identify such windings, terminal connections and typical nameplate data for these motor windings are also included.

THE DUAL-RATED, TWELVE-LEAD, THREE-PHASE MOTOR

The dual-rated motor has a lower starting torque than the standard motor. It is often referred to as a "soft-start" motor as compared with other types of soft-start methods. During start, the motor is connected series delta; when running, it reconnects to parallel wye (Figure 2-81). The characteristic soft-start of this type of motor makes it a natural for use in textile machinery, where the impact of the starting torque of a standard induction motor could damage the material in process.

FIGURE 2-81



Connections for dual-rated, twelve-lead, three-phase motors.

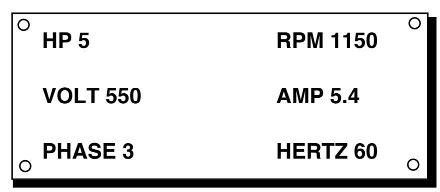
The internal connections for the dual-rated motor are the same as those for "Wye-Delta" connections in EASA's *Internal Connection Diagrams for Three-Phase Electric Motors*. Twelve motor leads are required, and the winding may be connected either adjacent pole or skip pole. The terminal connections for the dual-rated motor are shown in Table 2-35.

TABLE 2-35: TERMINAL MARKINGS AND CONNECTIONS FOR DUAL-RATED, TWELVE-LEAD, THREE-PHASE MOTORS

Torque mode	L1	L2	L3	Tie together
Low (start)	1 & 12	2 & 10	3 & 11	4 & 7, 5 & 8, 6 & 9
High (run)	1 & 7	2 & 8	3 & 9	4 & 5 & 6, 10 & 11 & 12

Typical nameplate data for the dual-rated motor is shown in Figure 2-82. Notice that the nameplate lists only one horsepower rating–the rating for the parallel-wye connection.

FIGURE 2-82



Typical nameplate information for dual-rated motors.

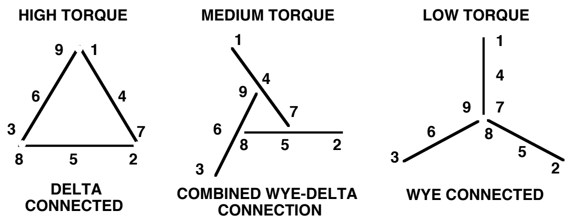
THE TRIPLE-RATED, NINE-LEAD, THREE-PHASE MOTOR

The triple-rated motor, which is used extensively as an oil well pump motor, is designed to operate at three torque levels: high, medium and low. The connections are changed from high through medium to low torque as load demands gradually change with time.

The nine-lead, triple-rated motor has three leads brought out from each phase–one from each end, and one from some intermediate point. The point of connection of this latter lead to the pole-phase groups is always determined by the medium torque rating of the motor. The winding connections described in this article for the triple-rated motor refer to those motors having Leads 4, 5 and 6 connected to the **center** of the phase.

Figure 2-83 indicates how the winding connection is altered to vary motor torque output. The high-torque and the

FIGURE 2-83

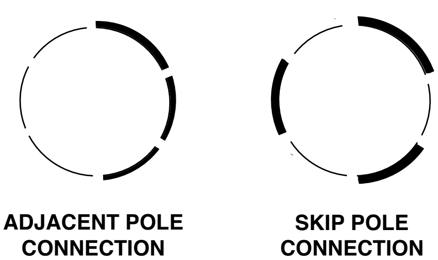


Connections for triple-rated, nine lead, three-phase motors.

low-torque connections are a full delta and a straight wye, respectively. The medium-torque connection is a combination of delta and wye with half of the winding connected in the delta branch and the other half connected in the wye branch. This combined delta and wye connection must have the coil groups connected in a specific sequence in order to neutralize the effect of unequal current distribution in the two branches of the winding

When the triple-rated motor is operating in the medium-torque mode, the current is not equal in all coil groups. The wye branch of a phase carries 100 percent of the line current while the delta branch carries only 58 percent of the line current. This results in a lower flux level in the delta branch than in the wye branch. Unless the internal connections are made so that the coil groups from the wye and the delta branches are intermingled, the flux will not be balanced when the motor operates in the medium-torque mode. In such cases, poor

FIGURE 2-84



Flux distribution in one phase of a 6-pole, triple-rated motor operating in the medium-torque mode.

performance will result.

The flux can be balanced by using the skip-pole connection for the winding. Figure 2-84 represents the flux distribution in one phase of a six-pole, triple-rated motor operating in the medium-torque mode. The coil groups in Figure 2-84 are connected adjacent pole (left) and skip pole (right). The coil groups from the wye branch (heavyline) are magnetically stronger than the coil groups from the delta branch (light line). Figure 2-84 shows that using adjacent-pole connections results in imbalanced flux distribution because the right-hand side of the stator carries more flux than the left.

Figure 2-84 shows that when the winding is connected skip pole, the flux in the motor is balanced. This method of interconnecting the coil groups assures that the magnetically strong and weak pole groups are alternately distributed in the stator. The inherent flux imbalance is neutralized because each pair of poles consists of a weak and a strong pole.

The internal connections for the four-, six- and eight-pole, triple-rated motors with single and multiple winding circuits are listed in Table 2-36 to Table 2-42. (Note: The connection for the six-pole, two-circuit winding is not shown because it is not possible to make the center connection, as described earlier, for the motor leads in this winding.) The terminal connections are shown in Table 2-43.

FIGURE 2-85

HP 3 - 1.5 - .75	RPM 1800
VOLT 550	AMP 3.4 - 1.8 - .8
PHASE 3	HERTZ 60

Typical nameplate information for triple-rated motors.

Typical nameplate data for the triple-rated motor is shown in Figure 2-85. The fact that three horsepower ratings are listed on this nameplate indicates that this single-speed motor has a triple-rated winding.

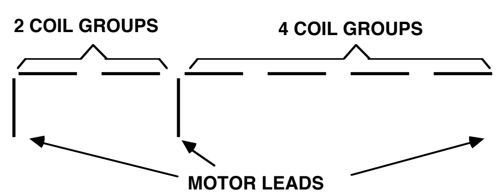
THE QUADRUPLE-RATED, NINE-LEAD, THREE-PHASE MOTOR

The six-pole, quadruple-rated motor, like the triple-rated motor, is used mainly for oil well pump duty. Because six-pole, quadruple-rated motors are the most common in use, all references in this article are to these motors.

The connections described for the nine-lead, triple-rated motor show Leads 4, 5 and 6 located at the center of the phases. If these leads were connected "off-center," the motor could also be operated in a fourth torque mode, still using only nine motor leads.

Figure 2-86 shows the three leads brought out from one

FIGURE 2-86



The "off-center" lead connection in quadruple-rated motor windings. (Only one phase of the winding shown.)

INTERNAL CONNECTIONS FOR TRIPLE-RATED, THREE-PHASE MOTORS WITH NINE LEADS*

These internal connections apply to a triple-rated motor winding in which leads 4, 5 and 6 are connected to the center of the phases.

TABLE 2-36: 4 POLE, 1 CIRCUIT

Lead number	Coil end number
1	1
5	4, 22
3	5
7	7
2	9
9	11
4	14, 20
8	15
6	18, 24
Pole connections	2-13, 3-16, 6-17, 8-19, 10-21, 12-23

TABLE 2-37: 4 POLE, 2 CIRCUIT

Lead number	Coil end number
1	1, 13
4	2, 8, 14, 20
8	3, 15
5	4, 10, 15, 22
3	5, 17
6	6, 12, 18, 24
7	7, 19
2	9, 21
9	11, 23

TABLE 2-38: 6 POLE, 1 CIRCUIT

Lead number	Coil end number
1	1
5	4, 34
3	5
2	9
7	19
9	23
4	26, 32
8	27
6	30, 36
Pole connections	2-13, 3-16, 6-17, 7-20, 10-21, 11-24, 14-25, 15-28, 18-29, 22-33, 31-8, 35-12

TABLE 2-39: 6 POLE, 3 CIRCUIT

Lead number	Coil end number
1	1, 13, 25
4	2, 8, 14, 20, 26, 32
8	3, 15, 27
5	4, 10, 16, 22, 28, 34
3	5, 17, 29
6	6, 12, 18, 24, 30, 36
7	7, 19, 31
2	9, 21, 33
9	11, 23, 35

TABLE 2-40: 8 POLE, 1 CIRCUIT

Lead number	Coil end number
1	1
5	4, 46
3	5
2	9
7	31
9	35
4	38, 44
8	39
6	42, 48
Pole connections	2-13, 3-16, 6-17, 7-20, 10-21, 11-24, 14-25, 15-28, 18-29, 19-32, 22-33, 23-36, 26-37, 27-40, 30-41, 34-45, 43-8, 47-12

TABLE 2-41: 8 POLE, 2 CIRCUIT

Lead number	Coil end number
1	1, 25
5	4, 22, 28, 46
3	5, 29
7	7, 31
2	9, 33
9	11, 35
4	14, 20, 38, 44
8	15, 39
6	18, 24, 42, 48
Pole connections	2-13, 3-16, 6-17, 10-21, 19-32, 23-36, 26-37, 27-40, 30-41, 34-45, 43-8, 47-12

TABLE 2-42: 8 POLE, 4 CIRCUIT

Lead number	Coil end number
1	1, 13, 25, 37
4	2, 8, 14, 20, 26, 32, 38, 44
8	3, 15, 27, 39
5	4, 10, 16, 22, 28, 34, 40, 46
3	5, 17, 29, 41
6	6, 12, 18, 24, 30, 36, 36, 42, 48
7	7, 19, 31, 43
2	9, 21, 33, 45
9	11, 23, 35, 47

* For numbering system, refer to EASA's publication *Internal Connection Diagrams for Three-Phase Motors*.

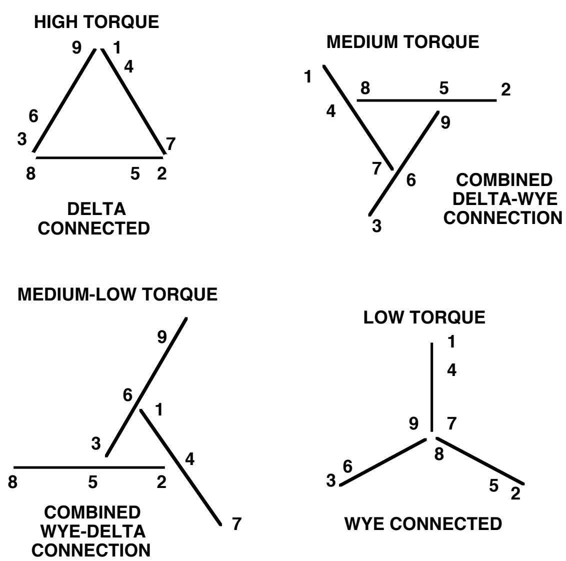
TABLE 2-43: TERMINAL MARKINGS AND CONNECTIONS FOR TRIPLE-RATED, NINE-LEAD, THREE-PHASE MOTORS

Torque mode	L1	L2	L3	Tie together	Open
High	1 & 9	2& 7	3 & 8		4 & 5 & 6
Medium	1	2	3	4 & 9, 5 & 7, 6 & 8	
Low	1	2	3	7 & 8 & 9	4 & 5 & 6

phase of a six-pole winding–one from each end, and one from an intermediate point–dividing the coil groups two to one. Using this connection, the motor can be operated in four torque modes: high, medium and low, as found in the triple-rated motor, as well as in a medium-low torque mode. The fourth torque rating (medium-low) is made possible by rearranging the connections and relocating the power supply leads.

Figure 2-87 illustrates the four torque mode connections and their varying strength–from high torque to low torque. The two medium-torque connections are designated delta-wye and wye-delta, the former being the stronger. The more coil groups there are in the delta branch, the higher the torque. Note that the high-, medium- and low-torque modes are connected to

FIGURE 2-87



Connections for quadruple-rated, nine-lead, three-phase motors.

the power source at Terminals 1, 2 and 3; the medium-low torque mode has the power connected to Terminals 7, 8 and 9.

The effect of unequal current distribution in both of the combined delta-wye connections can be neutralized by using a specific interconnection of the coil groups.

Two coil groups of a phase, placed opposite each other in the stator, are connected and joined with Leads 1 and 4. The remainder of the coil groups of the same phase are connected to Leads 4 and 7. The coil groups of the two other phases are arranged in the same manner. Using this method of connecting the coil groups assures a balanced flux distribution in the winding.

The internal connections for the one- and two-circuit six-pole, quadruple-rated motor windings are listed in Table 2-44 and Table 2-45. The terminal connections are shown in Table 2-46.

With Leads 4, 5 and 6 connected "off center" as described earlier, quadruple-rated motors can be operated in all four torque modes only if the winding is designed for one or two circuits. A three-circuit winding would offer only one choice–a medium-torque connection. A six-circuit winding would have no medium-torque connection.

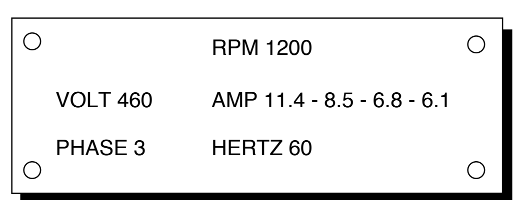
While most quadruple-rated motors are made with one- or two-circuit windings, some manufacturers of these six-pole motors also design them with three-circuit and six-circuit windings. The two medium-torque ratings are then established by separating the coils of each group into two sections and connecting one coil section in the wye branch and the other coil section in the delta branch. The separation of the coils is shown in the coil group drawing inserted in Figure 2-89.

This method of connecting the coils assures that all poles equally share the magnetically stronger and weaker coils. The flux is always distributed uniformly when the motor is in operation because all poles have the same strength.

The numbering system for the coil ends normally used in the three- and six-circuit windings has been changed because of the connections made within the coil groups themselves (see Figure 2-89 and Figure 2-90). Details of connections for one phase of the three-circuit winding are illustrated in Figure 2-89.

Internal connections for six-pole, quadruple-rated motors with three- and six-circuit windings are shown in Table 2-47 and Table 2-48. The terminal connections for these windings

FIGURE 2-88



Typical nameplate information for quadruple-rated motors.

are listed in Table 2-46.

Typical nameplate data for the quadruple-rated motor is shown in Figure 2-88. Note that no horsepower ratings are shown. The four ampere ratings on the nameplate provide an indication that this single-voltage, single-speed machine has

INTERNAL CONNECTIONS FOR QUADRUPLE-RATED, THREE-PHASE MOTORS WITH NINE LEADS*

These internal connections apply to a quadruple-rated motor winding in which leads 4, 5 and 6 are NOT connected to the center of the phases.

TABLE 2-44: 6 POLE, 1 CIRCUIT

Lead number	Coil end number
1	1
2	4
3	5
7	7
8	10
9	11
4	19, 25
5	22, 28
6	23, 29
Pole connections	2-20, 3-21, 6-24, 8-14, 9-15, 12-18, 13-31, 16-34, 17-35, 26-32, 27-33, 30-36

TABLE 2-45: 6 POLE, 2 CIRCUIT

Lead number	Coil end number
1	1, 20
4	2, 13, 19, 25
5	3, 16, 22, 28
2	4, 21
3	5, 24
6	6, 17, 23, 29
7	7, 31
8	10, 34
9	11, 35
Pole connections	8-14, 9-15, 12-18, 26-32, 27-33, 30-36

* For numbering system, refer to EASA's publication *Internal Connection Diagrams for Three-Phase Motors*.

TABLE 2-46: TERMINAL MARKINGS AND CONNECTIONS FOR QUADRUPLE-RATED, NINE-LEAD, THREE-PHASE MOTORS

Torque mode	L1	L2	L3	Tie together	Open
High	1 & 9	2 & 7	3 & 8		4 & 5 & 6
Medium	1	2	3	4 & 8, 5 & 9, 6 & 7	
Medium-low	7	8	9	2 & 4, 3 & 5, 1 & 6	
Low	1	2	3	7 & 8 & 9	4 & 5 & 6

INTERNAL CONNECTIONS FOR QUADRUPLE-RATED, THREE-PHASE MOTORS WITH NINE LEADS

These internal connections apply to a quadruple-rated motor winding in which leads 4, 5 and 6 are connected to coils within the phase groups.

TABLE 2-47: 6 POLE, 3 CIRCUIT

Lead number*	Coil end number
1	1, 13, 25
4	2a, 7, 14a, 19, 26a, 31
6	3, 10a, 15, 22a, 27, 34a
9	4a, 16a, 28a
2	5, 17, 29
5	6a, 11, 18a, 23, 30a, 35
7	8a, 20a, 32a
3	9, 21, 33
8	12a, 24a, 36a
Pole connections	1a-7a, 2-8, 5a-11a, 6-12, 9a-15a, 10-16, 13a-19a, 14-20, 17a-23a, 18-24, 21a-27a, 22-28, 25a-31a, 26-32, 29a-35a, 30-36, 33a-3a, 34-4

* For numbering system, refer to Figure 9.

TABLE 2-48: 6 POLE, 6 CIRCUIT

Lead number*	Coil end number
1	1, 7a, 13, 19a, 25, 31a
4	1a, 2a, 7, 8, 13a, 14a, 19, 20, 25a, 26a, 31, 32
7	2, 8a, 14, 20a, 26, 32a
6	3, 4, 9a, 10a, 15, 16, 21a, 22a, 27, 28, 33a, 34a
3	3a, 9, 15a, 21, 27a, 33
9	4a, 10, 16a, 22, 28a, 34
2	5, 11a, 17, 23a, 29, 35a
5	5a, 6a, 11, 12, 17a, 18a, 23, 24, 29a, 30a, 35, 36
8	6, 12a, 18, 24a, 30, 36a

* For numbering system, refer to Figure 10.

a quadruple rated winding.

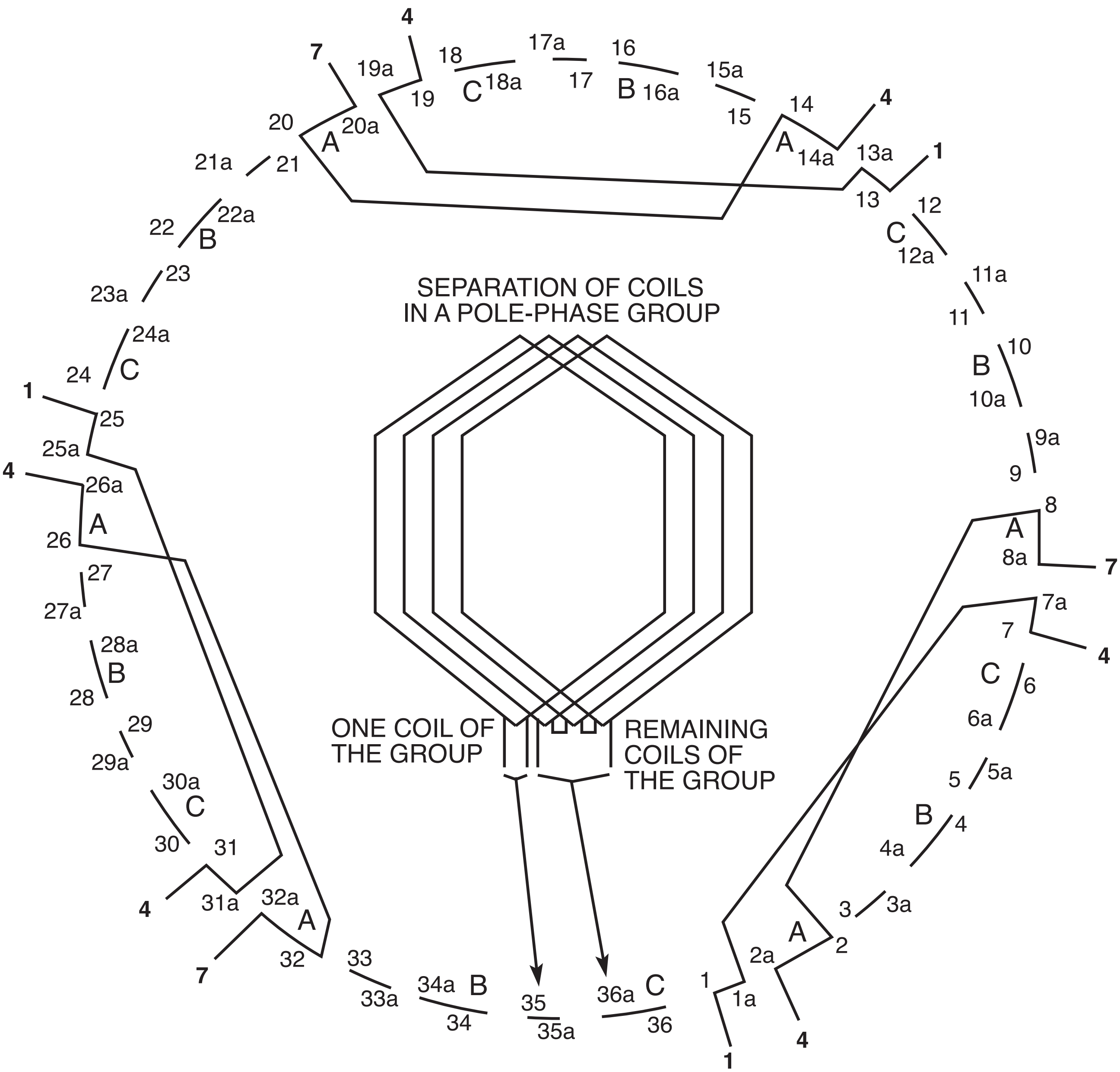
Knowledge of the various types of winding connections used in multi-mode motors is important for the technician who repairs such motors. In addition to obtaining the usual winding data, the technician is advised to note and record the following:

1. Any nameplate information indicating multi-mode operation.
2. Terminal connection information.
3. The number of motor leads supplied and the exact location of their connection to the winding.
4. The number of jumpers and the manner in which they are connected to the winding.
5. The method by which the coil groups are wound and connected (in separate groups or as one unit).

The technician also should compare the information obtained from the winding to be repaired with the tables of internal connections provided in this article. These tables provide the correct winding information for a representative group of multi-mode motors. Since there are many types of multi-mode winding variations, members are urged to contact EASA Headquarters should additional information be required.

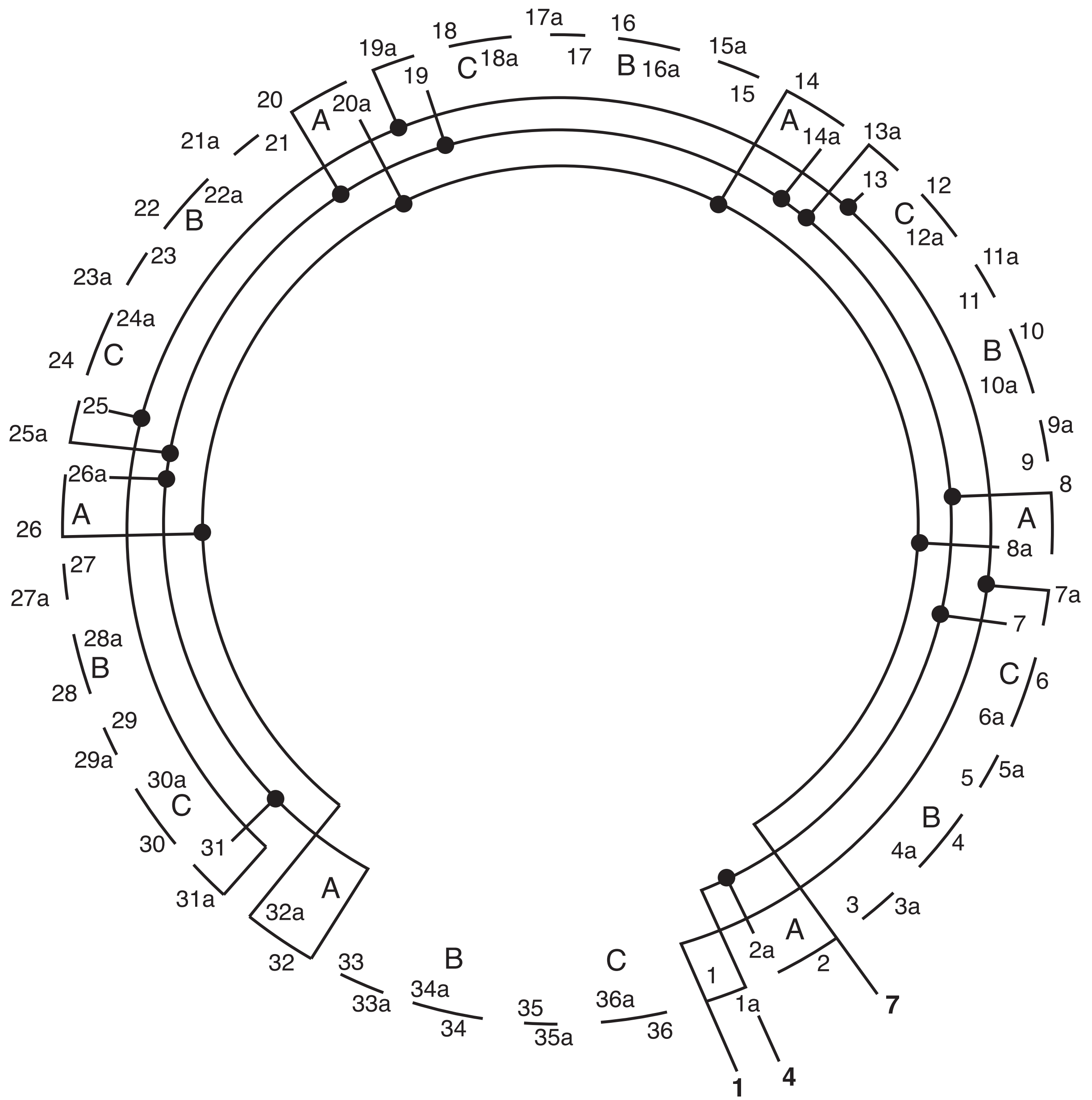
Note: This article was first published as *EASA Tech Note 10* (October 1986); it was reviewed and updated as necessary in August 2016. Some of the data used in preparing the article was provided by Century Electric (now A.O. Smith Electrical Products Co., which is part of Regal-Beloit Corp.) and Sargent Industries. EASA thanks these companies for their help and cooperation.

FIGURE 2-89



Quadruple-rated, three-phase motor winding (6 poles, 3 circuits). System of numbering coil ends and internal connections of Phase “A”.

FIGURE 2-90



Quadruple-rated, three-phase motor winding (6 poles, 6 circuits). System of numbering coil ends and internal connections of Phase “A”.

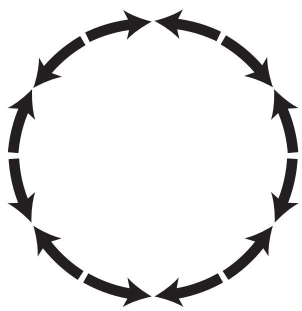
Designing the proper part-salient, part consequent winding

By Chuck Yung
EASA Senior Technical Support Specialist

Sometimes when redesigning a motor, the desired speed requires more poles than are possible for the number of stator slots. At other times, a motor arrives in the service center with a nameplate speed that does not seem to be compatible with the number of stator slots (e.g.,18 poles with 36 slots). In both cases, the answer may be a part-salient, part-consequent winding.

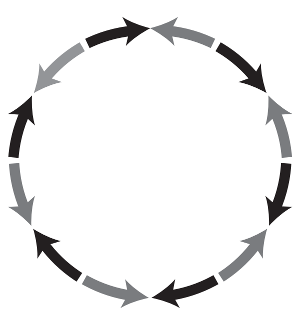
To understand how this winding works, let's compare it to "normal" winding designs. One winder's trick for verifying the integrity of a connection diagram is to trace through each phase and "arrow-diagram" the groups. For a salient-pole winding, the polarities alternate with each physical group (Figure 2-91). With a consequent-pole connection, all the arrows point the same direction (Figure 2-92).

FIGURE 2-91



Salient-pole (12 groups of coils)

FIGURE 2-92



Consequent-pole (6 groups of coils)

The examples in Figure 2-91 and Figure 2-92 both develop 4 poles. Phantom poles are indicated by gray arrows in Figure 2-92.

With a consequent-pole connection, an opposite polarity is induced between each physical group. The effect is as if there are twice as many groups. "Phantom poles"–induced between the actual poles–have polarities opposite those of the real poles.

HYBRID WINDING

By combining these two basic diagrams, it is possible to develop a hybrid winding that is *partly* salient-pole, and *partly* consequent-pole. That allows the designer to develop a winding such as a 10-pole with 24 slots, which would not otherwise be possible.

As long as some basic rules are followed, this method is reliable.

- Since each phase must be balanced, each phase must contain the same number of *real* groups.
- Each phase must have the same number of *real* poles and the same number of *induced* poles.
- The number of real poles and induced poles do not have to equal each other.
- Phantom groups must be placed so that the arrow diagram results in alternate polarity for the entire winding.

FOLLOW SIMPLE PROCESS

To simplify this, use a template with the actual number of slots. Determine the number of groups required (poles x 3 phases) for a normal salient-pole winding, and subtract from that the number of groups possible with the number of slots in the stator. The difference is the number of phantom groups required. Divide by 3 for the number of phantom groups required per phase.

For the 24-slot, 10-pole example:

10 poles x 3 phases = 30 groups

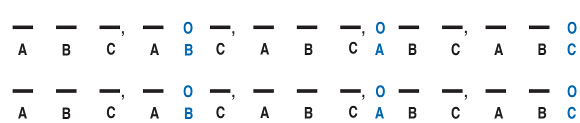
30 groups - 24 slots = 6 phantom groups required

The phantom groups must be uniformly distributed around the stator, so the next step is to determine the odd grouping sequence.

There are 24 groups of 1 coil, and 6 groups of zero. It may help to think of the "groups of zero" as placeholders for those phantom poles.

The groups of zero must be divided equally among the 3 phases, so group them A-B-C to visualize it better:

FIGURE 2-93

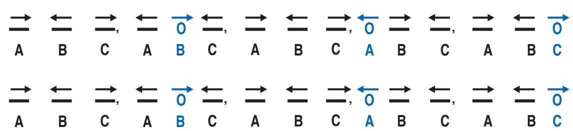


Use a highlighter to identify the location of each phantom group on the 24-slot template.

111,101,111,011,110; repeated once. This pattern places 2 zeros in each phase (Figure 2-93).

All that remains is to draw the connection, treating the zeros as place-holders (Figure 2-94). Use the direction of the arrows as a guide, and don't be confused by the fact that some jumpers are "inside to outside" while others are "inside to inside" or "outside to outside." Each time you get to a phantom group, simply bypass it and draw to the next group in that phase, following the direction of the *arrows*. Those two steps–labeling the phases and following the arrows that indicate the alternating north-south relationship of the groups–are the key to making this a simple process.

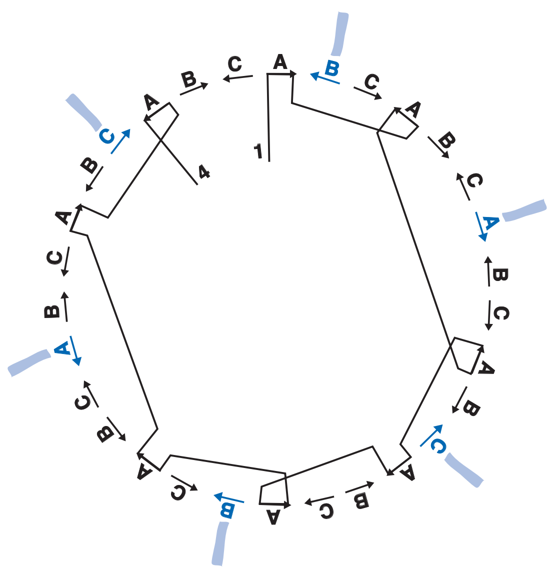
FIGURE 2-94



To simplify the connection diagram, the next step is to arrow-diagram the groups and label the phases, including the phantom groups, A-B-C.

The completed diagram should look like Figure 2-95.

FIGURE 2-95



Note the long jumpers where the phantom poles are bypassed.

With such a global economy, expect to see more small motors produced using this unique method. Manufacturers save money by using a few standard laminations for a variety of motor speeds. This method has been used successfully on motors up to about 10 hp (7.5 kW).

Tip: When tracing out an existing connection you suspect is part-salient, part-consequent, a sure clue is the mix of 1-3 jumpers or 1-6 jumpers with the expected 1-4 or 1-7 jumpers.

This article was first published in *EASA Currents* (August 2001); it was reviewed and updated as necessary in August 2016.

Connecting the variable-speed commutator motor

By David L. Gebhart, EASA Staff Engineer (deceased)

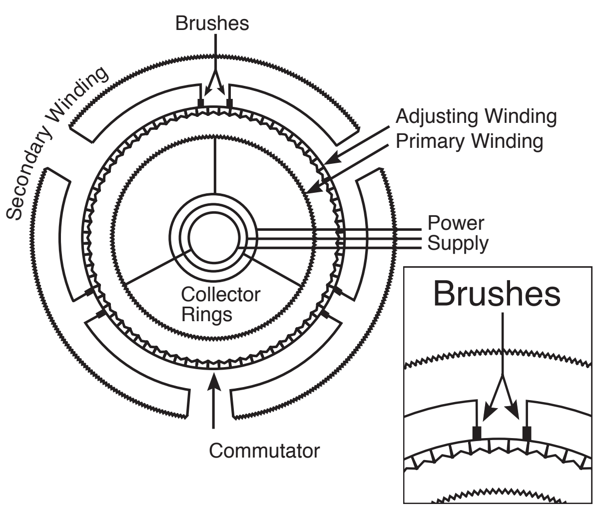
Connecting the stator winding of a three-phase, variable-speed commutator motor to the proper brushes has caused problems for many EASA members. Before explaining the proper connection procedure, we will briefly describe the motor and the way it functions.

The primary winding, located on the rotor, is a three-phase winding that is connected to the power source through a set of collector (slip) rings. An adjusting winding, also located on the rotor, is connected to a commutator. Two sets of brushes ride on the commutator and are connected to the beginning and end of each phase of the stator winding.

The sets of brushes are shifted simultaneously in opposite directions to change speeds. The farther apart the brushes are, the higher will be the voltage supplied to the stator (secondary) winding by the adjusting winding.

There is also a voltage induced into the stator winding by the primary winding. The vectorial addition of this voltage and the voltage supplied by the adjusting winding determines the speed. Figure 2-96 shows a circuit diagram of this motor.

FIGURE 2-96



Variable-speed commutator motor circuit diagram.

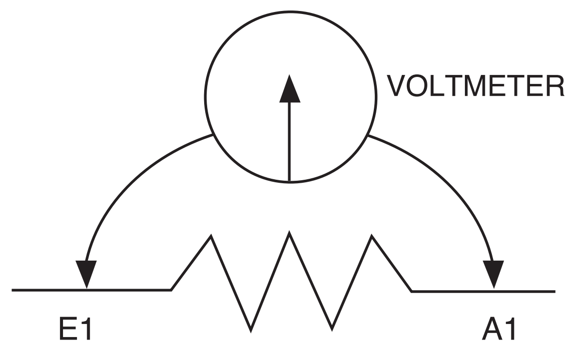
Variable-speed commutator motors, also known as Schrage motors, operate above and below synchronous speed. On the low speed side, the farther apart the brushes are of a given phase, the slower the motor will run. When brushes of the same phase are aligned on the same commutator bars, the stator winding is short-circuited, causing the motor to operate at synchronous speed. As the brushes pass and move away from each other in the opposite direction, the speed increases. The speed is practically independent of the applied load.

Even though the primary winding on the rotor is a three-phase winding, the stator winding may have more than three phases. The number depends on the pairs of brushes. When rewinding the stator, therefore, it is very important to start the winding in the correct slot. Phase A, for example, must start in the same slot that it started in originally. The same is true for the other phases. Mark the phases A1 and E1, A2 and E2, and so forth.

MAKING THE CONNECTIONS

To identify the lead pairs and the brushholders to which they must be connected, first make sure all stator leads are disconnected and not touching each other. Next, while applying half the nameplate voltage to the collector rings, measure the voltage on one of the phases of the stator, as shown in Figure 2-97. Record this voltage. (Note: the rotor should not turn when voltage is applied to the collector rings.)

FIGURE 2-97



Now move the brush rigging to the lowest rpm position and measure the voltage between a brush on the inside ring and one 90 degrees apart on the outside ring (see Figure 2-98). Record this voltage.

The next step is to connect one stator lead to a brush and measure the voltage between the other stator lead and the other brush, as shown in Figure 2-99.

This reading should exactly equal the difference between the two readings you recorded earlier. For example, if the phase voltage is 50 and the voltage between the two brushes 90 degrees apart is 30, the reading with one lead connected to a brush must be 20 (50 - 30 = 20).

If this is not the case, run the test again with a different set of stator leads. Always disconnect each wire before going to the next set of leads

Once the proper pair of leads has been found, mark them to identify which holder they should be connected to, and

FIGURE 2-98

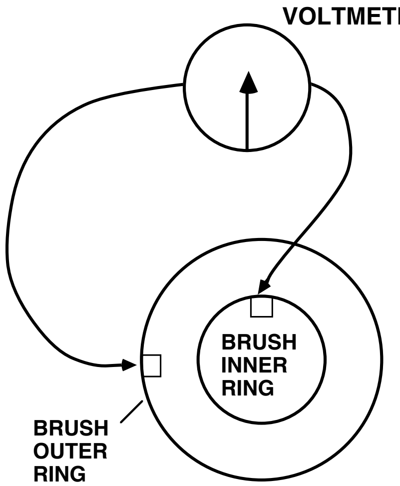
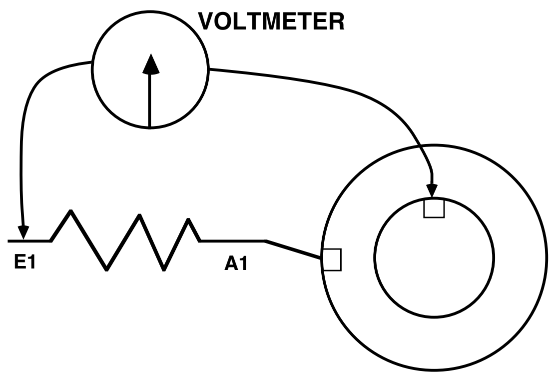


FIGURE 2-99



disconnect them. Move on to the next set of brushes and repeat the process until all stator leads and their proper brush positions have been identified. Now connect all stator leads to their proper brushes.

TESTING THE MOTOR

To test the motor, first make sure the brushes are set for operation at the lowest rpm. Now start the motor and bring it to maximum rpm. After measuring and recording the primary current in all three phases, reduce the speed to the lowest rpm and stop the motor.

Next, reverse two of the primary leads, start the motor and run it up to maximum speed. Again measure and record the current in all three phases. The readings obtained here should be exactly the same as those measured previously.

If the two current readings are not identical, loosen the set screws on one brush rig and adjust it to balance the currents. Although it may be necessary to adjust both brush rigs to balance the current, only one rig should be adjusted at a time.

Note: This article was first published as *EASA Tech Note 3* (February 1984); it was reviewed and updated as necessary in August 2016.

2.13 DESIGN/REDESIGN OF WINDINGS

Concentric-to-lap/lap-to-concentric conversions

By Chuck Yung, EASA Senior Technical Support Specialist

INTRODUCTION

Concentric windings are used by most motor manufacturers to facilitate machine-insertion of windings and reduce production costs. Windings designed for 4 or more poles can usually be converted to an equivalent lap winding to improve performance, including efficiency.

Two-pole motors, when lap wound, must be short-pitched for reasons of practicality. The narrower the coil pitch, the more actual turns are required to achieve the correct number of effective turns. In many cases a 2-pole concentric winding cannot be converted to an equivalent lap winding without reducing conductor area. Those windings should be duplicated to avoid degrading the efficiency of the motor. Some end-users also require their motors to be rewound "in like kind"–with no changes to the original design.

When a winding must be rewound concentric, the layer-insertion method may be confusing to winders accustomed to the symmetry of the lap winding. This document is intended to help in those cases where a concentric winding must be used.

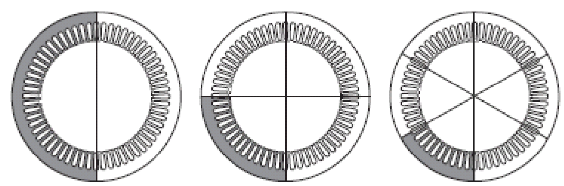
COIL PITCH AND SPAN

Before going further, it is important to note that the terms coil pitch and coil span are often used interchangeably and incorrectly. Coil span describes the number of teeth enclosed, or spanned, by the coil (see Figure 2-100). Coil pitch describes the slots occupied by the coil. If the sides of a coil lie in slots 1 and 11, the coil spans 10 teeth, but its pitch is 1-11. Using the wrong coil pitch will change the chord factor (one of the variables that determines the effectiveness of each turn in a coil). A larger chord factor reduces motor torque; a smaller chord factor increases magnetic flux densities. (More information about chord factor is provided later.)

CONCENTRIC WINDING BASICS

EASA Tech Note 12, "Conversion factors for lap and concentric windings" on Page 2-187 and the *EASA AC Motor Verification and Redesign* program are useful when redesigning from concentric to lap windings. *Tech Note 12* can also be used (in reverse) to redesign from a lap to a concentric winding. The breadth of concentric winding schemes is apparent from *Tech Note 12*. Despite the large variety of pitches and turn ratios, certain basic rules apply to all (see Figure 2-101).

FIGURE 2-101



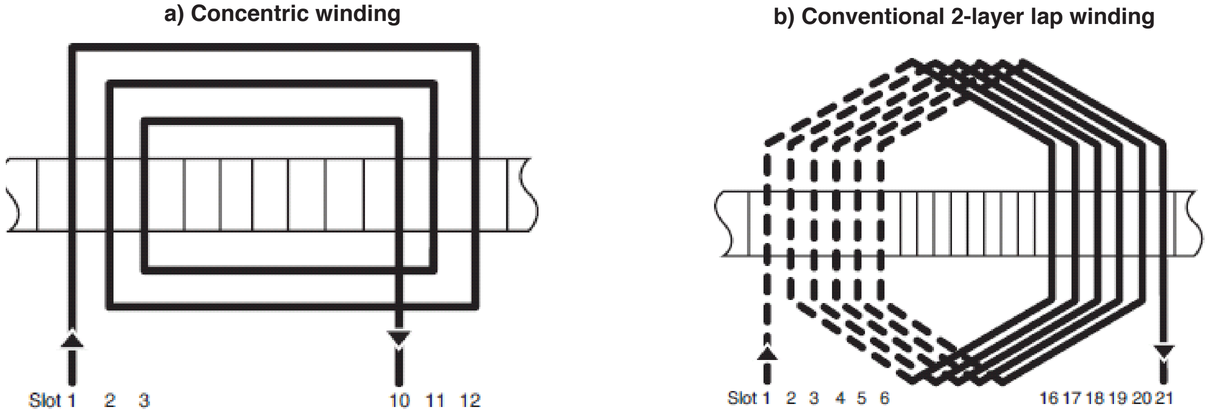
Pole distribution in 2-, 4- and 6-pole machines.

The first is pole-phase group spacing, which is the same as for lap windings. Within each phase, the poles are equally distributed around the circumference of the bore. Spacing from phase-to-phase follows the 120-degree electrical spacing of lap windings. The difference is that concentric windings are often inserted in layers, whereas the lap windings are not (see Figure 2-102).

The phases, which are machine wound into the slots, have different conductor lengths and therefore differing resistances (see Figure 2-103).

FIGURE 2-100

a) Concentric winding **b) Conventional 2-layer lap winding**



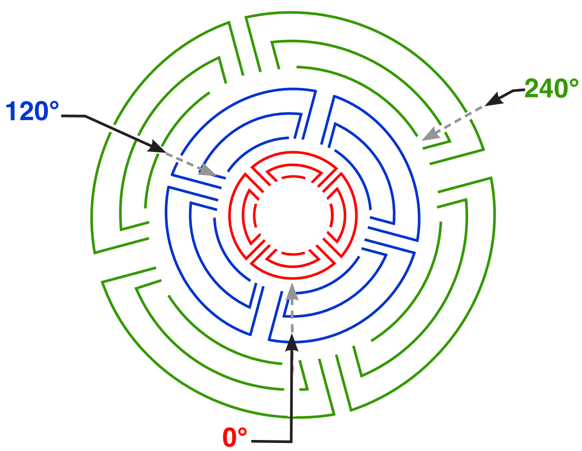
Coil pitch: 1-8, 10, 12 (spans 7, 9, 11)

Coil pitch: 1-16 (span 15); 83% = .966 chord factor

FIGURE 2-102

Typical concentric winding.

FIGURE 2-103



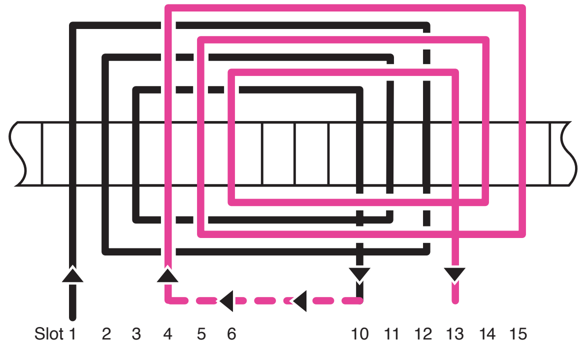
Phase A = red; Phase B = blue; Phase C = green

Spacing from phase-to-phase in concentric windings follows the 120-degree electrical spacing of lap windings.

Traditional concentric windings utilize coil groups where the centerline of the group is also the centerline of each coil of the group (Figure 2-100a). Because the coil group is concentrated (i.e., not distributed, like the lap winding), the distribution factor is 1.0.

Some manufacturers now use a concentric winding where each group is divided into 2 subgroups (see Figure 2-104). While the coils within each subgroup are concentrated, the 2 subgroups do not share a common centerline; hence, a corrected distribution factor is needed. So far, this is only being done on 2-pole motors. An increasingly common example is a 36-slot, 2-pole winding with 6 groups of 6 coils, where

FIGURE 2-104



Concentric winding group divided into 2 subgroups.

Coil group for 2-layer concentric winding.

Coil pitch: 1-8, 10, 12; 1-8, 10, 12; Spans: 7, 9, 11

each group of 6 is divided into 2 subgroups with coil pitches of 1-11,13,15, 1-11,13,15.

The benefits of this winding method are several. First, concentric coils can be machine-inserted, which reduces labor costs for the manufacturer.

Second, the wider coil pitch makes more efficient use of each actual turn. That permits more effective use of copper and increases the circular mils/amp that will fit within a fixed slot configuration. As the discussion of chord factor (k_p) demonstrates, a chord factor of 1.0 results in 100% effectiveness for each turn. A chord factor of 0.500 results in each turn being only 50% effective. Neither a 1.0 or 0.500 chord factor is practical because they do not suppress harmonics. The smaller chord factor also wastes costly materials (copper and steel). Designers use a chord factor between 0.866 (2/3 pitch) and 0.966 (¾ pitch) to achieve the best performance with the most effective use of material.

Here are several options for the same winding that have the same effective turns (and therefore the same magnetic flux densities). The actual turns required are given for each option, along with the comparative conductor area.

1. 6 groups of 6 coils; 1-13,15,17, 1-13,15, 17
   Turns/coil = 28
   Wire size: y
2. 6 groups of 3 coils; 1-14,16,18
   Turns/coil = 54.4, round to 54
   Wire size: 3½% more than Option 1
3. 6 groups of 6 coils; 1-14 lap winding
   Turns/coil = 30
   Wire size: 7% less than Option 1
4. 6 groups of 6 coils; 1-14,16,18,1-14,16,18
   Turns/coil = 27
   Wire size: 3.7% more than Option 1

The lap option (Option 3) is the least desirable of the choices. While Options 2 and 4 appear equal, the MMF curve (see Figure 2-105) of Option 4 is superior to that of Option 2, making it the better choice. Note that this is only true for the 2-pole winding. Conducting the same exercise for windings with 4 or more poles will demonstrate the advantages of a lap winding.

WINDING CONFIGURATIONS

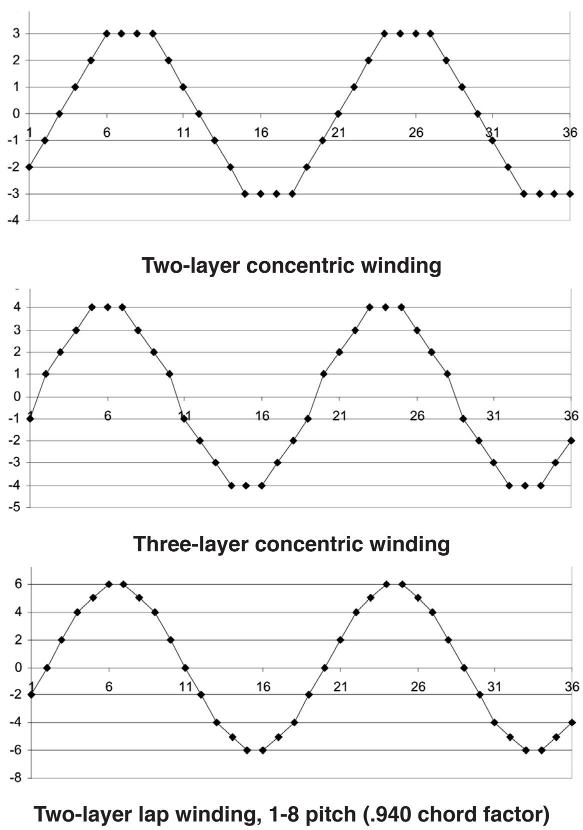
The magneto motive force (MMF) plots in Figure 2-105 are for typical winding configurations now in use. The variations in waveforms and deviation from a sine wave are influenced by the actual winding configuration and harmonic content. The lap winding has the best shape and the lowest stray loss content.

Concentric windings usually require more mean length of turn (MLT) to achieve the same amount of effective turns as a lap winding. Therefore, they will have the highest amount of I_2R loss. Because the concentric windings are normally machine inserted, they usually have a lower copper content in the slots than lap windings, which also leads to increased I_2R losses for the same number of effective turns. In many cases the lap winding will generate less electrical noise than a concentric winding with the same slot combination.

The ideal winding configuration will have:

- Minimum harmonic content
- Shared slots
- Symmetry among all coils
- Moderate end turn length

FIGURE 2-105



Magneto motive force (MMF) plots.

- A pitch that minimizes 5th and 7th harmonics
- Tightly controlled coil geometry to minimize loose wires and high-potential (voltage) crossovers
  - Better placement of phase paper
  - Reduced likelihood of buried coils.

Figure 2-105 shows the MMF patterns for a 36-slot, 4-pole winding. The three plots represent a two-layer concentric winding, a three-layer concentric winding, and a two-layer lap winding, span 1-8 (0.940 chord factor).

CONCENTRIC-TO-LAP CONVERSION

In choosing a replacement winding, the repairer has two options:

- Duplicate the winding already in the motor (provided it is the manufacturer's original).
- Choose a different style of winding which will give the same or better performance than the original.

The safest method of ensuring that efficiency is not reduced is to duplicate the original winding, keeping the end turns as short as possible (certainly no longer than those of the original winding) and increasing the copper cross-section when possible. For motors with 4 or more poles, a lap winding is usually superior to a concentric winding. For 2-pole designs, the coil extension is critical to heat dissipation. Too short an extension may result in an increase in I_2R losses. The end turn reactance (for 2-pole motors only) can be significantly greater for lap designs than for concentric windings. *Proceed with caution when considering a concentric-to-lap redesign of a 2-pole winding.*

A concentric winding is one in which each coil in the group has a different span. The coils of the group thus lay concentrically (one within another).

A lap winding is one in which all coils in the group have the same span. Thus, when placed in a motor they overlap each other–which gives us the term lap winding.

TABLE 2-49: DISTRIBUTION FACTOR FOR THREE-PHASE WINDINGS

Coils per group	Standard winding	Consequent pole winding	Concentric winding
1	1.000	1.000	The distribution factor is always equal to 1.0
2	0.966	0.866	
3	0.960	0.844	
4	0.958	0.837	
5	0.957	0.833	
6 or more	0.956	0.831	

Manufacturers use concentric windings because they can be wound efficiently by machines. From a repair standpoint, some concentric winding schemes use fewer coils than would be required with a lap winding; therefore less coil winding time is required. With only one coil side per slot, no separators are required.

Caution: Voltage stresses are higher in the coil extensions–where the conductors cross at oblique angles–than within the slots–where the strands are more-or-less parallel (see

"Voltage Stress: Not as simple as it sounds," in Section 2.13 of this manual. Phase insulation is therefore required in the coil extensions, even for concentric windings. It is also more difficult to reliably insert phase insulation between concentric coil groups than in a lap winding.

To make the conversion properly, first determine the effective turns per pole. To do so, multiply the turns in each coil in a group by the chord factor of that coil, and then add the products.

Effective turns per pole = $(T_1 \times k_{p1}) + (T_2 \times k_{p2}) + (T_3 \times k_{p3}) + \ldots$

Where: $T_1, T_2, T_3, \ldots$ = turns in each coil
$k_{p1}, k_{p2}, k_{p3}, \ldots$ = chord factor of each coil

The next step is to determine the effective turns per coil for the lap winding. To do this, divide the effective turns per pole by the number of coils in each group of the lap winding.

Because the coils in a group do not have a common center, a lap winding has a distribution factor. A span must be decided upon in order to determine the chord factor. The actual turns per coil may now be calculated by dividing the effective turns per coil by the product of the distribution factor times the chord factor. Distribution factors are shown in Table 2-49.

If the original concentric winding was connected for consequent pole operation (all groups have the same polarity), the calculated turns are actually the effective turns for two poles. Therefore, at some point, they must be divided by two.

Examples–Concentric-to-lap conversion

Use for: 4-pole and slower motors.

Use a double-layer, short-pitched lap winding (two coils per slot). The double-layer winding gives better performance than a single-layer lap winding.

Recommendation: Use the optimal pitch (83% = 0.966 chord factor) double-layer winding when practical.

To optimize the efficiency of a lap winding:

- Use a double-layer lap winding. Calculate chord factor and turns/coil to keep flux constant.
- Do not change turns per coil without making a corresponding change to chord factor.
- Use the same (preferably shorter) mean length turn (MLT).
- Same (preferably larger) copper cross-sectional area.
- Same (preferably lower) winding resistance (temperature corrected).

Notes for short-pitched lap winding:

- Chord factor = Sin[(8 x 90°)/9] = 0.985, or Cos[(1 x 90/9] = 0.985
- For constant flux, turns per coil increased 1/0.985 or 1.5%.

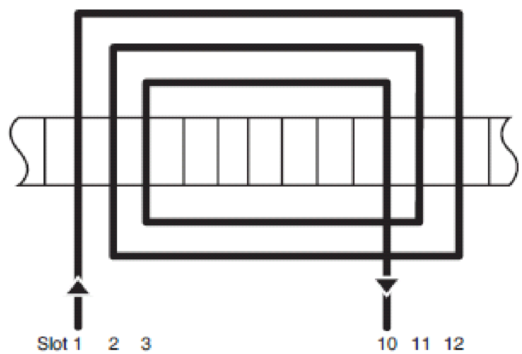
Example 1. 2-layer concentric to double-layer lap conversion, winding short-pitched 1-9 (span 8)

A 36-slot, 4-pole motor has 18 coils with 24 turns per coil; coil pitch for each group is 1-8, 10, 12 (see Figure 2-106).

From the table below, the chord factor for each separate coil pitch is:

Coil pitch	k_p
1-8	0.940
1-10	1.000
1-12	0.940

FIGURE 2-106



Concentric winding.

Coil pitch: 1-8, 10, 12; Spans 7, 9, 11

To calculate effective turns per pole for a complete group of coils:

$(T/C_1 \times K_{p1}) + (T/C_2 \times K_{p2}) + (T/C_3 \times K_{p3})$

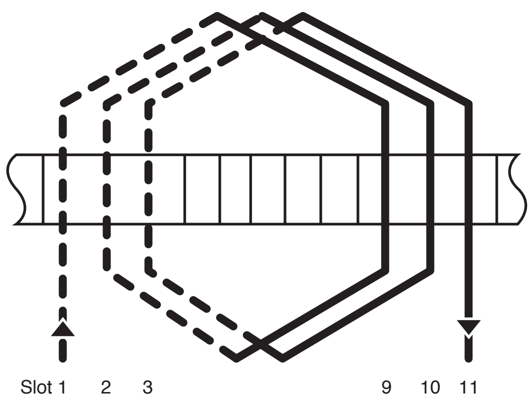
A suitable lap winding conversion would be calculated as follows:

24 turns per coil. Pitch: 1-8, 10, 12, resulting in chord factors of 0.940, 1.0 and 0.940, respectively.

24 (0.940) + 24 (1.0) + 24 (0.940) = 69.12 effective turns

FIGURE 2-107

(Dotted lines indicate coil sides in lower half of slot.)



Double-layer lap winding.

Coil pitch: 1-9; Span: 8

If a coil pitch of 1-9 (see Figure 2-107) is selected for the lap conversion:

69.12/3 = 23.04 effective turns per coil

Actual turns per coil are calculated by dividing the effective turns per coil by ($k_p \times k_d$):

23.04/(0.985 x 0.960) = 24.37 turns per slot

Rounding down to 24 turns will result in a flux increase of 1%.

(**Note:** When a concentric winding has only 1 coil side per slot, and the replacement lap winding has 2 coil sides per slot, divide the turns per slot value by 2 to obtain the turns per coil.)

Depending on the coil pitch selected for the lap winding, the turns per slot for the lap winding might be fewer than, equal to, or greater than the number of turns per slot for the original concentric design.

Example 2. Double-layer concentric to conventional double-layer lap winding conversion

Use for: Larger motors with 2 or more poles if repairer does not want to copy the original lap/concentric winding.

Advantages

- MLT can be made the same as that of the original winding (possibly shorter) on a coil group basis.
- Efficiency can be maintained or improved.
- All coils are the same.

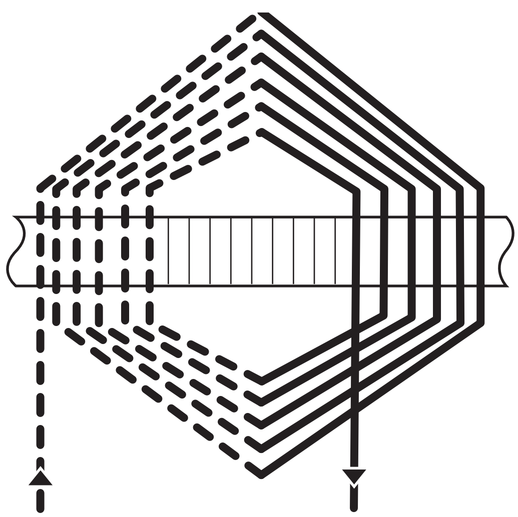
Caution

Care needed to calculate pitch of new winding correctly.

Example: Change a 4-pole, 72 slot stator having 12 coil groups with 6 coils per group and 15 turns per coil to a 72-slot, 2-layer winding with optimal pitch.

FIGURE 2-108

(Dotted lines indicate coil sides in lower half of slot.)



Coil group for concentric double-layer lap winding.

Coil pitch: 1-11, 13, 15, 17, 19, 21 (average 1-16) Spans: 10, 12, 14, 16, 18, 20.

The concentric winding (see Figure 2-108) would typically be pitched:

1-11 (span 10)	1-17 (span 16)
1-13 (span 12)	1-19 (span 18)
1-15 (span 14)	1-21 (span 20)

Average coil pitch = 1-16 (span 15)

Pole pitch is 72/4 = 1-19 (span 18)

If the same turns and wire size are used, efficiency will be maintained with a conventional double-layer lap winding pitched 1-16 (span 15).

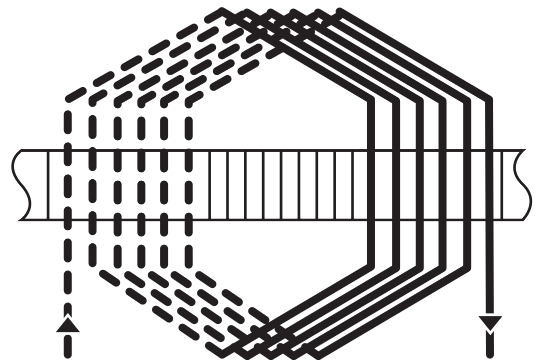
83.13/6 = 13.855 effective turns per coil

13.855/(0.966 x 0.956) = 15.00

Use 15 turns per coil; pitch of 1-16 (see Figure 2-109).

FIGURE 2-109

(Dotted lines indicate coil sides in lower half of slot.)



Coil group for conventional 2-Layer lap winding.

Coil pitch: 1-16; Span: 15; 63% = 0.966 Chord factor

CHANGING TO A TWO-LAYER LAP WINDING

Repairers often prefer to use lap windings because all coils have the same mean length of turn (MLT) and exposure to air flow for uniform cooling. The lap winding also results in a better MMF curve (better performance).

Advantages

- Efficiency can be maintained or improved. The double-layer winding gives best results
- MLT can be made the same as, or less than, that of the original winding
- All coils are the same.
- All coils have equal exposure to air flow for cooling.
- The MMF curve more closely resembles a sine wave.
- Phase insulation and coil bracing are more uniformly placed.

Disadvantages

- None, provided that the conversion is done correctly.
- May require wire area reduction for 2-pole windings, unless slot fill can be increased.

SPAN OR CHORD FACTOR CHANGE

The chord factor, also called pitch factor (k_p), is defined as the factor by which short pitching each coil of a lap winding would reduce the back electromagnetic force (emf), assuming the flux/pole is unchanged.

Mathematically, it is:

k_p= Sin [(teeth spanned x 90)/slots per pole]

or

k_p= Cos [((pole pitch - coil pitch) x 90)/pole pitch]

Note: Pole pitch is the number of slots per pole.

Example of pitch factor calculation. A 4-pole, 48-slot motor has a pole pitch of 12 slots (48 ÷ 4 = 12). A full-pitch lap coil would therefore span 12 teeth (1-13). If the coil pitch were reduced to 1-11), then:

k_p= Sin [(10 x 90) / 12] = 0.966, or

k_p= Cos [((12-10) x 90)/12] = 0.966

This applies to both single-layer and double-layer (i.e., two coils per slot) lap windings, but the latter gives a better air gap flux distribution. The degree to which coils can be short-pitched will be dictated to some extent by the number of slots/pole, and by slot size.

Coil pitch is commonly described either as a fraction of full pitch or as the chord factor of the angle. Ideal pitch for a motor with 4 or more poles is 83% of full pitch, or a chord factor of 0.966. For a 2-pole winding, the use of a shorter pitch is usually required to make coil insertion practical.

One method for eliminating a fractional part of a turn when making a redesign is to change the coil pitch. This results in a new chord factor. The formula is:

$T_2 = T_1 \times k_{p1}/k_{p2}$

Where:

T_2 = new turns per coil

T_1 = calculated or original turns per coil

k_{p1} = original chord factor

k_{p2} = new chord factor

The chord factor of 0.966 is the most effective in eliminating the adverse effects of harmonics that are present in all motors and generators. Unfortunately, this ideal pitch is not always possible to achieve. It is physically impossible, for instance, to have a pitch with a 0.966 chord factor on a 36-slot, 4-pole motor. With motors having 4 or more poles, the best results are obtained if the chord factor is kept between 0.900 and 0.991. On 2-pole motors, however, such a high chord factor would make winding very difficult, because the coil pitch would be almost halfway around the stator. Therefore, for 2-pole motors, the pitch is often shortened until the chord factor is between 0.707 and 0.866. (See Table 2-50 for common chord factors)

Chorded windings. A chorded or fractional pitch winding should be used whenever possible. It reduces the magnitude of air gap harmonics and decreases leakage reactance, thereby improving performance. The span of a chorded winding is always shorter than the span of a full-pitch winding. The chord factor for a full-pitch winding is 1.0.

The only time it is not advisable to use a chorded winding is when there is only one slot per pole per phase (i.e., groups of 1 coil), such as with a 36-slot, 12-pole winding.

Two-pole motors present special issues, especially when converting them from concentric to lap windings. The pitch is especially important. Certain coil pitches will cause harmonics that rob the motor of torque and affect performance. The key is to avoid certain coil pitches for 2-pole windings, and the "problem" pitch depends on the number of slots and the coil pitch. Table 2-51 summarizes the 2-pole coil pitches to avoid.

BENEFIT OF INCREASING COIL PITCH

Increasing the coil pitch has the advantage of requiring fewer turns per coil to produce the same flux, so the copper

TABLE 2-50: COIL PITCH/CHORD FACTOR

Coil pitch	Slots per pole											
	24	20	18	16	15	12	10	9	8	6	4	3
1-25	1.000	0.951	0.866									
1-24	0.998	0.972	0.906									
1-23	0.991	0.988	0.940	0.831								
1-22	0.981	0.997	0.966	0.882								
1-21	0.966	1.000	0.985	0.924	0.866							
1-20	0.947	0.997	0.996	0.957	0.914							
1-19	0.924	0.988	1.000	0.981	0.951							
1-18	0.897	0.972	0.966	0.995	0.978	0.793						
1-17	0.866	0.951	0.983	1.000	0.995	0.863						
1-16	0.831	0.924	0.966	0.995	1.000	0.924	0.707					
1-15	0.793	0.891	0.940	0.981	0.995	0.966	0.809	0.643				
1-14	0.752	0.853	0.906	0.957	0.978	0.991	0.891	0.766				
1-13	0.707	0.809	0.866	0.924	0.951	1.000	0.951	0.866	0.707			
1-12		0.760	0.819	0.882	0.914	0.991	0.988	0.940	0.831			
1-11		0.707	0.766	0.931	0.866	0.966	1.000	0.985	0.924			
1-10			0.707	0.743	0.809	0.924	0.988	1.000	0.981	0.707		
1-9			0.643	0.707	0.743	0.866	0.951	0.985	1.000	0.866		
1-8				0.634	0.669	0.793	0.891	0.940	0.981	0.966		
1-7				0.556	0.588	0.707	0.809	0.866	0.924	1.000	0.707	
1-6					0.500	0.609	0.707	0.766	0.831	0.966	0.9224	
1-5							0.588	0.643	0.707	0.866	1.000	0.868
1-4									0.556	0.707	0.924	1.000
1-3											0.707	0.866

TABLE 2-51: COIL PITCHES TO AVOID

	18 Slot, 2 pole		24 Slot, 2 pole	36 Slot, 2 pole		48 Slot, 2 pole	54 Slot, 2 pole		60 Slot, 2 pole	
Coil pitch	**1-7**	**1-6**	**1-9**	**1-12**	**1-11**	**1-15**	**1-17**	**1-16**	**1-18**	**1-19**
K_p	0.866	0.831	0.966	0.819	0.766	0.793	0.802	0.766		
5th Harm.	5%	6%	6%	5%	5.1%	5.1%	5.1%	5%	5%	5%
7th Harm.	<3%	<3%	<3%	<3%	<3%	<3%	<3%	<3%		

area can be increased in inverse proportion to the turn change. As part of any redesign involving a 2-pole (e.g., a concentric-to-lap conversion), coil pitch selection should consider the calculated turns per coil, the flux density and the desirability of the coil pitch options. Be sure to maintain the same magnetic flux densities.

To determine the new turns per coil, divide the old k_p by the new k_p, and multiply by the old turns per coil. For example, a 100 hp, 2-pole motor has 36 slots, and the following data: 13 turns per coil, pitch 1-11, 2-delta connection. Checking Table 2-51, we find that the original coil pitch has a 5.1% 5th harmonic. One option is to increase the coil pitch to 1-14, which has less than 3% harmonic content. The new turns per coil are determined by:

13 x (0.766/0.904) = 11

In this case, increasing the coil pitch by 3 slots will reduce the required turns per coil from 13 to 11. The increased slot room permits a wire area increase of 18% (13/11 = 1.18) without increasing the slot fill.

That increase in wire area reduces the winding (I^2R) losses, meaning the motor should operate cooler.

The performance was improved without making the windings tighter in the slots, so insertion time should not increase.

Reduced I^2R losses improve reliability and in this case could increase the efficiency by close to ½ a percentage point.

Many 2-pole motors in service have less-than-optimum coil pitches, offering possible opportunities to improve performance and better serve our customers.

When a 2-pole motor requires rewind, coil pitch is one variable the service center can control. Avoid certain coil pitches, when possible, to prevent reduction in performance. Increasing the coil pitch permits the use of fewer turns, with an increase in copper area. For any design change, coil pitch is one of several variables. Use Table 2-51 to avoid selecting the wrong coil pitch.

Consider the bore diameter when considering an increase in coil pitch. A change of more than 2 slots is not generally recommended.

Another consideration with 2-pole machines is the effect of end turn reactance. The coil pitch of a 2-pole machine is large enough that the coil extension plays a larger role in starting current than is true of lower speed machines. The starting current may be decreased by an increase in coil pitch even at the same magnetic flux densities. To restate this: Even with a redesign that yields the same air gap density, using too short a coil pitch can result in a motor drawing higher starting current, and nuisance tripping when the motor is installed.

DISTRIBUTION FACTOR

The distribution factor, K_d, simply put, accounts for the fact that all coils in a group are not centered on the group (see Table 2-50). Instead of being concentrated, like a concentric winding, they are spread out, or distributed, over a number of slots. Because the coils are distributed, they do not simultaneously contribute to the torque.

K_d is calculated from the formula:

K_d= sin (nd°/2), or K_d = n x sin (d°/2)

Where:

k_d= distribution factor

n = number of slots per pole per phase

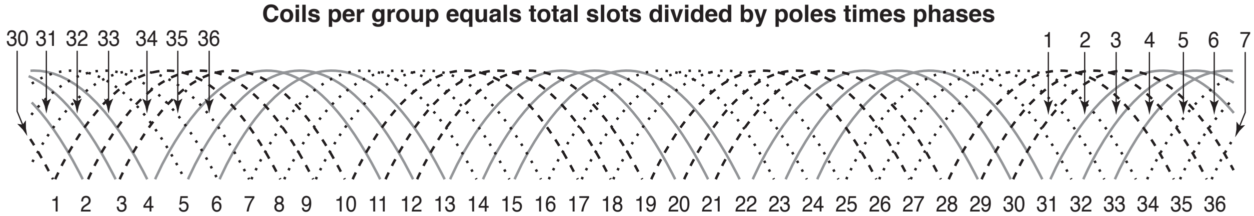
d°= number of electrical degrees between slots occupied by coils of the group*

* Textbooks usually calculate K_d using electrical degrees per slot. That method does not take into account the full-slot lap winding.

It follows, then, that coil placement affects the actual distribution factor. Figure 2-110 shows the standard two-layer lap winding where each slot contains a top and bottom coil and the number of coils per group = total slots divided by (poles times phases). There are two variations of full-slot lap windings where each slot contains only one coil side. In Figure 2-111, the coils are placed in adjacent slots, whereas in Figure 2-112 they are inserted skip-slot.

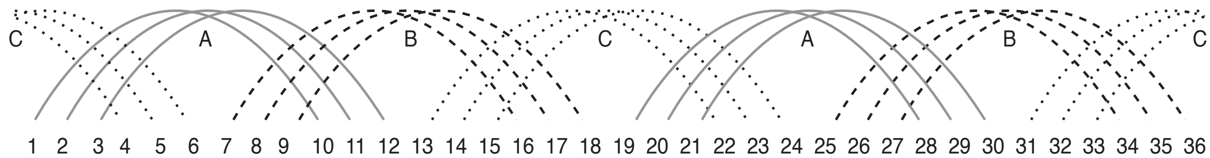
FIGURE 2-110

Coils per group equals total slots divided by poles times phases



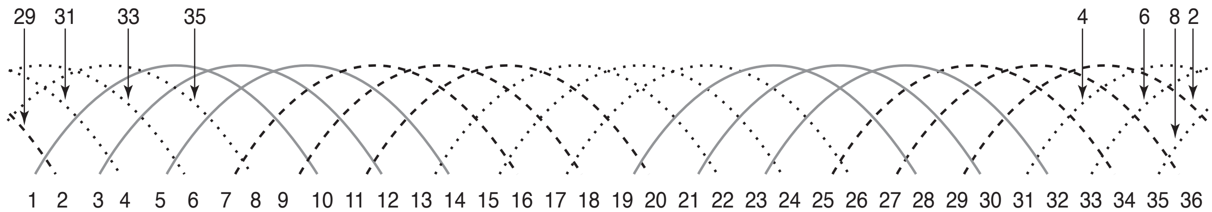
Standard 2-layer lap winding with a top and a bottom coil in each slot.

FIGURE 2-111



Coils placed in adjacent slots.

FIGURE 2-112



Coils inserted skip-slot.

For a 48 slot, 4-pole winding, here are the results:

Standard lap winding: $k_d =$ 0.958

Full-slot lap (sequential slots): 0.966

Full-slot lap (skip slot): 0.991

The portion of the total stator bore covered by the group varies, depending on the method used. Therefore the k_d also differs. Not shown by the basic calculation is the effect when each slot no longer contains two coil sides. The result is a marked increase in harmonics. For the skip-slot method, the ratio of k_d to the fundamental harmonic is shown below.

Method	5th Harmonic	7th Harmonic
Standard lap	21%	17%
Skip slot lap	80%	61%

When there is an unequal number of coils per group, the k_d is determined by the numerator of the reduced fraction for the grouping. See Table 2-52 (Page 2-184) for more details.

The k_d also is calculated differently for consequent poles compared to a standard winding with salient poles. The standard winding has wound north and south poles, whereas the consequent winding has poles wound for one polarity only. For example, if the north poles are wound, then the south poles are created as a consequence of the wound poles. The unwound poles are sometimes termed "phantom" poles.

Traditional concentric windings, with their common center, always have a k_d of 1.000. However, manufacturers sometimes use a repeated sequence concentric winding in 2-pole machines, which requires a change to the distribution factor to properly account for it.

Standard/salient pole:

$$\text{Distribution factor} = \frac{\text{Sin}\left(A \times \frac{B}{2}\right)}{B \times \text{Sin}\left(\frac{A}{2}\right)}$$

Consequent pole:

$$\text{Distribution factor} = \frac{\text{Sin}\left(\frac{A \times B}{2}\right)}{2 \times B \times \text{Sin}\left(\frac{30}{B}\right)}$$

Where: A = 180/slots per pole

B = slots/(poles* x phases)

*Use wound poles to calculate B

The complex formulas above illustrate that it is better to use the K_d table (Table 2-49). The chance of an error is great with so many fractions to calculate and convert to trigonometric (sin) functions, and with many values in parentheses.

LAP-TO-CONCENTRIC CONVERSION

When the goal is to convert a lap winding to a concentric winding, the first step is to determine the concentric winding pattern desired. This choice is often dictated by the winder's familiarity, or by the concentric winding heads available.

Once the desired pattern has been selected, use "Conversion Factors for Lap and Concentric Windings" in Section 2.13 of this manual to find the multiplier used to convert this particular pattern to a lap winding. Apply the multiplier as a divisor to the lap winding turns to determine the required turns/coil for the equivalent concentric winding. Fractions can be dealt with by changing the circuits, changing between wye and delta connection types, or by using a slightly different turn count for one coil of the group (usually the widest coil pitch).

To double-checked the result, run it through the *EASA AC Motor Verification and Redesign* program as a concentric-to-lap conversion and compare the result to the original lap winding. Another alternative is to input the lap and concentric winding data separately into the program, and compare the magnetic flux densities. If the air gap density is within 2%, the redesign was correctly done.

CAUTIONS

Magnetic flux limits. Do not change winding data just because it has "high" or "low" flux densities. The criteria used are intended to serve as a guide only. Manufacturers may have application-related reasons for intentionally using values that are exceptional. Compared to approximately 1960, manufacturers today obtain nearly 4 times the kW/hp per unit of core weight.

Torque is proportional to the square of the flux density. Flux density is inversely proportional to the number of coil turns. Thus, increasing winding turns by 10% would reduce the torque to 81% (0.9 x 0.9). This illustrates the importance of properly counting the turns.

The no-load current, compared to the full-load current rating, will be relatively low for low fluxes. Conversely, high flux density designs will draw higher no-load amps. The no-load amps may even approach the FLA rating for high flux or low speed designs (high number of poles).

Circuit change. When the turns per coil of a redesigned winding do not calculate to a whole number, the fractional part of a turn may be eliminated by changing the number of parallel circuits. Circuits and turns/coil may be changed in direct proportion, without reducing performance.

There are limits to the number of parallel circuits that can be used:

- The number of circuits cannot be more than the number of poles. (The exception is an interleaved winding.)
- The number of poles must be equal to or be a multiple of the number of circuits.
- Unequal (odd) grouping limits the number of circuits. There must be the same number of turns in each path of the parallel circuit.
- The volts per coil of a random winding should not exceed 80, if possible. The voltage stresses are highest in the coil extensions, where wires cross at sharp angles.

If the original design of a motor has few turns and a large wire size or many wires in hand, it may be easier to rewind if the number of parallel circuits is increased. Doubling the circuits, for example, doubles the turns per coil and halves the wire area in hand. **Caution:** doubling the circuits also doubles the volts per coil.

To reduce the number of wires in multiple, winders may want to increase the number of parallel circuits when winding an AC stator (or wound rotor). However, the number of parallel circuits that can be used in an AC winding is limited to integer multiples of the poles. See Table 2-52.

TABLE 2-52: PERMISSIBLE CIRCUITS FOR VARIOUS POLE COUNTS (3 PHASE WINDINGS)

Poles/Circuits	1	2	3	4
2	Yes	Yes	—	—
4	Yes	Yes	No	Yes
6	Yes	Yes	Yes	No
8	Yes	Yes	No	Yes

Motor manufacturers are using concentric windings for progressively larger motors. Often, these designs have a low number of turns per coil. Therefore, it is often desirable to increase the number of parallel circuits, to reduce the number of wires in hand required for the coil-making process.

Maximum circuits. The number of parallel circuits cannot be more than the number of poles. One exception is the interleaved winding, where for example it is possible to have a 4-circuit connection on a 2-pole motor. With the interleaved winding, each group is divided into paralleled subgroups, resulting in double the allowable circuits, as well as double the turns. For more information on interleaved windings, refer to the January 2003 issue of *EASA Currents*, "Interleaved Windings Provide Useful Alternative."

Additionally, except for a few special cases, the number of poles must be equal to or a multiple of the number of circuits. For example, a 2-delta connection on a 6-pole winding cannot be changed to a 4-delta connection.

Coil grouping. Use the coil grouping tables beginning on Page 2-206 of this manual to determine the correct unequal coil grouping sequence for the connection required. Some grouping sequences only work for adjacent- or skip-pole connections, but not for both.

Volts per coil. For form-wound coils, the turn-to-turn voltage stresses are used to determine the required insulation between turns. For random-wound coils, the volts per coil (V/C) is the main concern. The voltage stresses are greatest between adjacent strands in the coil extensions. They can be from different groups or phases, raising the voltage potential between them.

$$\text{Volts per coil} = \frac{(\text{3 phases x phase voltage x circuits})}{\text{Coils}}$$

Where:

Phase voltage for a delta connection = line voltage

Phase voltage for a wye connection = 0.58 x line voltage

Voltage stresses in excess of approximately 90 volts/coil should alert the winder to use additional phase insulation midway through each coil group to reduce the risk of failure. In general, if a winding has as many delta circuits as poles, the volts/coil stresses warrant the additional insulation. Volts/coil stresses are calculated according to the formula:

$$\text{Volts per coil stresses} = \frac{(\text{Phase voltage x circuits})}{(\text{Turns per coil x coils})}$$

INCREASE THE COPPER CROSS-SECTION IN EACH COIL

It often is possible to increase the copper cross-section in each coil when hand winding motors which were originally machine wound, or when rewinding an older motor. It is more difficult and may be impractical to do so with higher efficiency motors (EPACT, EFF1 or NEMA Premium Efficiency™ grades). When possible, it is a useful way of further reducing I^2R losses and helping to maintain (or improve) motor efficiency after a repair.

Experience will tell how much the copper area can be increased. The best method is to change conductor sizes in each coil, remembering that the slot fill (i.e., the cross-section of copper in each slot ÷ slot area) increases if fewer, larger conductors are used–but so also does the difficulty of inserting the winding. Record the wire sizes used in the new winding.

Too large a wire size leaves large voids between strands within the slot. Too small a wire size results in many multiple strands of small wire, with a higher proportion of film insulation to copper wire. AWG wire sizes from #15 to #18 (or metric wires between 1.0 and 1.5 mm) work best in most slot cross-sections. To determine the largest wire size that can be comfortably used, try inserting two wires side-by-side into the slot opening. If it is a tight fit, use the next size smaller wire.

TABLE 2-53: EFFECT OF CHANGES TO THE END TURN LENGTH ON TYPICAL TEFC/IP54, 460V DESIGNS

HP/kW	Poles	End turn length	Full load efficiency (%)	Total losses (watts)	Change in total losses (%)
50/37	4	10% short	93.1	2746	-2.8
		Nominal	93.0	2825	
		10% long	92.8	2911	3.0
100/75	4	10% short	94.9	4020	-2.6
		Nominal	94.8	4129	
		10% long	94.6	4243	2.8
200/150	4	10% short	95.6	6921	-2.5
		Nominal	95.5	7099	
		10% long	95.3	7278	2.5
50/37	2	10% short	92.7	2935	-2.9
		Nominal	92.5	3024	
		10% long	92.3	3122	3.2
100/75	2	10% short	93.9	4881	-3.3
		Nominal	93.7	5047	
		10% long	93.5	5212	3.3
200/150	2	10% short	95.1	7697	-2.3
		Nominal	95.0	7875	
		10% long	94.9	8075	2.5

Caution: Effect of increasing wire size. In the past, there was a misconception that the horsepower/kW rating of very old motors could be increased by rewinding them using larger wire than the original, or by increasing the temperature rating of the insulation system with the same turns. This is untrue. NEMA and IEC standards specify the starting torque and the maximum torque motors are to produce according to their rated output power and rpm.

Using larger wire or improving the temperature rating of the insulation will not increase the torque. Consequently, such measures will *NOT* increase the rated hp or kW. Increasing wire size, however, does reduce the winding loss and temperature rise under a given load, so the motor can be operated at a higher overload or service factor. (Overload is when a motor operates beyond its rated torque design hp or kW.)

MINIMIZE THE LENGTH OF THE COIL EXTENSIONS

The coil extensions consist of “inactive” copper, merely serving to connect the “active” conductors or coil-sides inside the slots. For the majority of stator windings, especially in 2-pole and 4-pole motors, the coil extension copper weight exceeds that of the copper in the slots, and therefore makes a dominant contribution to the total stator I^2R losses. It is important therefore to keep the coil extensions as short as possible. If the mean turn length (MLT) of the rewind exceeds the original, the I^2R losses will increase.

Attention to the following rules will prevent this:

- Keep the coil extensions within the measured dimensions of the original winding.
- Do not extend the slot insulation beyond the slot ends any more than is necessary to prevent voltage creepage.
- Do not extend the straight portions of the coil sides any farther than necessary.

Reducing the length of the coil extension will reduce the amount of copper in the winding and reduce losses. Taking this too far, however, can make coil insertion difficult or even impossible. Cooling may even be affected. In extreme cases, the winding temperature may increase. See Table 2-53.

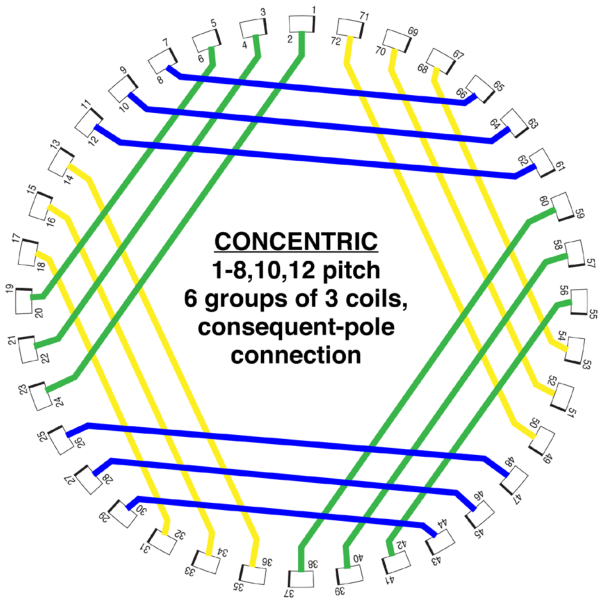
Figure 2-113, Figure 2-114, Figure 2-115 and Figure 2-116 on the following page provide comparative examples of winding designs that use consequent-pole and salient pole connections for a motor with 4 poles and 36 slots.

By careful duplication of the winding and coil dimensions, it is usually possible to equal or improve the performance of the manufacturer’s original winding in regard to copper losses. Record the coil dimensions of the new winding.

Note: This article was originally published as *EASA Tech Note 47* (April 2011); it was reviewed and updated as necessary in August 2016.

FIGURE 2-113

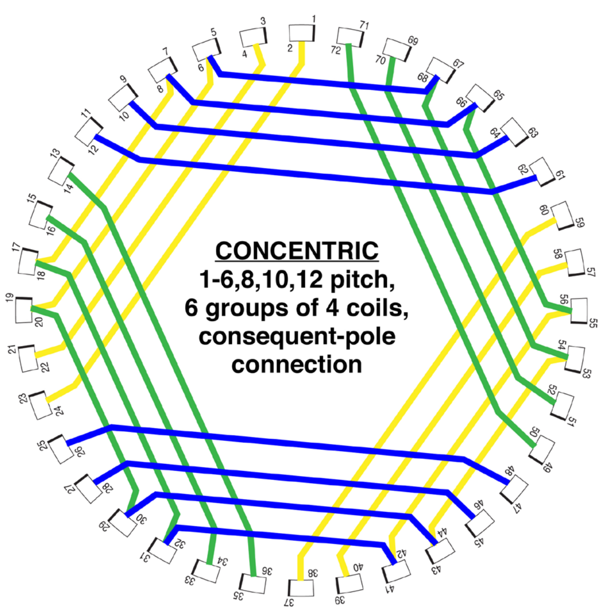
4 poles, 36 slots



This is one of the most common concentric winding designs. Six groups of coils are connected consequent-pole. It has no shared slots, making it quick and easy to insert, but the efficiency of later designs is better.

FIGURE 2-114

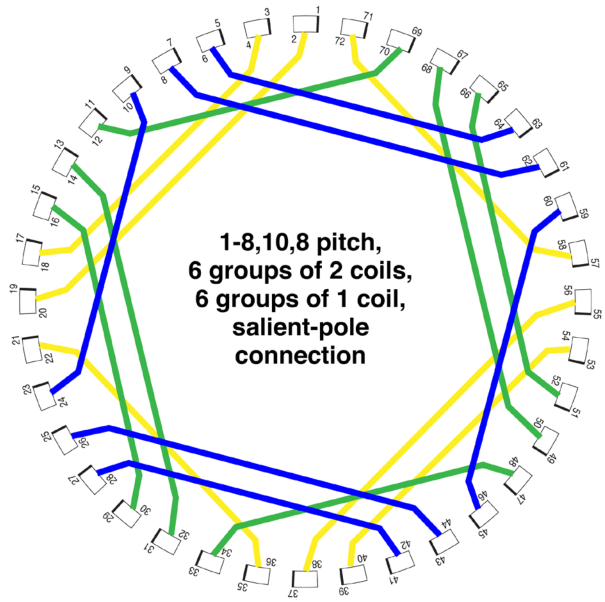
4 poles, 36 slots



This design uses shared- and full-slots, resulting in better efficiency than the design shown in Figure 2-113. Phase insulation requires more care.

FIGURE 2-115

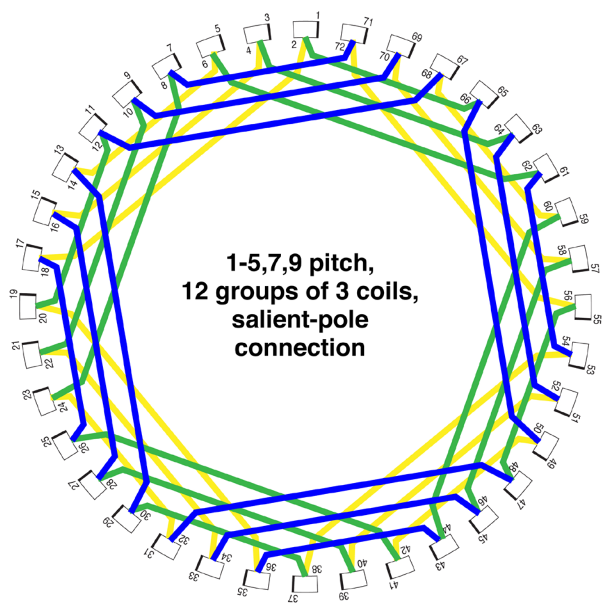
4 poles, 36 slots



This variant is similar to Figure 2-113, but slightly less efficient.

FIGURE 2-116

4 poles, 36 slots



This design, with all shared slots, is more efficient than the other 3 schemes shown. It offers no advantage over the lap winding, either in material or efficiency. Because all slots harbor 2 coils, it is sometimes referred to as a "concentric lap" winding.

Conversion factors for lap and concentric windings

The tables on the following pages have been developed to aid in making winding conversions between concentric and lap windings. Although the EASA Technical Services Committee does not recommend changing the winding configuration, they want you to do it right when you find it necessary to do so. **The lap windings used with these charts are always salient pole with two coil sides per slot.**

The term "N" stands for the number of turns for the inside coil of the concentric winding. The figure preceding "N" on coils other than the inside coil is a factor obtained by dividing the turns of that coil by the turns of the inside coil. That is, if there are 10 turns on the inside coil and 20 turns on a second coil, the configuration is N-2N.

The conversion factors were arrived at by the method shown in the EASA's *AC Motor Redesign* book (see the chapter on "Converting Concentric Windings to Lap Windings"). To obtain the lap winding turns for a concentric-to-lap change, multiply the turns of the inside coil by the conversion factor for the lap winding span intended to be used. For a lap-to-concentric conversion, select the type of concentric winding desired and then divide the lap winding turns by the conversion factor for the span the lap winding had. This gives the turns "N" for the inside coil. For other coils, multiply "N" by its preceding factor to obtain the turns for those coils.

EXAMPLE 1—CONCENTRIC TO LAP

4 poles, 48 slots, 36 coils, 5-10-15 turns, with spans of 1-8-10-12.

N = 5, 10/5 = 2, 15/5 = 3.

Therefore, the turns ratio is N-2N-3N.

Multiplying 5 (N) by the conversion factors for the recommended spans yields:

Span	"N"	Conversion factors	New turns
1-10	5	1.586	7.93
1-11	5	1.517	7.585
1-12	5	1.478	7.39
1-13	5	1.465	7.325

Since the 1-10 span line is closest to a whole number, the lap winding will be 8 turns at a 1-10 span. Use the same connection and same wire size, if possible. However, in this example it may not be possible. The original winding had 15 turns in a slot. The new winding will have 16 turns plus a center stick. The wire size may have to be reduced, which is one of the disadvantages of making these conversions.

EXAMPLE 2—LAP TO CONCENTRIC

4 poles, 36 slots, 8 turns, 1-8 span.

Concentric winding is to be 18 coils, spans 1-8-10-12, with all coils having "N" turns.

Conversion factor for a 1-8 span is 0.532.

New turns = 8/0.532 = 15.04.

Use 15 turns with the same wire size and connection.

Note: This article was originally published as *EASA Tech Note 12*; it was reviewed and updated as necessary in August 2016.

Caution: Do not change hazardous location motor windings from concentric to lap or vice versa.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED

2 POLES—18 SLOTS

Coils	Concentric winding		Lap winding				
	Coil spans	Turns ratio	Coil span and conversion factor				
			1-6*	1-7*	1-8	1-9	1-10*
12	1-7,9	N-2N	1.286	1.137	1.048	1.000	0.985
	1-8,8,10	N-N-N	—	—	0.530	—	—
18	1-5,7,9	N-.85N-1.7N	1.384	1.224	1.128	1.077	1.060
		N-N-N	1.131	1.000	0.921	0.879	0.866

2 POLES—24 SLOTS

Coils	Concentric winding		Lap winding						
	Coil spans	Turns ratio	Coil span and conversion factor						
			1-7	1-8	1-9*	1-10	1-11	1-12	1-13*
12	1-10,12	N-N	0.707	0.630	0.577	0.541	0.517	0.504	0.500
		N-1.15N	0.762	0.679	0.622	0.583	0.557	0.543	0.539
18	1-8,10,12	N-N-2N	1.365	1.217	1.115	1.045	1.000	0.974	0.965
		N-1.75N-2.5N	1.804	1.608	1.473	1.380	1.320	1.287	1.275
		N-2N-3N	2.072	1.847	1.692	1.586	1.517	1.478	1.465
		N-2.15N-3.15N	2.178	1.942	1.778	1.667	1.594	1.554	1.540
24	1-5,7,9,11	N-N-N-N	1.122	1.000	0.916	0.858	0.821	0.800	0.793
	1-6,8,10,12	N-N-N-N	1.224	1.092	1.000	0.937	0.896	0.873	0.866
		N-1.25N-1.5N-2.25N	1.926	1.717	1.573	1.474	1.410	1.374	1.362
		N-1.25N-1.65N-2.45N	2.050	1.827	1.673	1.568	1.500	1.462	1.449
	1-7,9,11,13	N-N-N-N	1.306	1.165	1.066	1.000	0.956	0.932	0.924
	1-10,11,11,12	N-.63N-.63N-N	1.156	1.031	0.944	0.885	0.846	0.825	0.817
30	1-5,7,9,11,13	N-1.15N-1.4N-1.6N-.8N	1.798	1.603	1.468	1.376	1.316	1.283	1.271
36	1-3,5,7,9,11,13	.5-N-N-N-N-N-.5N	1.35	1.207	1.106	1.037	0.991	0.966	0.957

2 POLES—30 SLOTS

Coils	Concentric winding		Lap winding							
	Coil spans	Turns ratio	Coil span and conversion factor							
			1-9	1-10*	1-11	1-12	1-13	1-14	1-15	1-16*
18	1-11,13,15	N-1.75N-1.75N	1.201	1.103	1.031	0.977	0.939	0.913	0.897	0.893
		N-2N-2N	1.338	1.229	1.148	1.088	1.046	1.017	1.000	0.994

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

2 POLES—36 SLOTS

Coils	Concentric winding		Lap winding									
	Coil span	Turns ratio	Coil span and conversion factor									
			1-10	1-11*	1-12*	1-13	1-14	1-15	1-16	1-17	1-18	1-19*
18	1-14,16,18	N-N-N	0.707	0.653	0.611	0.577	0.552	0.532	0.518	0.508	0.502	0.500
		N-N-1.1N	0.732	0.675	0.613	0.597	0.571	0.550	0.536	0.525	0.519	0.517
		N-N-1.25N	0.769	0.709	0.664	0.627	0.600	0.578	0.563	0.552	0.546	0.543
		N-1.33N-1.33N	0.867	0.800	0.748	0.708	0.676	0.652	0.634	0.622	0.615	0.613
		N-1.4N-1.4N	0.637	0.639	0.646	0.659	0.677	0.703	0.753	0.778	0.831	0.901
	1-14,16,18,20, 22, 24	N-N-N-N-N-N	0.707	0.653	0.611	0.577	0.552	0.532	0.518	0.508	0.502	0.500
30	1-10,12,14,16, 18	N-N-N-N-2N	1.329	1.227	1.147	1.085	1.037	1.000	0.973	0.954	0.943	0.940
36	1-5,7,9,11,13, 15	N-N-N-N-N-N	1.000	0.923	0.864	0.817	0.781	0.752	0.732	0.718	0.710	0.707
	1-8,10,12,14, 16, 18	N-N-N-N-N-N	1.225	1.130	1.057	1.000	0.956	0.921	0.896	0.879	0.869	0.866
		N-1.17N-1.33N-N-1.17N-1.33N	1.443	1.332	1.245	1.178	1.125	1.085	1.056	1.036	1.024	1.020
		N-1.25N-1.5N-1.6N-1.7N-1.8N	1.867	1.723	1.611	1.524	1.457	1.404	1.366	1.340	1.325	1.320
		N-1.5N-1.65N-1.8N-1.9N-2.05N	2.094	1.933	1.808	1.710	1.634	1.575	1.533	1.503	1.487	1.481
	1-12,14,16,12, 14, 16	N-N-N-N-N-N	1.327	1.225	1.145	1.083	1.035	0.998	0.971	0.953	0.942	0.938
	1-13,15,17,13, 15, 17	N-N-N-N-N-N	1.376	1.270	1.188	1.123	1.073	1.035	1.007	0.988	0.977	0.973
	1-14,16,18,14, 16, 18	N-N-N-N-N-N	1.414	1.305	1.221	1.155	1.104	1.064	1.035	1.015	1.004	1.000

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

2 POLES—48 SLOTS

Coils	Concentric winding		Lap winding									
	Coil span	**Turns ratio**	**Coil span and conversion factor**									
24			**1-13**	**1-14**	**1-15***	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-18,20,22,24	N-N-N-N	0.707	0.665	0.630	0.602	0.577	0.557	0.541	0.528	0.517	.510
										1-23	**1-24**	**1-25***
										0.504	0.501	0.500
			1-13	**1-14**	**1-15***	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-18,20,22,24	N-1.2N-N-1.2N	0.779	0.733	0.694	0.663	0.636	0.614	0.596	0.582	0.570	0.562
										1-23	**1-24**	**1-25***
										0.556	0.552	0.551
			1-13	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
		N-1.25N-N-1.25N	0.797	0.749	0.711	0.678	0.651	0.628	0.610	0.595	0.583	0.574
										1-23	**1-24**	**1-25***
										0.569	0.565	0.563
48			**1-13**	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-10,12,14,16,	N-N-N-N-N-N-N-N	1.224	1.151	1.092	1.042	1.000	0.965	0.937	0.914	0.896	0.882
	18, 20,22,24									**1-23**	**1-24**	**1-25***
										0.873	0.867	0.866
			1-13	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-12,14,16,18,	N-N-N-N-N-N -N-N	1.213	1.141	1.082	1.032	0.991	0.956	0.928	0.906	0.888	0.874
	20,14,16,18									**1-23**	**1-24**	**1-25***
										0.866	0.860	0.858
			1-13	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-12,14,16,18,	N-N-N-N-N-N-N-N	1.307	1.229	1.162	1.111	1.067	1.030	1.000	0.976	0.957	0.942
	20,22,24,26									**1-23**	**1-24**	**1-25***
										0.932	0.926	0.924
			1-13	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-14,16,18,20,	N-1.5N-N-1.5N-N-	1.714	1.612	1.527	1.457	1.399	1.351	1.311	1.280	1.254	1.235
	22,24,26,28	1.5N-N-1.5N								**1-23**	**1-24**	**1-25***
										1.222	1.214	1.212
			1-13	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-16,18,20,22,	N-N-N-N-N-N-N-N	1.353	1.272	1.206	1.150	1.104	1.066	1.035	1.010	.990	.975
	16,18,20,22									**1-23**	**1-24**	**1-25***
										0.964	0.959	0.956
			1-13	**1-14**	**1-15**	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**
	1-18,20,22,24,	N-N-N-N-N-N-N-N	1.414	1.329	1.261	1.203	1.154	1.115	1.082	1.056	1.035	1.019
	18,20,22,24									**1-23**	**1-24**	**1-25***
										1.009	1.002	1.000

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

2 POLES—54 SLOTS

Coils	Concentric winding		Lap winding									
	Coil span	Turns ratio	Coil span and conversion factor									
30	1-20,22,24,26,28	N-N-N-N-.5N	**1-15**	**1-16***	**1-17***	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**	**1-23**	**1-24**
			0.687	0.652	0.623	0.598	0.577	0.559	0.544	0.532	0.522	0.514
									1-25	**1-26**	**1-27**	**1-28***
									0.507	0.503	0.501	0.500

2 POLES—60 SLOTS

Coils	Concentric winding		Lap winding									
	Coil span	Turns ratio	Coil span and conversion factor									
30	1-22,24,26,28,30	N-N-N-N-N	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**	**1-23**	**1-24**	**1-25**
			0.707	0.673	0.643	0.618	0.596	0.577	0.561	0.547	0.535	0.525
							1-26	**1-27**	**1-28**	**1-29**	**1-30**	**1-31***
							0.517	0.511	0.506	0.503	0.500	0.500
		N-N-1.15N-1.15N-1.15N	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**	**1-23**	**1-24**	**1-25**
			0.772	0.735	0.703	0.675	0.651	0.631	0.613	0.598	0.585	0.574
							1-26	**1-27**	**1-28**	**1-29**	**1-30**	**1-31***
							0.565	0.558	0.553	0.549	0.547	.546
		N-N-1.2N-1.2N-1.2N	**1-16**	**1-17**	**1-18**	**1-19**	**1-20**	**1-21**	**1-22**	**1-23**	**1-24**	**1-25**
			0.795	0.756	0.723	0.694	0.670	0.649	0.631	0.615	0.602	0.591
							1-26	**1-27**	**1-28**	**1-29**	**1-30**	**1-31***
							0.582	0.574	0.569	0.565	0.563	0.562

2 POLES—72 SLOTS

Coils	Concentric winding		Lap winding									
	Coil span	Turns ratio	Coil span and conversion factor									
36	1-26,28,30,32,34,36	N-N-N-N-N-N	**1-19**	**1-20**	**1-21**	**1-22**	**1-23**	**1-24**	**1-25**	**1-26**	**1-27**	**1-28**
			0.707	0.678	0.652	0.630	0.610	0.593	0.577	0.563	0.551	0.541
				1-29	**1-30**	**1-31**	**1-32**	**1-33**	**1-34**	**1-35**	**1-36**	**1-37***
				0.531	0.524	0.517	0.512	0.507	0.504	0.502	0.500	0.500

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

4 POLES—24 SLOTS

Coils	Concentric winding		Lap winding	
	Coil span	Turns ratio	Coil span and conversion factor	
			1-6	**1-7***
12	1-6,8	N-N	0.518	0.500
18	1-4,6,8	N-N-2N	0.966	0.933
24	1-4,6	N-N	0.896	0.866
		N-1.5N	1.155	1.116
	1-5,7	N-N	1.000	0.966
36	1-3,5,7	N-4N-2N	3.196	3.087

4 POLES—36 SLOTS

Coils	Concentric winding		Lap winding		
	Coil span	Turns ratio	Coil span and conversion factor		
			1-8	**1-9**	**1-10***
18	1-8,9,9	N-N-N	0.537	0.513	0.505
	1-8,10,8	N-.6N-.8N	0.423	0.404	0.398
		N-.64N-N	0.465	0.444	0.437
		N-.7N-N	0.495	0.472	0.465
		N-.75N-N	0.486	0.464	0.457
		N-N-N	0.532	0.508	0.500
	1-8,10,12	N-N-N	0.532	0.508	0.500
		N-1.08N-1.25N	0.590	0.563	0.555
		N-1.1N-1.1N	0.568	0.542	0.534
		N-1.15N-1.15N	0.586	0.559	0.551
		N-1.25N-1.5N	0.665	0.635	0.625

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

4 POLES—36 SLOTS—CONTINUED

Coils	Concentric winding		Lap winding		
	Coil span	Turns ratio	Coil span and conversion factor		
			1-8	1-9	1-10*
24	1-6,8,10,12	N-N-2N-2N	1.032	0.985	0.970
	1-7,9	N-1.5N	0.866	0.826	0.814
		N-1.65N	0.920	0.878	0.865
		N-1.8N	0.975	0.930	0.916
		N-1.9N	1.011	0.965	0.951
		N-2N	1.048	1.000	0.985
		N-2.1N	1.084	1.034	1.019
		N-2.25N	1.139	1.087	1.070
		N-2.4N	1.193	1.139	1.122
		N-2.66N	1.288	1.223	1.210
		N-2.85N	1.357	1.295	1.275
		N-3N	1.411	1.347	1.327
	1-7,9,11,13	N-2N-2N-N	1.048	1.000	0.985
	1-8,10	N-.3N	0.458	0.437	0.431
		N-.44N	0.510	0.486	0.479
		N-.5N	0.532	0.508	0.500
		N-.6N	0.569	0.543	0.535
30	1-6,8,10,6,8	N-N-2N-N-N	1.000	0.954	0.940
36	1-5,7,9	N-N-N	0.921	0.879	0.866
		N-1.25N-1.25N	1.092	1.042	1.027
		N-1.4N-1.8N	1.340	1.279	1.260
		N-1.4N-2N	1.413	1.348	1.328
		N-1.9N-2.1N	1.609	1.536	1.513
		N-2.1N-3.3N	2.110	2.013	1.983
		N-2.6N-4.2N	2.600	2.479	2.442
		N-2.65N-3.6N	2.348	2.240	2.206
	1-6,8,10	N-N-N	1.000	0.954	0.940
		N-2N-1.5N	1.531	1.462	1.440
	1-7,9,11	N-N-N	1.048	1.000	0.985
48	1-3,5,7,9	N-2N-2.25N-3N	2.413	2.302	2.268
		N-2N-2.3N-3.2N	2.501	2.387	2.351

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

4 POLES—48 SLOTS

Coils	Concentric winding		Lap winding			
	Coil span	Turns ratio	Coil span and conversion factor			
			1-10	1-11	1-12	1-13*
24	1-10,12	N-.77N	0.477	0.456	0.444	0.440
		N-.82N	0.490	0.469	0.457	0.453
		N-.85N	0.499	0.477	0.465	0.461
		N-.9N	0.513	0.491	0.478	0.474
		N-N	0.541	0.517	0.504	0.500
		N-1.1N	0.569	0.544	0.530	0.526
		N-1.2N	0.597	0.571	0.556	0.551
		N-1.25N	0.611	0.585	0.570	0.565
	1-10,12,14,16	N-N-N-N	0.541	0.517	0.504	0.500
30	1-9,11,13,9,11	N-2N-2N-N-2N	1.073	1.026	1.000	0.991
		N-2.25N-2.25N-N-2.25N	1.176	1.125	1.097	1.087
36	1-8,10,12	N -N-1.82N	0.994	0.951	0.927	0.919
		N-N-2N	1.045	1.000	0.974	0.965
		N-N-2.1N	1.073	1.026	1.000	0.991
		N-N-2.25N	1.115	1.066	1.039	1.030
		N-N-2.5N	1.185	1.133	1.105	1.095
		N-1.1N-2.1N	1.099	1.051	1.024	1.015
		N-1.4N-2.3N	1.233	1.179	1.150	1.139
		N-1.5N-2.5N	1.315	1.258	1.226	1.215
		N-1.8N-2.7N	1.449	1.386	1.351	1.339
		N-1.8-2.8N	1.503	1.413	1.378	1.365
		N-1.8N-2.9N	1.505	1.440	1.404	1.391
		N-1.85N-2.85N	1.504	1.439	1.403	1.390
		N-2N-3N	1.586	1.517	1.478	1.465
		N-2.16N-3.16N	1.673	1.600	1.559	1.546
		N-2.25N-3.25N	1.722	1.647	1.605	1.591
		N-2.4N-3.6N	1.858	1.777	1.732	1.717
		N-2.5N-3.8N	1.940	1.856	1.809	1.792
		N-2.6N-4N	2.040	1.952	1.902	1.885
		N-3N-4N	2.126	2.034	1.983	1.965
		N-3N-4.2N	2.184	2.089	2.035	2.018
		N-3.15N-4.3N	2.251	2.153	2.098	2.080
		N-3.25N-4.25N	2.263	2.165	2.109	2.091
		N-3.4N-4.6N	2.400	2.294	2.237	2.216
		N-3.75N-5.25N	2.672	2.556	2.491	2.469

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

4 POLES—48 SLOTS—CONTINUED

Coils	Concentric winding		Lap winding			
	Coil span	Turns ratio	Coil span and conversion factor			
			1-10	**1-11**	**1-12**	**1-13***
48	1-6,8,10,12	N-N-N-N	0.937	0.896	0.873	0.866
		N-1.5N-1.5N-1.5N	1.319	1.262	1.230	1.212
		N-2N-3.25N-4.25N	2.658	2.542	2.478	2.455
		N-2.5N-3.5N-5N	3.045	2.912	2.839	2.813
		N-2.5N-4N-6N	3.455	3.305	3.221	3.192
		N-2.5N-4.5N-6N	3.586	3.430	3.343	3.313
		N-2.75N-4.25N-6N	3.579	3.423	3.335	3.306
		N-3N-4.75N-6.25N	3.833	3.666	3.574	3.541
		N-3.33N-5N-7.33N	4.274	4.088	3.985	3.949
	1-7,9,11,13	N-N-N-N	1.000	0.956	0.932	0.924
		N-N-N-1.25N	1.070	1.024	0.998	0.989
		N-1.1N-1.1N-1.1N	1.079	1.033	1.006	0.997
		N-1.5N-N-1.5N	1.263	1.208	1.178	1.167
		N-2N-2N-N	1.517	1.451	1.414	1.402
		N-2.15N-2.15N-N	1.595	1.525	1.487	1.473
	1-8,10,12,14	N-.9N-N-.9N	0.991	0.948	0.924	0.915
		N-N-N-N	1.045	1.000	0.974	0.965
		N-1.07N-N-1.07N	1.083	1.036	1.010	1.001
		N-1.15N-N-1.15N	1.267	1.078	1.050	1.041
		N-1.33N-N-1.33N	1.223	1.167	1.140	1.130
	1-9,11,13,15	N-N-N-N	1.073	1.026	1.000	0.991
	1-10,12,10,12	N-.875N-N-.875N	1.012	0.968	0.943	0.935
		N-N-N-N	1.082	1.035	1.007	1.000

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

4 POLES—60 SLOTS

	Concentric winding		Lap winding				
Coils	Coil spans	Turns ratio	Coil span and conversion factor				
			1-12	1-13	1-14	1-15	1-16*
30	1-12,14,16,12,14	N-N-N-N-N	0.547	0.526	0.511	0.502	0.500
	1-12,14,16,18,20	N-N-N-N-N	0.547	0.526	0.511	0.502	0.500
36	1-11,13,15	N-2N-2N	1.088	1.046	1.017	1.005	0.994
	1-12,14,16	N-N-.5N	0.547	0.526	0.511	0.503	0.500
48	1-9,11,13,15	N-N-N-2N	1.040	1.000	0.972	0.956	0.951
		N-N-N-2.1N	1.063	1.030	0.994	0.977	0.972
		N-N-N-2.3N	1.109	1.066	1.036	1.019	1.013
		N-N-N-2.5N	1.154	1.109	1.079	1.060	1.055
		N-1.16N-1.5N-2.16N	1.218	1.170	1.138	1.119	1.113
		N-1.2N-1.2N-2.6N	1.260	1.211	1.177	1.157	1.151
		N-1.2N-1.4N-2.6N	1.303	1.253	1.218	1.197	1.191
		N-1.2N-1.5N-2.5N	1.303	1.252	1.217	1.197	1.191
		N-1.25N-1.5N-2.75N	1.369	1.316	1.280	1.258	1.251
		N-1.33N-1.83N-2.83N	1.475	1.418	1.378	1.355	1.348
		N-1.33N-1.83N-3N	1.515	1.455	1.415	1.391	1.384
		N-1.37N-1.62N-2.5N	1.363	1.309	1.273	1.252	1.245
		N-1.4N-1.8N-3N	1.521	1.462	1.421	1.397	1.390
		N-1.43N-1.86N-3N	1.540	1.480	1.439	1.415	1.408
		N-1.5N-2N-3.16N	1.621	1.558	1.515	1.489	1.481
		N-1.75N-2.25N-3.5N	1.803	1.732	1.684	1.656	1.647
60	1-9,11,13,15,17	N-N-N-N-N	1.041	1.000	0.972	0.956	0.951
		N-1.2N-1.2N-1.2N-N	1.169	1.123	1.092	1.074	1.068
	1-11,13,15,17,19	N-N-N-N-N	1.089	1.046	1.017	1.000	0.995

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

4 POLES—72 SLOTS

Coils	Concentric winding		Lap winding					
	Coil spans	Turns ratio	Coil span and conversion factor					
			1-14	1-15	1-16	1-17	1-18	1-19*
36	1-14,16,18	N-N-.8N	0.513	0.494	0.481	0.472	0.466	0.465
		N-N-.9N	0.533	0.514	0.500	0.490	0.484	0.483
		N-N-N	0.552	0.532	0.518	0.508	0.502	0.500
		N-N-1.15N	0.581	0.560	0.545	0.534	0.528	0.526
48	1-12,14,16,18	N-N-2N-2N	1.087	1.048	1.019	1.000	0.989	0.985
		N-N-2.17N-2.17N	1.151	1.110	1.080	1.059	1.047	1.043
		N-N-2.5N-2.5N	1.275	1.220	1.197	1.174	1.160	1.156
		N-1.2N-2.4N-2.4N	1.273	1.227	1.194	1.171	1.158	1.153
60	1-10,12,14,16,18	N-N-N-N-2N	1.037	1.000	0.973	0.954	0.943	0.940
		N-1.4N-1.6N-2.6N-3.2N	1.732	1.670	1.625	1.594	1.575	1.569
		N-2N-2.5N-4N-5N	2.588	2.496	2.428	2.382	2.354	2.346
		N-3N-3.5N-5N-6.5N	3.394	3.271	3.183	3.122	3.087	3.075
		N-3.5N-4N-6.5N-8N	4.125	3.978	3.870	3.796	3.753	3.739
72	1-10,12,14,16, 18, 20	N-.67N-N-.67N-N-.67N	0.861	0.829	0.807	0.792	0.783	0.780
		N-.75N-N-.75N-N-.75N	0.903	0.871	0.847	0.831	0.822	0.818
		N-.8N-N-.8N-N-.8N	0.930	0.897	0.872	0.856	0.846	0.843
		N-N-N-N-N-N	1.037	1.000	0.973	0.954	0.943	0.940
		N-1.2N-N-1.2N-N-1.2N	1.144	1.103	1.073	1.052	1.041	1.037
		N-1.33N-N-1.33N-N-1.33N	1.213	1.170	1.138	1.117	1.104	1.100
		N-1.5N-N-1.5N-N-1.5N	1.304	1.258	1.224	1.200	1.187	1.182
	1-11,13,15,17,19, 21	N-N-N-N-N-N	1.066	1.028	1.000	0.981	0.970	0.966
		N-1.1N-N-1.1N-N-1.1N	1.120	1.086	1.051	1.031	1.019	1.015
	1-12,14,16,18,20,22	N-1.5N-N-1.5N-N-1.5N	1.363	1.314	1.278	1.254	1.240	1.235

4 POLES—96 SLOTS

Coils	Concentric winding		Lap winding						
	Coil spans	Turns ratio	Coil span and conversion factor						
			1-19	1-20	1-21	1-22	1-23	1-24	1-25*
48	1-18,20,22,24	N-N-N-N	0.541	0.528	0.518	0.510	0.504	0.501	0.500

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

6 POLES—36 SLOTS

Coils	Concentric winding		Lap winding	
	Coil spans	Turns ratio	Coil span and conversion factor	
			1-6	1-7*
18	1-6,8	N-N	0.518	0.500
36	1-4,6	N-N	0.896	0.866
		N-1.25N	1.026	0.991
		N-1.33N	1.067	1.031
		N-1.5N	1.155	1.116
		N-2N	1.414	1.366
		N-2.7N	1.776	1.716
		N-3N	1.932	1.866
		N-3.2N	2.035	1.966
	1-5,7	N-N	1.000	0.966

6 POLES—48 SLOTS

Coils	Concentric winding		Lap winding		
	Coil spans	Turns ratio	Coil span and conversion factor		
			1-7	1-8	1-9*
48	1-6,8,10,6,8,10,7,9	N-N-N-N-N-N-N-N	1.057	0.996	0.977

6 POLES—54 SLOTS

Coils	Concentric winding		Lap winding		
	Coil spans	Turns ratio	Coil span and conversion factor		
			1-8	1-9	1-10*
27	1-8,10,12	N-N-N	0.532	0.508	.500
36	1-7,9	N-2N	1.048	1.000	0.985
	1-8,10	N-.5N	0.532	0.508	0.500
54	1-6,8,10	N-N-N	1.000	.954	0.940

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

6 POLES—72 SLOTS

	Concentric winding		Lap winding			
Coils	Coil spans	Turns ratio	Coil span and conversion factor			
			1-10	**1-11**	**1-12**	**1-13***
36	1-10,12	N-N	0.541	0.517	0.504	0.500
	1-10,12,14,16	N-N-N-N	0.541	0.517	0.504	0.500
	1-12,14	N-1.17N	0.607	0.581	0.566	0.561
72	1-7,9,11,13	N-N-N-N	1.000	0.956	0.932	0.924
	1-8,10,12,14	N-.75N-N-.75N	0.910	0.871	0.848	0.841
		N-.83N-N-.83N	0.954	0.912	0.889	0.881
		N-N-N-N	1.045	1.000	0.974	0.965
		N-1.06N-N-1.06N	1.078	1.031	1.005	0.996
		N-1.125N-N-1.125N	1.112	1.064	1.037	1.028
		N-1.2N-N-1.2N	1.153	1.103	1.075	1.065
	1-8,10,12,14	N-1.33N-N-1.33N	1.224	1.171	1.141	1.131
	1-9,11,13,15	N-N-N-N	1.073	1.026	1.000	0.991
	1-12,14,12,14	N-1.17N-N-1.17N	1.215	1.162	1.132	1.122

6 POLES—90 SLOTS

	Concentric winding		Lap winding				
Coils	Coil spans	Turns ratio	Coil span and conversion factor				
			1-12	**1-13**	**1-14**	**1-15**	**1-16***
54	1-12,14,16	N-N-.5N	0.547	0.526	0.511	0.502	0.500

6 POLES—108 SLOTS

	Concentric winding		Lap winding					
Coils	Coil spans	Turns ratio	Coil span and conversion factor					
			1-14	**1-15**	**1-16**	**1-17**	**1-18**	**1-19***
54	1-14,16,18	N-N-N	0.552	0.532	0.518	0.508	0.502	.500

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

8 POLES—36 SLOTS

	Concentric winding		Lap winding
Coils	Coil spans	Turns ratio	Coil span and conversion factor
			1-5
24	1-4,6	N-2N	0.984
		N-2.5N	1.155
	1-5,7	N-.5N	0.492
36	1-3,5,4	N-N-N	0.844
	1-3,5,7	N-N-N	0.866
		N-1.5N-1.25N	1.112
	1-4,6,6	N-N-N	0.985
	1-5,7,5	N-N-N	0.985

8 POLES—48 SLOTS

	Concentric winding		Lap winding	
Coils	Coil spans	Turns ratio	Coil span and conversion factor	
			1-6	**1-7***
24	1-6,8	N-N	0.518	0.500
48	1-5,7	N-N	1.000	0.966

8 POLES—72 SLOTS

	Concentric winding		Lap winding		
Coils	Coil spans	Turns ratio	Coil span and conversion factor		
			1-8	**1-9**	**1-10***
36	1-8,10,12	N-N-N	0.532	0.508	0.500
72	1-5,7,9	N-2.7N-4.6N	2.776	2.649	2.607
	1-6,8,10	N-N-N	1.000	0.954	0.940
		N-1.2N-N	1.070	1.020	1.005
	1-7,9,11	N-N-N	1.048	1.000	.985
		N-1.2N-N	1.121	1.069	1.053

8 POLES—96 SLOTS

	Concentric winding		Lap winding			
Coils	Coil spans	Turns ratio	Coil span and conversion factor			
			1-10	**1-11**	**1-12**	**1-13***
48	1-10,12,14,16	N-N-N-N	.541	.518	.504	.500

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR ONE SPEED—CONTINUED

10 POLES—90 SLOTS

Coils	Concentric winding		Lap winding		
	Coil spans	Turns ratio	Coil span and conversion factor		
			1-8	1-9	1-10*
60	1-9,11,8,10	N-.5N-N-.5N	0.539	0.514	0.507

10 POLES—120 SLOTS

Coils	Concentric winding		Lap winding			
	Coil spans	Turns ratio	Coil span and conversion factor			
			1-10	1-11	1-12	1-13*
60	1-10,12	N-N	0.541	0.518	0.504	.500

*Avoid using this coil span; it results in unacceptably high slot spatial harmonics or it is full pitch.

CONVERSION FACTOR CHARTS
FOR USE WITH WINDINGS DESIGNED FOR TWO SPEEDS

2/4 POLES—36 SLOTS

Coils	Concentric winding		Lap winding	
	Coil spans	Turns ratio	Coil span and conversion factor	
			1-10	**1-11**
36	1-5,7,9,11,13,15	N-N-N-N-N-N	1.000	– –
	1-6,8,10,12,14,16	N-N-N-N-N-N	1.084	1.000
	1-8,10,12,8,10,12	N-N-N-N-N-N	1.035	0.935

4/8 POLES—36 SLOTS

Coils	Concentric winding		Lap winding	
	Coil spans	Turns ratio	Coil span and conversion factor	
			1-5	**1-6**
24	1-5,7	N-.5N	0.581	0.488
36	1-3,5,7	N-N-N	1.000	– –
	1-4,6,8	N-N-N	– –	1.000

8/16 POLES—96 SLOTS

Coils	Concentric winding		Lap winding	
	Coil spans	Turns ratio	Coil span and conversion factor	
			1-6	**1-7**
96	1-5,7,5,7	N-N-N-N	1.034	– –
	1-6,8,6,8	N-N-N-N	– –	1.038

CHORD FACTOR TABLE

Coil span	Slots per pole													
	24	**22**	**20**	**18**	**16**	**15**	**12**	**11**	**10**	**9**	**8**	**6**	**4**	**3**
1-25	1.000	0.990												
1-24	0.998	0.997	0.972											
1-23	0.991	1.000	0.988											
1-22	0.981	0.997	0.997	0.966										
1-21	0.966	0.990	1.000	0.985										
1-20	0.947	0.977	0.997	0.996	0.957									
1-19	0.924	0.959	0.988	1.000	0.981	0.951								
1-18	0.897	0.937	0.972	0.996	0.995	0.978								
1-17	0.866	0.910	0.951	0.985	1.000	0.995								
1-16	0.831	0.878	0.924	0.966	0.995	1.000	0.924							
1-15	0.793	0.841	0.891	0.940	0.981	0.995	0.966	0.910						
1-14	0.752	0.801	0.853	0.906	0.957	0.978	0.991	0.959	0.891					
1-13	0.707	0.756	0.809	0.866	0.924	0.951	1.000	0.990	0.951	0.866				
1-12	0.659	0.707	0.760	0.819	0.882	0.914	0.991	1.000	0.988	0.940	0.831			
1-11	0.609	0.655	0.707	0.766	0.831	0.866	0.966	0.990	1.000	0.985	0.924			
1-10	0.556	0.599	0.649	0.707	0.773	0.809	0.924	0.959	0.988	1.000	0.981	0.707		
1-9	0.500	0.541	0.588	0.643	0.707	0.743	0.866	0.910	0.951	0.985	1.000	0.866		
1-8	0.442	0.479	0.522	0.574	0.634	0.669	0.793	0.841	0.891	0.940	0.981	0.966		
1-7	0.383	0.415	0.454	0.500	0.556	0.588	0.707	0.756	0.809	0.866	0.924	1.000	0.707	
1-6	0.321	0.349	0.383	0.423	0.471	0.500	0.609	0.655	0.707	0.766	0.831	0.966	0.924	
1-5	0.259	0.282	0.309	0.342	0.383	0.407	0.500	0.541	0.588	0.643	0.707	0.866	1.000	0.866
1-4	0.195	0.213	0.233	0.259	0.290	0.309	0.383	0.415	0.454	0.500	0.556	0.707	0.924	1.000
1-3	0.131	0.142	0.156	0.174	0.195	0.208	0.259	0.282	0.309	0.342	0.383	0.500	0.707	0.866

$$\text{Chord factor} = \text{Sin}\left(90 \times \frac{\text{Teeth spanned}}{\text{Slots per pole}}\right)$$

For a coil span of 1-8, teeth spanned = 7.

For a 36 slot, four-pole motor with a 1-8 span:

$$\text{Chord factor} = \text{Sin}\left(90 \times \frac{7}{36 \div 4}\right) = \text{Sin } 70° = .940$$

Distribution factor for three-phase windings

Coils per group	Standard winding	Consequent-pole winding	Concentric winding
1	1.000	1.000	The distribution factor is always equal to 1.0
2	0.966	0.866	
3	0.960	0.844	
4	0.958	0.837	
5	0.957	0.833	
6 or more	0.956	0.831	

The "Coils Per Group" in the table are for windings with an even coil grouping. The distribution factor for windings which do not have an even coil grouping is determined by the reduced slot/group ratio.

Reduce the number of slots per pole per phase to a fraction, where numerator and denominator are both whole numbers containing no common factor.

Example: 3 phase, 8-pole standard winding, 36 slots; coil grouping: 1 and 2 coils per group.

$$\frac{\text{Slots}}{\text{Poles x Phases}} = \frac{36}{8 \text{ x } 3} = \frac{36}{24}$$

Which can be reduced to $\frac{3}{2}$. Then numerator = 3.

The distribution factor for this winding, which does not have an even coil grouping, is the same as for that of a standard winding with a numerator that equals 3 coils per group (even coil grouping). Therefore, the distribution factor from the table is 0.960.

Coil grouping for three-phase windings

The tables on the next four pages were developed to help you select the correct coil grouping for three-phase stator and rotor windings of various pole-slot combinations. The number of poles from 2 to 24 and the number of slots most commonly used (from 12 to 120) are shown.

Coil groupings with the number of circuits permissible are listed for windings having 1-4 (adjacent pole) or 1-7 (skip pole) group connection.

If unsure which pole-group connection to select, refer to Table 2-54 below. Other than these limiting factors, the adjacent- and skip-pole connections are equivalent.

TABLE 2-54: POLE-GROUP CONNECTIONS

	Type of winding	Pole-group connection
2 poles	Any winding	1-4 connection
4 poles and up	Single-speed motors, one winding	Either the 1-4 or 1-7 connection may be used, but the coil grouping may differ within these two choices.
	Two-speed motors, one winding	Follow the appropriate connection diagram.
	Two-speed motors, two windings	Refer to the table* on Page 2-213 to determine whether to use the 1-4 or 1-7 connection. (The number of winding circuits permissible may differ within these two choices.)
	Multi-mode windings	Refer to Page 2-164, "Winding connections for multi-mode, three-phase motors."

* "Pole-group connections for three-phase motors with two windings."

Special jumpers

Special jumpers are recommended to balance the magnetic forces acting on the air gap of motors that have half as many circuits as poles (e.g., a 3Y 6-pole motor as shown in Figure 2-117).

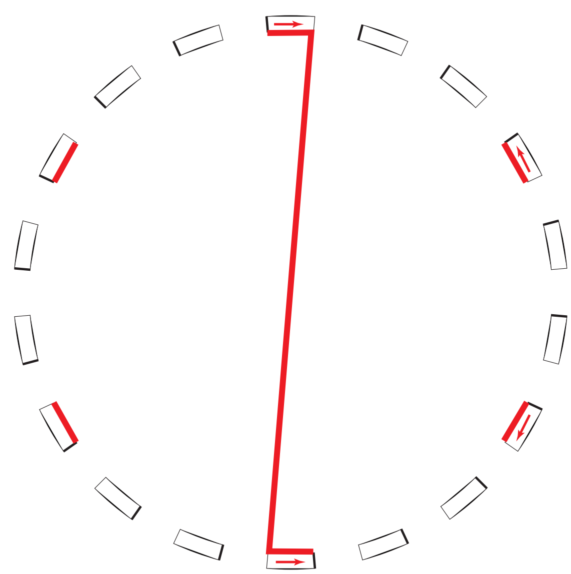
It takes more current to force flux across the air gap than through steel, so a larger air gap requires more magnetizing current than a smaller one. When a rotor is not centered radially within the stator bore, the groups nearest the largest air gap draw more current than the ones near the smallest air gap. Since both the rotor body and stator bore are round, connecting the pole-phase groups that are directly opposite each other in series can mitigate the effect of an imperfect air gap.

That is the reason for the special, extra-long jumpers recommended in Table 2-55; they connect pairs of groups directly across the stator bore to better balance the magnetic forces and the current between parallel paths.

TABLE 2-55: SPECIAL JUMPERS

Poles / Circuits	Jumpers
6 / 3	1-10
8 / 4	1-13
10 / 5	1-16
12 / 6	1-19
14 / 7	1-21

FIGURE 2-117



6 pole (3 circuit) with 1-10 jumper.

COIL GROUPING FOR THREE-PHASE WINDINGS—ADJACENT POLE CONNECTION (1-4)

Slots	Number of poles					
	2	**4**	**6**	**8**	**10**	**12**
12	6 groups of 2 2 2 2 1,2 cir	12 groups of 2 1 1 1 1,2,4 cir				
18	6 groups of 3 3 3 3 1,2 cir	6 groups of 1 6 groups of 2 121,212 1,2 cir	18 groups of 1 1 1 1 1,2,3,6 cir			
24	6 groups of 4 4 4 4 1,2 cir	12 groups of 2 2 2 2 1,2,4 cir	12 groups of 1 6 groups of 2 211,121,112 1,2 cir	24 groups of 1 1 1 1 1,2,4,8 cir		
30	6 groups of 5 5 5 5 1,2 cir	6 groups of 2 6 groups of 3 232,323 1,2 cir	6 groups of 1 12 groups of 2 122,212,221 1,2 cir	18 groups of 1 6 groups 2 211,121,112,111 1,2 cir	30 groups of 1 1 1 1 1,2,5,10 cir	
36	6 groups of 6 6 6 6 1,2 cir	12 groups of 3 3 3 3 1,2,4 cir	18 groups of 2 2 2 2 1,2,3,6 cir	12 groups of 1 12 groups of 2 121,212 1,2,4 cir	24 groups of 1 6 groups of 2 211,112,111,121,111 1,2 cir	36 groups of 1 1 1 1 1,2,3,4,6,12 cir
42	6 groups of 7 7 7 7 1,2 cir	6 groups of 3 6 groups of 4 343,434 1,2 cir	12 groups of 2 6 groups of 3 322,232,223 1,2 cir	6 groups of 1 18 groups of 2 122,212,221,222 1,2 cir	18 groups of 1 12 groups of 2 121,211,212,112,121 1,2 cir	30 groups of 1 6 groups of 2 211,111,121,111,112,111 1,2 cir
45	3 groups of 8 3 groups of 7 878,787 1 cir	9 groups of 4 3 groups 3 444,344,434,443 1 cir	9 groups of 3 9 groups of 2 323,232 1,2,3 cir	21 groups of 2 3 groups of 1 222,222,212,222, 222,122,222,221 1 cir	15 groups of 2 15 groups of 1 212,121 1,2,5 cir	
48	6 groups of 8 8 8 8 1,2 cir	12 groups of 4 4 4 4 1,2,4 cir	6 groups of 2 12 groups of 3 233,323,332 1,2 cir	24 groups of 2 2 2 2 1,2,4,8 cir	12 groups of 1 18 groups of 2 212,122,121,221,212 1,2 cir	24 groups of 1 12 groups of 2 211,121,112 1,2,4 cir
54	6 groups of 9 9 9 9 1,2 cir	6 groups of 4 6 groups of 5 454,545 1,2 cir	18 groups of 3 3 3 3 1,2,3,6 cir	18 groups of 2 6 groups of 3 322,232,223,222 1,2 cir	6 groups of 1 24 groups of 2 122,221,222,212, 222 1,2 cir	18 groups of 1 18 groups of 2 121,212 1,2,3,6 cir
60	6 groups of 10 10 10 10 1,2 cir	12 groups of 5 5 5 5 1,2,4 cir	12 groups of 3 6 groups of 4 433,343,334 1,2 cir	12 groups of 2 12 groups of 3 232,323 1,2,4 cir	30 groups of 2 2 2 2 1,2,5,10 cir	12 groups of 1 24 groups of 2 122,212,221 1,2,4 cir
72	6 groups of 12 12 12 12 1,2 cir	12 groups of 6 6 6 6 1,2,4 cir	18 groups of 4 4 4 4 1,2,3,6 cir	24 groups of 3 3 3 3 1,2,4,8 cir	18 groups of 2 12 groups of 3 232,322,323,223, 232 1,2 cir	36 groups of 2 2 2 2 1,2,3,4,6,12 cir
84	6 groups of 14 14 14 14 1,2 cir	12 groups of 7 7 7 7 1,2,4 cir	6 groups of 4 12 groups of 5 455,545,554 1,2 cir	12 groups of 3 12 groups of 4 343,434 1,2,4 cir	6 groups of 2 24 groups of 3 233,332,333,323, 333 1,2 cir	24 groups of 2 12 groups of 3 322,232,223 1,2,4 cir
90	6 groups of 15 15 15 15 1,2 cir	6 groups of 7 6 groups of 8 787,878 1,2 cir	18 groups of 5 5 5 5 1,2,3,6 cir	6 groups of 3 18 groups of 4 344,434,443,444 1,2 cir	30 groups of 3 3 3 3 1,2,5,10 cir	18 groups of 2 18 groups of 3 232,323 1,2,3,6 cir
96	6 groups of 16 16 16 16 1,2, cir	12 groups of 8 8 8 8 1,2,4 cir	12 groups of 5 6 groups of 6 655,565,556 1,2 cir	24 groups of 4 4 4 4 1,2,4,8 cir	24 groups of 3 6 groups of 4 433,334,333,343,333 1,2 cir	12 groups of 2 24 groups of 3 233,323,332 1,2,4 cir
108	6 groups of 18 18 18 18 1,2 cir	12 groups of 9 9 9 9 1,2,4 cir	18 groups of 6 6 6 6 1,2,3,6 cir	12 groups of 4 12 groups of 5 454,545 1,2,4 cir	12 groups of 3 18 groups of 4 434,344,343,443,434 1,2 cir	36 groups of 3 3 3 3 1,2,3,4,6,12 cir
120	6 groups of 20 20 20 20 1,2 cir	12 groups of 10 10 10 10 1,2,4 cir	6 groups of 6 12 groups of 7 677,767,776 1,2 cir	24 groups of 5 5 5 5 1,2,4,8 cir	30 groups of 4 4 4 4 1,2,5,10 cir	24 groups of 3 12 groups of 4 433,343,334 1,2,4 cir

COIL GROUPING FOR THREE-PHASE WINDINGS—ADJACENT POLE CONNECTION (1-4)—CONT.

Slots	Number of poles					
	14	16	18	20	22	24
42	42 groups of 1 1 1 1 1,2,7,14 cir					
45						
48	36 groups of 1 6 groups of 2 211,111,121,111,112,111, 111 1,2 cir	48 groups of 1 1 1 1 1,2,4,8,16 cir				
54	30 groups of 1 12 groups of 2 211,211,121,121,112, 112,111 1,2 cir	42 groups of 1 6 groups of 2 211,111,112,111,111,121, 111,111 1,2 cir	54 groups 1 1 1 1 1,2,3,6,9,18 cir			
60	24 groups of 1 18 groups of 2 121,212,112,121,211, 212,121 1,2 cir	36 groups of 1 12 groups of 2 211,121,112,111 1,2,4 cir	48 groups of 1 6 groups of 2 211,111,111,121,111,111, 112,111,111 1,2 cir	60 groups of 1 1 1 1 1,2,4,5,10,20 cir		
72	12 groups of 1 30 groups of 2 122,122,212,212,221, 221,222 1,2 cir	24 groups of 1 24 groups of 2 121,212 1,2,4,8 cir	36 groups of 1 18 groups of 2 211,121,112 1,2,3,6 cir	48 groups of 1 12 groups of 2 211,112,111,121,111 1,2,4 cir	60 groups of 1 60 groups of 2 211,111,111,112,111,111, 111,121,111,111,111 1,2 cir	72 groups of 1 1 1 1 1,2,3,4,6,8,12,24 cir
84	42 groups of 2 2 2 2 1,2,7,14 cir	12 groups of 1 36 groups of 2 122,212,221,222 1,2,4 cir	24 groups of 1 30 groups of 2 221,221,212,212,122, 122,112,121,211 1,2 cir	36 groups of 1 24 groups of 2 121,211,212,112,121 1,2,4 cir	48 groups of 1 18 groups of 2 211,121,112,112,111,211, 121,121,112,111,211 1,2 cir	60 groups of 1 12 groups of 2 211,111,121,111,112,111 1,2,4 cir
90	36 groups of 2 6 groups of 3 322,222,232,222,223, 222,222 1,2 cir	6 groups of 1 42 groups of 2 122,222,221,222,222,212, 222,222 1,2 cir	18 groups of 1 36 groups of 2 122,212,221 1,2,3,6 cir	30 groups of 1 30 groups of 2 121,212 1,2,5,10 cir	42 groups of 1 24 groups of 2 121,211,121,211,212,111, 212,112,121,112,121 1,2 cir	54 groups of 1 18 groups of 2 211,121,112,111 1,2,3,6 cir
96	30 groups of 2 12 groups of 3 322,322,232,232,223,223, 222 1,2 cir	48 groups of 2 2 2 2 1,2,4,8,16 cir	12 groups of 1 42 groups of 2 122,221,222,212,221,222, 122,212,222 1,2 cir	24 groups of 1 36 groups of 2 212,122,121,221,212 1,2,4 cir	36 groups of 1 30 groups of 2 121,212,121,211,212,121, 212,112,121,212,121 1,2 cir	48 groups of 1 24 groups of 2 211,121,112 1,2,4,8 cir
108	18 groups of 2 24 groups of 3 323,232,332,323,233,232, 323 1,2 cir	36 groups of 2 12 groups of 3 322,232,223,222 1,2,4 cir	54 groups of 2 2 2 2 1,2,3,6,9,18 cir	12 groups of 1 48 groups of 2 122,221,222,212,222 1,2,4 cir	24 groups of 1 42 groups of 2 212,122,212,122,121,222, 121,221,212,221,212 1,2 cir	36 groups of 1 36 groups of 2 121,212 1,2,3,4,6,12 cir
120	6 groups of 2 36 groups of 3 233,333,323,333, 332,333,333 1,2, cir	24 groups of 2 24 groups of 3 232,323 1,2,4,8 cir	42 groups of 2 12 groups of 3 322,223,222,232,223,222, 322,232,222 1,2 cir	60 groups of 2 2 2 2 1,2,4,5,10,20 cir	12 groups of 1 54 groups of 2 222,122,212,222,221,222, 122,222,212,221,222 1,2 cir	24 groups of 1 48 groups of 2 122,212,221 1,2,4,8 cir

Note: Not all odd-grouping sequences work for both adjacent pole (1-4) and skip pole (1-7) connections. Be sure to determine which connection method will be used before selecting the odd-grouping sequence. If the larger quantity of groups divided by the smaller quantity of groups results in an odd integer, the coil grouping pattern for 1-7 jumpers will "mirror image" after the 1-4 jumper pattern is complete.

COIL GROUPING FOR THREE-PHASE WINDINGS—SKIP POLE CONNECTION (1-7)

Slots	Number of poles					
	4	**6**	**8**	**10**	**12**	**14**
12	12 groups of 1 1 1 1 1,2,4 cir					
18	6 groups of 1 6 groups of 2 121,212,212,121 1,2 cir	18 groups of 1 1 1 1 1,2,3,6 cir				
24	12 groups of 2 2 2 2 1,2,4 cir	12 groups of 1 6 groups of 2 211,121,112 1,2 cir	24 groups of 1 1 1 1 1,2,4,8 cir			
30	6 groups of 2 6 groups of 3 232,323,323,232 1,2 cir	6 groups of 1 12 groups of 2 122,212,221 1,2 cir	18 groups of 1 6 groups of 2 211,121,112,111,111,211, 121,112 1,2 cir	30 groups of 1 1 1 1 1,2,5,10 cir		
36	12 groups of 3 3 3 3 1,2,4 cir	18 groups of 2 2 2 2 1,2,3,6 cir	12 groups of 1 12 groups of 2 121,212,212,121 1,2,4 cir	24 groups of 1 6 groups of 2 211,112,111,121,111 1,2 cir	36 groups of 1 1 1 1 1,2,3,4,6,12 cir	
42	6 groups of 3 6 groups of 4 343,434,434,343 1,2 cir	12 groups of 2 6 groups of 3 322,232,223 1,2 cir	6 groups of 1 18 groups of 2 122,212,221,222,222,122, 212,221 1,2 cir	18 groups of 1 12 groups of 2 121,211,212,112,121 1,2 cir	30 groups of 1 6 groups of 2 211,111,121,111,112,111, 111,211, 111,121,111,112 1,2 cir	42 groups of 1 1 1 1 1,2,7,14 cir
45	9 groups of 4 3 groups of 3 444,344,434,443 1 cir	9 groups of 3 9 groups of 2 323,232 1 cir	21 groups of 2 3 groups of 1 222,222,212,222 1,2 cir	15 groups of 2 15 groups of 1 212,121,222,122,222,221 1 cir		
48	12 groups of 4 4 4 4 1,2,4 cir	6 groups of 2 12 groups of 3 233,323,332 1,2 cir	24 groups of 2 2 2 2 1,2,4,8 cir	12 groups of 1 18 groups of 2 212,122,121,221,212 1,2 cir	24 groups of 1 12 groups of 2 211,121,112 1,2,4 cir	36 groups of 1 6 groups of 2 211,111,121,111,112,111, 111 1,2 cir
54	6 groups of 4 6 groups of 5 454,545,545,454 1,2 cir	18 groups of 3 3 3 3 1,2,3,6 cir	18 groups of 2 6 groups of 3 322,232,223,222,222,322, 232,223 1,2 cir	6 groups of 1 24 groups of 2 122,221,222,212,222 1,2 cir	18 groups of 1 18 groups of 2 122,212,221 1,2,4 cir	30 groups of 1 12 groups of 2 211,211,121,121,112,112, 111 1,2 cir
60	12 groups of 5 5 5 5 1,2,4 cir	12 groups of 3 6 groups of 4 433,343,334 1,2 cir	12 groups of 2 12 groups of 3 232,323,323,232 1,2,4 cir	30 groups of 2 2 2 2 1,2,5,10 cir	12 groups of 1 24 groups of 2 122,212,221 1,2,4 cir	24 groups of 1 18 groups of 2 121,212,112,121,211,212, 121 1,2 cir
72	12 groups of 6 6 6 6 1,2,4 cir	18 groups of 4 4 4 4 1,2,3,6 cir	24 groups of 3 3 3 3 1,2,4,8 cir	18 groups of 2 12 groups of 3 232,322,323,223,232 1,2 cir	36 groups of 2 2 2 2 1,2,3,4,6,12 cir	12 groups of 1 30 groups of 2 122,122,212,212,221, 221,222 1,2 cir
84	12 groups of 7 7 7 7 1,2,4 cir	6 groups of 4 12 groups of 5 455,545,554 1,2 cir	12 groups of 3 12 groups of 4 343,434,434,343 1,2,4 cir	6 groups of 2 24 groups of 3 233,332,333,323,333 1,2 cir	24 groups of 2 12 groups of 3 322,232,223 1,2,4 cir	42 groups of 2 2 2 2 1,2,7,14 cir
90	6 groups of 7 6 groups of 8 787,878,878,787 1,2 cir	18 groups of 5 5 5 5 1,2,3,6 cir	6 groups of 3 18 groups of 4 344,434,443,444,444,344, 434,443 1,2 cir	30 groups of 3 3 3 3 1,2,5,10 cir	18 groups of 2 18 groups of 3 232,323,323,232 1,2,3,6 cir	36 groups of 2 6 groups of 3 322,222,232,222,223,222, 222 1,2 cir
96	12 groups of 8 8 8 8 1,2,4 cir	12 groups of 5 6 groups of 6 655,565,556 1,2 cir	24 groups of 4 4 4 4 1,2,4,8 cir	24 groups of 3 6 groups of 4 433,334,333,343,333 1,2 cir	12 groups of 2 24 groups of 3 233,323,332 1,2,4 cir	30 groups of 2 12 groups of 3 322,322,232,232,223,223, 222 1,2 cir
108	12 groups of 9 9 9 9 1,2,4 cir	18 groups of 6 6 6 6 1,2,3,6 cir	12 groups of 4 12 groups of 5 454,545,545,454 1,2,4 cir	12 groups of 3 18 groups of 4 434,344,343,443,434 1,2 cir	36 groups of 3 3 3 3 1,2,3,4,6,12 cir	18 groups of 2 24 groups of 3 323,232,332,323,233,232, 323 1,2 cir
120	12 groups of 10 10 10 10 1,2,4 cir	6 groups of 6 12 groups of 7 677,767,776 1,2 cir	24 groups of 5 5 5 5 1,2,4,8 cir	30 groups of 4 4 4 4 1,2,5,10 cir	24 groups of 3 12 groups of 4 433,343,334 1,2,4 cir	6 groups of 2 36 groups of 3 233,333,323,333,332,333, 333 1,2 cir

COIL GROUPING FOR THREE-PHASE WINDINGS—SKIP POLE CONNECTION (1-7)—CONT.

Slots	Number of poles: 16	18	20	22	24
48	48 groups of 1 1 1 1 1,2,4,8,16 cir				
54	42 groups of 1 6 groups of 2 211,111,112,111,111,121,111,111,111,111, 121,111,111,211,111,112 1,2 cir	54 groups of 1 1 1 1 1,2,3,6,9,18 cir			
60	36 groups of 1 12 groups of 2 211,121,112,111,111,211,121,112 1,2 cir	48 groups of 1 6 groups of 2 211,111,111,121,111,111,112, 111,111 1,2 cir	60 groups of 1 1 1 1 1,2,4,5,10,20 cir		
72	24 groups of 1 24 groups of 2 121,212,212,121 1,2,4,8 cir	36 groups of 1 18 groups of 2 211,121,112 1,2,3,6 cir	48 groups of 1 12 groups of 2 211,112,111,121,111 1,2,4 cir	60 groups of 1 6 groups of 2 211,111,111,112,111,111,111, 121,111,111,111 1,2 cir	72 groups of 1 1 1 1 1,2,3,4,6,8,12,24 cir
84	12 groups of 1 36 groups of 2 122,212,221,222,222,122,212,221 1,2,4 cir	24 groups of 1 30 groups of 2 221,221,212,212,122, 122,112,121,211 1,2 cir	36 groups of 1 24 groups of 2 121,211,212,112,121 1,2,4 cir	48 groups of 1 18 groups of 2 211,121,112,112,111,211,121, 121,112,111,211 1,2 cir	60 groups of 1 12 groups of 2 211,111,121,111,112,111,111, 211,111,121,111,112 1,2,4 cir
90	6 groups of 1 42 groups of 2 122,222,221,222,222,212,222,222,222,222, 212,222,222,122,222,221 1,2 cir	18 groups of 1 36 groups of 2 122,212,221 1,2,3,6 cir	30 groups of 1 30 groups of 2 121,212,212,121 1,2,5,10 cir	42 groups of 1 24 groups of 2 121,211,121,211,212,111,212, 112,121,112,121 1,2 cir	54 groups of 1 18 groups of 2 211,121,112,111,111,211, 121,112 1,2,3,6 cir
96	48 groups of 2 2 2 2 1,2,4,8,16 cir	12 groups of 1 42 groups of 2 122,221,222,212,221, 222,122,212,222 1,2 cir	24 groups of 1 36 groups of 2 212,122,121,221,212 1,2,4 cir	36 groups of 1 30 groups of 2 121,212,121,211,212,121, 212,112,121,212,121 1,2 cir	48 groups of 1 24 groups of 2 211,121,112 1,2,4,8 cir
108	36 groups of 2 12 groups of 3 322,232,223,222,222,322,232,223 1,2,4 cir	54 groups of 2 2 2 2 1,2,3,6,9,18 cir	12 groups of 1 48 groups of 2 122,221,222,212,222 1,2,4 cir	24 groups of 1 42 groups of 2 212,122,212,122,121,222, 121,221,212,221,212 1,2 cir	36 groups of 1 36 groups of 2 121,212,212,121 1,2,3,6,12 cir
120	24 groups of 2 24 groups of 3 232,323,323,232 1,2,4,8 cir	42 groups of 2 12 groups of 3 322,223,222,232,223, 222,322,232,222 1,2 cir	60 groups of 2 2 2 2 1,2,4,5,10,20 cir	12 groups of 1 54 groups of 2 222,122,212,222,221,222, 122,222,212,221,222 1,2 cir	24 groups of 1 48 groups of 2 122,212,221 1,2,4,8 cir

Note: Not all odd-grouping sequences work for both adjacent pole (1-4) and skip pole (1-7) connections. Be sure to determine which connection method will be used before selecting the odd-grouping sequence. If the larger quantity of groups divided by the smaller quantity of groups results in an odd integer, the coil grouping pattern for 1-7 jumpers will "mirror image" after the 1-4 jumper pattern is complete.

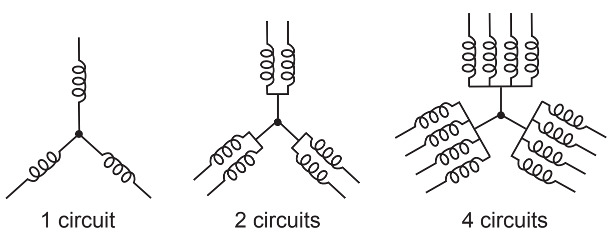
The (potential) pitfalls of parallel circuits

By Cyndi Nyberg
Former EASA Technical Support Specialist

INTRODUCTION

To make more efficient use of materials, winders may want to increase the number of parallel circuits when winding an AC stator (or wound rotor). However, there are limits to the number of parallel circuits that can be used in these designs. For example, a 4-pole, wye-connected winding can have a maximum of 4 circuits (see Figure 2-118). This article describes some of the potential problems associated with increasing the number of parallel circuits.

FIGURE 2-118



Possible circuits for a 4-pole, wye-connected winding.

If the original design of a motor has few turns with large wires, or many wires in hand, increasing the number of parallel circuits may make it easier to rewind. Doubling the circuits, for example, requires doubling the turns per coil and reduces by half the cross-sectional area of wire in hand. The volts/coil stresses are also proportional to the number of circuits.

Motor manufacturers are winding progressively larger motors using concentric windings. Most service centers convert these motors to lap windings to improve performance. But rewinding requires reducing the turns per coil when the same connection is used. Very often these designs also have a low number of turns, with unequal turns being common as well. Therefore, it is often desirable to increase the number of parallel circuits to make winding the coils less difficult.

MAXIMUM CIRCUITS

The number of parallel circuits cannot exceed the number of poles–except with interleaved windings, where it is possible to have a 4-circuit connection on a 2-pole motor. With interleaved windings, each group of coils is divided into paralleled subgroups, resulting in double the allowable circuits, as well as double the turns. For more information on interleaved windings, see "Interleaved Windings Provide Useful Alternative," *EASA Currents*, January 2003.

Additionally, the number of poles must be equal to or a multiple of the number of circuits. For example, a 2-delta connection on a 6-pole winding cannot be changed to a 4-delta connection.

UNEQUAL COIL GROUPING

With even coil grouping (i.e., all groups have the same number of coils), it is usually possible to have a balanced winding with the maximum number of parallel circuits. Unequal grouping, however, limits the number of possible circuits in a winding, because each path of the parallel circuit must have the same number of turns.

For windings with an unequal grouping sequence, always check the Coil Grouping tables in Section 3 of the *EASA Technical Manual* to confirm that it is possible to increase the number of circuits without creating a circulating current.

The following example illustrates what would happen if the connection for a winding with unequal grouping were changed from 2 circuits to 3.

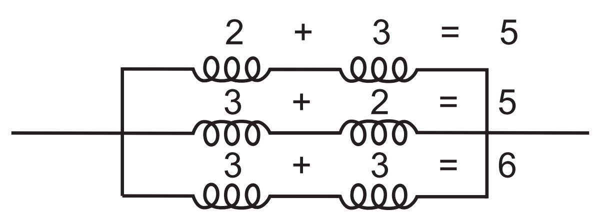
Example: 6 poles, 48 slots, 6 groups of 2 and 12 groups of 3 coils

Grouping sequence: 2 3 3, 3 2 3, 3 3 2

For the 6-pole, 48-slot winding only 1 or 2 circuits are allowed.

Since this winding has 48 coils (16 coils per phase), connecting it for 3 circuits would result in 2 of the parallel circuits in a phase with 5 coils in series and 1 circuit with 6 coils in series–i.e., 16 coils ÷ 3 circuits = 5 coils per circuit + 1 remaining (see Figure 2-119). Paralleling these 3 circuits would create an undesirable circulating current, which would cause high current and heating.

FIGURE 2-119



Changing this connection to 3 parallel circuits would produce circulating currents.

VOLTS PER COIL

For form coils, the calculated turn-to-turn stresses are used to determine the required insulation between turns. For random-wound coils, the volts per coil (v/c) is the main concern. This does not necessarily mean the stresses between two adjacent coils in a group. Anyplace where two turns can come into contact can be a potential concern–e.g., between two coils in the same slot, or between coils on the end turns.

The coils can also be from different groups or phases, which raises the voltage potential between them.

$$\text{Volts per coil} = \frac{\text{Phase voltage x No. of circuits x 3 phases}}{\text{No. of coils}}$$

Where:

Phase voltage = Line voltage for delta, or
58% of line voltage for wye

Example: A motor rated 460v, 4-delta, 48 slots

$$\text{Volts per coil} = \frac{460 \times 4 \times 3}{48} = 115$$

Historically, the rule was that the volts per coil of a random-wound coil should not exceed 40, if possible. However, this number is really too conservative. The winding materials used in today's motors, including improved wire and insulation, better protect the winding from voltage stresses. We also now know that winding failures are more likely to be caused by inter-turn failures than by steady-state volts per coil. For a random winding, a more realistic maximum value would be 80 volts/coil, although many designs from reputable manufacturers exceed 100 v/c. (See "Voltage Stress: Not as Simple as It Sounds," *EASA Currents*, August 2007.)

Rather than using a specific value for volts per coil to decide when to use more insulation, it is more important to look at the application and environment in which the motor operates. Things like starting frequency, power supply, across-the-line starts, and the application are all considerations.

Another important consideration: If the first and the last turn of a coil contact one another and the volts per coil are too high, a turn-to-turn failure is likely. **Caution:** Many designs have high volts per coil, so it is very important to use the correct insulation materials and handle the wire carefully. (Again, see "Voltage Stress: Not as Simple as It Sounds," *EASA Currents*, August 2007.)

It is not always possible to design or redesign a winding without using multiple circuits. Say, for example, it is necessary to redesign a motor from 2300V to 460V. Reducing the rated voltage can result in very few turns per coil for a large horsepower motor. To offset this, we normally increase the number of circuits, which also increases the volts per coil. The real danger here is that often this type of voltage change also involves a change from form-wound to random-wound coils, which increases the potential voltage stresses on the coils.

CONNECTION TIME

More time is required to connect a winding with multiple parallel circuits. These connections are also bulkier.

SPLITTING GROUPS

Increasing the circuits is an option when too many wires in hand would otherwise be required when making coils. In many cases, even using a 2-delta connection, there are still relatively few turns per coil, with many (often large diameter) wires in multiple. But increased connection time and higher voltage stresses are drawbacks.

To make the winding process easier in these cases, each group can be wound in two steps and then paralleled. Wind each "half coil" with the same turns per coil as the original but with half the circular mils of wire. If the winding head can accommodate the wire, simply wind the second half on top of the first half. Then tie the group, and treat it normally. If there is too much bulk for the winding head, treat it like two separate windings. If the static volts/coil is more than 80 volts, use additional phase insulation midway through each coil group. This reduces the potential for turn-to-turn failure in the coil extension. Then wind each coil as two halves in the same slot. Bring out the two ends on the start and the two ends on the finish of the group each as one group end.

2-SPEED, 2-WINDING DESIGNS

The easiest way to avoid circulating currents in a 2-speed, 2-winding motor is to use a 1-wye connection for both windings. In the case of a voltage change or a relatively large horsepower motor, however, it may not be possible to get the desired design characteristics by using a 1-wye connection–the turns may be too low or calculate to a fractional turn.

When changing one or both of the windings of a 2-speed, 2-winding motor, be sure to consider not only the issues previously covered but also possible circulating currents.

If either winding has more than one circuit, always document whether adjacent- or skip-pole connections were used for each winding. Then compare the connections with those in the Pole-Group Connections table in Section 3 of the *EASA Technical Manual*.

Before reconnecting a motor with multiple windings for a different operating voltage, consult the same table. It may not be practical to completely reconnect the windings, especially if either winding has unequal grouping.

Note: This article was first published as *EASA Tech Note 46* (December 2010); it was reviewed and updated as necessary in August 2016.

Pole-group connections for three-phase motors with two windings

Winding circuits permissible

The table on the next page was developed to help you select the correct pole-group connection for three-phase, multi-speed motors having two windings of various pole combinations. Up to 12 poles are shown for high speed, and up to 36 for low speed. The first column of the table lists the poles for the high-speed winding; grouped with them in the second column are the poles possible for the low-speed winding.

The number of winding circuits permissible for the various pole combinations shown are listed for windings having 1-4 or 1-7 pole-group connections.

To use the table, first locate the poles for the high-speed winding. Next locate the poles for the low-speed winding that are grouped with the just selected high-speed poles.

The number of circuits permissible for both windings is found on the same horizontal line as the number of poles for the low-speed winding. The pole-group connection for both windings is indicated at the top of the columns in which the number of circuits selected is located.

Note:

- Avoid closed delta connections in two-winding motors.
- Avoid parallel circuits if either winding has odd coil grouping.

For additional information, refer to the chapter on "Single-Speed To Two-Speed, Two Windings" in EASA's *AC Motor Redesign*.

Example

Determine the number of winding circuits and pole-group connections permissible for a two-speed motor with a 4-pole and a 16-pole winding.

The table shows that the maximum number of winding circuits permissible for the 4-pole, high-speed winding is 2, which requires a 1-4 pole-group connection. The use of 1 circuit only permits a choice of either an adjacent (1-4) or a skip (1-7) pole connection.

The table also shows that 1, 2 or 4 circuits are permissible for the 16-pole, low-speed winding. The 4-circuit winding requires the use of a 1-7 pole-group connection, while both 1- or 2-circuit connections may be used with either adjacent- or skip-pole connections.

POLE-GROUP CONNECTIONS FOR THREE-PHASE WINDINGS

WINDING CIRCUITS PERMISSIBLE

Poles for high speed	Poles for low speed	Pole-group connections and winding circuits			
		High-speed winding		Low-speed winding	
		Adjacent pole 1-4	Skip pole 1-7	Adjacent pole 1-4	Skip pole 1-7
2	4, 8, 12, 16, 20, 24, 28, 32, 36	1	—	1	1, 2
	6, 10, 14, 18, 22, 26, 30, 34	1	—	1, 2	1, 2
4	6, 10, 14, 18, 22, 26, 30, 34	1	1, 2	1	1, 2
	8, 16, 24, 32	1, 2	1	1, 2	1, 2, 4
	12, 20, 28, 36	1	1	1, 2, 4	1, 2, 4
6	8, 16, 20, 28, 32	1	1, 2	1	1, 2
	10, 14, 22, 26, 34	1, 2	1, 2	1, 2	1, 2
	12, 24, 36	1, 3	1	1, 3	1, 2, 3, 6
	18, 30	1	1	1, 2, 3, 6	1, 2, 3, 6
8	10, 14, 18, 22, 26, 30, 34	1	1, 2	1	1, 2
	12, 20, 28, 36	1, 2	1, 2, 4	1, 2	1, 2, 4
	16, 32	1, 2, 4	1	1, 2, 4	1, 2, 4, 8
	24	1	1	1, 2, 4, 8	1, 2, 4, 8
10	12, 16, 24, 28, 32, 36	1	1, 2	1	1, 2
	14, 18, 22, 26, 34	1, 2	1, 2	1, 2	1, 2
	20	1, 5	1	1, 5	1, 2, 5, 10
	30	1	1	1, 2, 5, 10	1, 2, 5, 10
12	14, 22, 26, 34	1	1, 2	1	1, 2
	16, 32	1, 2	1, 2, 4	1, 2	1, 2, 4
	18, 30	1, 3	1, 2, 3, 6	1, 3	1, 2, 3, 6
	20, 28	1, 2, 4	1, 2, 4	1, 2, 4	1, 2, 4
	24	1, 2, 3, 6	1	1, 2, 3, 6	1, 2, 3, 4, 6, 12
	36	1	1	1, 2, 3, 4, 6,12	1, 2, 3, 4, 6, 12

STATOR-ROTOR SLOT COMBINATIONS TABLE

Poles	Noise	Cogging	Cusp
2	±1, ±2, ±3, ±4	±6, ±12, ±18, ±24	±2, -4, -10
4	±1, ±2, ±3, ±4, ±5, ±6	±12, ±24, ±48, ±60	±4, -8, -20
6	±1, ±2, ±4, ±5, ±7, ±8	±18, ±36, ±54, ±72	±6, -12, -30
8	±1, ±2, ±6, ±7, ±9, ±10	±24, ±48, ±72	±8, -16, -40
10	±1, ±2, ±8, ±9, ±11, ±12	±30, ±60, ±90	±10, -20, -50
12	±1, ±2, ±10, ±11, ±13, ±14	±36, ±72	±12, -24, -60
14	±1, ±2, ±12, ±13, ±15, ±16	±42	±14, -28
16	±1, ±2, ±14, ±15, ±17, ±18	±48	±16, -32
18	±1, ±2, ±16, ±17, ±19, ±20	±54	±18, -36
20	±1, ±2, ±18, ±19, ±21, ±22	±60	±20, -40
24	±1, ±2, ±22, ±23, ±25, ±26	±72	±24, -48
32	±1, ±2, ±30, ±31, ±33, ±34	±96	±32, -64
36	±1, ±2, ±34, ±35, ±37, ±38	±108	±36, -72
48	±1, ±2, ±46, ±47, ±49, ±50	±144	±48, -96

The above table shows combinations of stator slots minus rotor slots that may cause problems (excessive noise, cogging or a cusp) when a motor is redesigned for a different number of poles.

When considering a redesign involving a change in the number of poles, subtract the number of rotor slots from the number of stator slots and see if the difference appears in the table. Use the plus figures when the number of stator slots exceeds the number of rotor slots. Use the minus figures where the rotor slots exceed the stator slots.

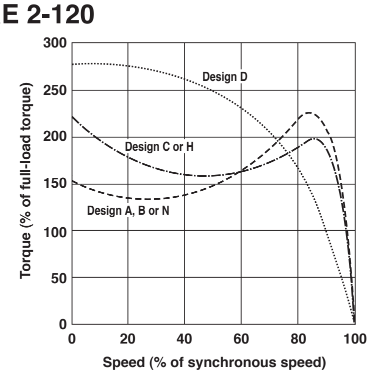
If the difference appears in the table, consider how it may affect motor performance on the desired application.

ROTOR SKEW

Motor manufacturers would prefer having unlimited stator and rotor lamination options. But to control costs, they use the same laminations for as many different designs as possible. For example, they may use the same rotor laminations for both a 4- and a 6-pole motor by skewing the bars to achieve favorable stator-rotor slot combinations for both speeds.

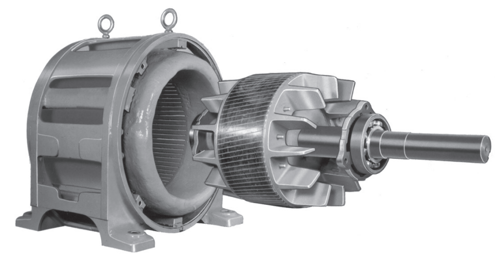
The purpose of skewing rotor bars is to reduce the magnitude of the harmonics in the air gap flux that can result from certain stator-rotor slot combinations. This smooths out the speed-torque curve (see Figure 2-120) and reduces noise.

FIGURE 2-120



General speed-torque characteristics of three-phase induction motors

FIGURE 2-121



Example of rotor with skewed bars.

This can be done by skewing rotor or stator laminations. Usually the bars will be angled as shown in Figure 2-120. Other ways of skewing bars include herringbone (V-shaped) bars and straight bars that are offset in the center of the stack.

The rotor is more commonly skewed than the stator, because skewed stator slots decrease slot opening cross-sections, making it more difficult to insert coils.

The degree of rotor skew varies, but typically equals whichever distance is greater: one stator slot or one rotor slot. Too little skew may not effectively reduce the harmonics, while too much will only further increase losses. If stator slots outnumber rotor bars, the bars will normally be skewed one rotor slot. If rotor bars outnumber stator slots, the required skew angle will be smaller. The goal is for a rotor bar to span two adjacent stator slots at all times.

Although rotor skew smooths the torque curve and reduces noise, it also increases stray load losses, which may make the motor may run hotter. To the manufacturer, however, the torque or noise benefits are acceptable tradeoffs.

Tip: The number of bars in an open slot rotor are easy to count. When the rotor bars are not visible, use a growler with magnetic imaging paper (or iron filings on a piece of paper) to count them.

EASA The Electro•Mechanical Authority

Data Verification & Redesign Request

IMPORTANT: To send a data verification and redesign request to EASA's Technical Support staff, complete this form and fax it back to **314-993-2998**. (**Note:** You may submit your request electronically. Go to www.easa.com/resources/tech_support.) Complete all **required fields (*)**. Inquiries will be handled in the order received.

EASA Fax: 314-993-2998

***Your Company**__________ ***Company I.D. No.** __________ **Date**__________

***Your First & Last Names** __________ **City/State (Province)** __________

***Phone No. (** ____ **)**__________ ***Fax No. (** ____ **)**__________ **E-mail Address**__________

Manufacturer __________ **Frame**__________

Model__________ **Type** __________

Nameplate Data	
*Hp or KW	
*RPM or poles	
*Frequency (Hz)	
*Volts	
*Amperes	
Enclosure	
Duty	

Core Data & Dimensions ❑inches ❑mm	
*No. of stator slots	
*Bore diameter	
*Gross core length	
No. of air ducts	
Width of air ducts	
*Avg. tooth width	
*Backiron	
No. of rotor slots	

Form Coil Windings Only	
❑inches ❑mm	
Slot width	
Net slot depth	
Total slot depth	

WINDING INFORMATION

________ ***groups of** ________ ***coils.**

________ **groups of** ________ **coils.**

***Total coils** __________

***Wire**
(Complete at least first row.)

Wires in Multiple	Wire Size	Wire Stnd. (AWG, SWG, etc.)

***Connection**

No. Circuits	Connection

Coil	Turns	Span
* 1	____	* 1- ____
2	____	1- ____
3	____	1- ____
4	____	1- ____
5	____	1- ____
6	____	1- ____
7	____	1- ____
8	____	1- ____

NEW RATING

Hp or **kW**__________ **RPM** or **poles** __________ **HZ** ______ **Volts** ______

Reason for Inquiry __________

Version 1007

Note: This sheet is intended to assist you in completing the *Engineering Inquiry Form* on the reverse. It is not necessary to submit this sheet with your Inquiry Form.

Figure A

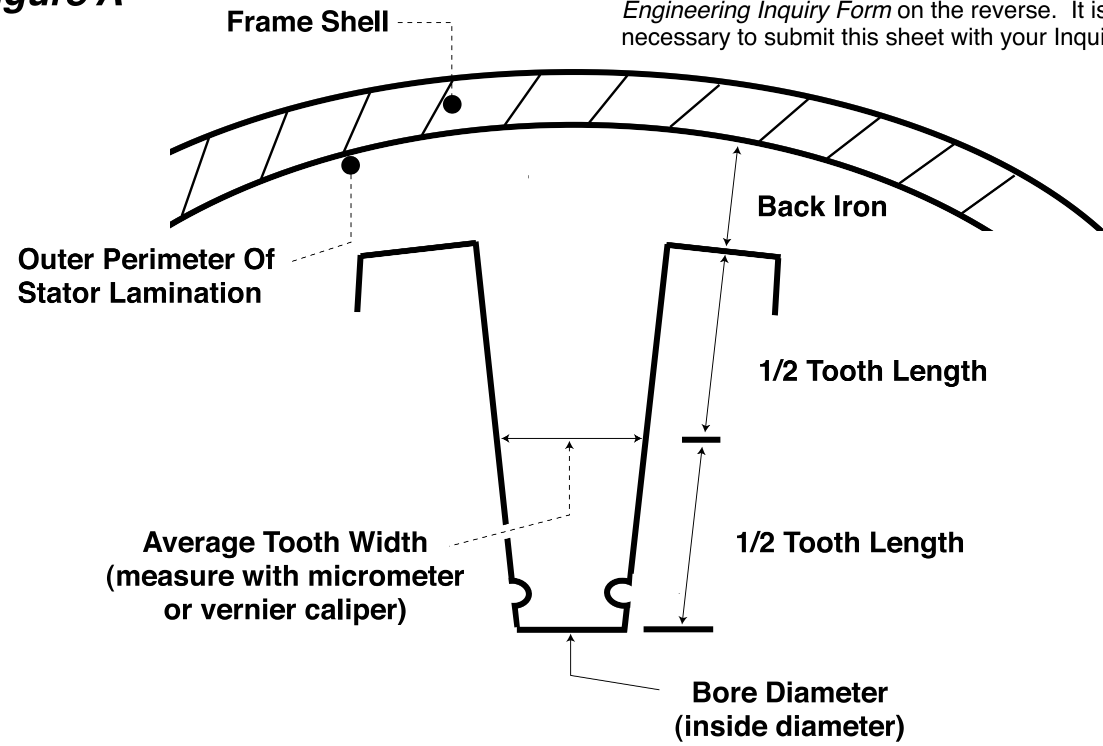
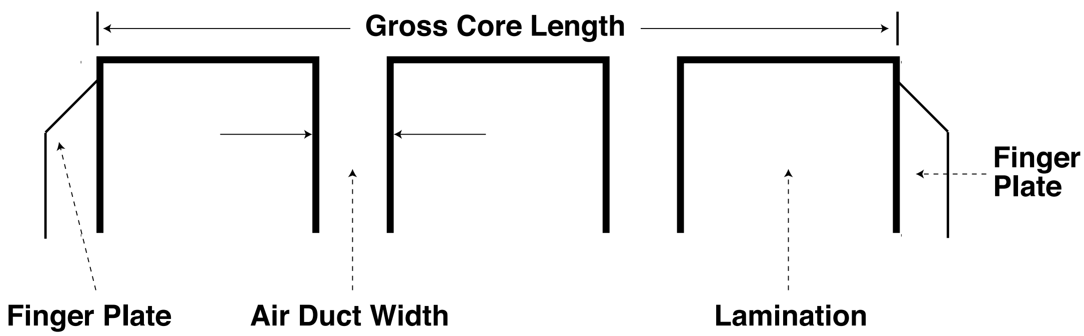


Figure B



Stator Core

Important Information For Taking Measurements

A
- The **bore diameter** is the inside diameter of the stator core.
- The **average tooth width** is measured *half-way down* the tooth (or slot). Accurate measurement of the tooth width is critical in many redesigns; therefore, this measurement should always be made with a micrometer or a vernier caliper—*never with a tape or ruler!*
- The **back iron dimension** is the radial measurement from the *bottom* of a stator slot to the *outer perimeter* of the lamination. This measurement does *not* include the thickness of the frame shell.

B
- The **gross core length** is the total length of the stator core lamination, including the ventilating or air ducts. The finger plates at the core ends are *not* included in this measurement.
- The **number of air ducts**, when used, and the **air duct width** must also be recorded on the data sheet.

Voltage stress: Not as simple as it sounds

By Chuck Yung
EASA Senior Technical Support Specialist

The term "voltage stress" refers to the electrical stress that the insulation system of an electrical winding is subject to. Simply put, it is a measure of voltage potential between two conductors (one of which may be ground). Windings generally fail due to a combination of stresses (mechanical, environmental, electrical and thermal), but ultimately it is voltage stress that causes the failure. In theory, voltage stress is fairly easy to understand. In practice, though, its effects on electrical windings are often complicated by a number of other factors.

STATIC VOLTAGE STRESS

When the topic comes up, many technicians mistakenly think voltage stress cannot exceed the line voltage of the winding. And early assumptions were that voltage stresses followed a linear pattern that could easily be calculated from the relationship of circuits, coils and turns per coil. In fact, the traditional equation for determining volts per coil (i.e., voltage stress limits) is based on the number of coils, circuits and phases, and whether the connection is delta or wye:

$$\text{Volts per coil} = \frac{\text{Phase voltage x Number of circuits x 3 phases}}{\text{Number of coils}}$$

Where: Phase voltage = line voltage (delta connection)

Phase voltage = 58% of line voltage (wye connection)

OTHER FACTORS

Volts-per-coil and turn-to-turn stresses. Today it is clear that the effects of voltage stress also depend on other factors. For a random winding, for instance, the first and last turns within a coil could be in direct contact, which means the volts/coil stress could occur between those turns. With a form-wound machine, the turn placement is managed, so the voltage stress between turns (volts/coil ÷ turns/coil) becomes more important. Manufacturers of form coils use the guidelines in Table 2-56 to determine minimum turn insulation.

TABLE 2-56: TURN-TO-TURN INSULATION FOR FORM-WOUND MACHINES

Turn-to-turn insulation	Volts/turn
Film coating of the wire	Up to 30 volts/turn
Single Daglass* (SDG) over film	Up to 40 volts/turn
Double Daglass* (DDG) over film	Up to 60 volts/turn
Mica turn tape	Above 60 volts/turn

*Daglass and Polyglass are trade names for polyester/fiberglass insulation.

Ground potential. Another consideration regarding voltage stress is the voltage potential to ground. The ground potential depends on whether the connection is wye or delta, and on whether or not the motor is operating in a properly grounded system. Assuming proper grounding, the voltage stress to ground equals line voltage for a delta-connected motor, but only 58% of line voltage for a wye-connected motor. However, if the motor is operating on an ungrounded system, the voltage potential equals line voltage, regardless of the connection type.

Some motor manufacturers insulate for ground potential. Repairers usually use the conservative values in Table 2-57, which are based on voltage stress limits from the static voltage stress calculation above. Through the years manufacturers have increased the voltage stress limits for random windings, first from 40 to 80 volts per coil. Now they routinely design for 115 volts per coil. There are even 2300V random windings in production today with higher voltage stress limits.

TABLE 2-57: TYPICAL GROUND-WALL INSULATION THICKNESS

	Coil insulation allowance			
	2.3 kV	4 kV	6.9 kV	13 kV
Total	0.120" (3.0 mm)	0.14" (3.6 mm)	0.180" (4.6 mm)	0.220" (5.6 mm)
Per side	0.060" (1.5 mm)	0.070" (1.8 mm)	0.090" (2.3 mm)	0.110" (2.8 mm)

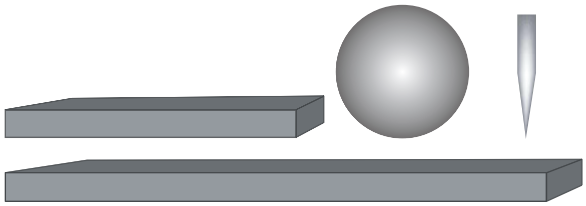
The slot fill combinations referred to in this article follow these guidelines.

What do motor manufacturers do differently than service centers, and how do they successfully wind motors with such high volts per turn? For one thing, they use phase insulation and add "phase paper" midway through the groups. Although these measures reduce the voltage potential within the group, the real benefit is in decreasing the voltage potential where wires cross at anything approaching right angles. That underscores the value in the old technique of taping each coil at the end-turns.

HOW GEOMETRY AFFECTS VOLTAGE STRESSES

Another factor that can affect voltage stresses has influenced the methods of insulating electrical windings for the past century–geometry. A lightning rod is a good example of how the pointed shape of an object can raise voltage stresses, causing the voltage potential from a storm cloud to ground to be higher for the rod than for the building it protects. For the same reason, winding failures often can be traced to the geometry of a coil, a connection, or a sharp corner within a stator frame. The geometry of conductors affects voltage stresses of intended conductors like magnet wire and form coils, as well as unintended conductors like a stator frame.

FIGURE 2-122



Conductor geometry: For the same gap, the voltage stress is greater for the sharp point (right).

For the various combinations of shapes in Figure 2-122, the voltage stress between two parallel flat plates is the lowest. The voltage stress between a rounded surface and a flat surface is higher, while the voltage stress between a sharp point and a flat plate can be significantly higher. We will get to the math behind this shortly.

You can demonstrate the physics behind this by experimenting with a Van de Graaf generator (Figure 2-123) at your local science center. First, extend your flattened palm towards the sphere, noting how far the static charge jumps to reach it. If you then extend only one finger towards the sphere, you'll quickly discover that the same magnitude voltage will jump considerably farther. The reason is that your fingertip has a much smaller radius than your palm. This same simple principle influences the design and construction of electric motors.

FIGURE 2-123

Van de Graaf generator can store high-voltage static charges across its spherical surface.

Geometry can affect voltage stress in several areas that repairers deal with daily:

- Voltage stress is highest at the corners of form coils closest to the bore.
- Gradient tapes must be used with conductive tapes to control partial discharge (PD) in machines rated above 6 kV.
- The way connections are made, especially series connections for form coil windings.
- Conductors crossing each other in a perpendicular direction have considerably higher voltage stress than if they are parallel or cross at a slight angle.
- A chamfer at the end of a commutator reduces the potential for flashovers.

LOOP-SERIES CONNECTION

In the early days, when manufacturers and repairers were still trying to understand how electricity works, they used loop-series connections (Figure 2-124 [bottom]) even on 440-volt stators. Although the influence of conductor geometry on voltage stress was gradually being learned by trial-and-error, "stub-series" connections (Figure 2-124 [top]) required less time and insulation to form. Therefore the loop-series connection was soon relegated to windings rated 2300V and higher, then to windings rated above 4000V, and finally (for most manufacturers) to windings rated above 6000V.

FIGURE 2-124

Stub-series (top) and loop-series (bottom) connections are used to connect coils within a coil group.

Older winders may remember the admonishment against using a "sore-thumb" or stub-series lead connection. They may even recall an old-timer cautioning them to use a loop-series connection, because "all the voltage can run out the end" of a straight-stub. As it turns out, that description was not as inaccurate as you might think.

RELATIONSHIP BETWEEN VOLTAGE STRESS AND RADIUS

There is an inverse relationship between voltage stress and the radius of a conductor. That applies to sharp versus gradual bends, to corners of rectangular wire on form-coil machines, and to the voltage stress that is present at the end of conductive coatings on high-voltage machines.

The following equation describes the voltage stress between a flat surface and a conductor with a radius (corner/point/round). The reality is that repairers are often concerned with voltage stresses between two conductors, neither of which is a flat plate. Therefore the voltage stresses involved may be even higher than determined by this equation.

$$E = \frac{2V}{(r \ln (4d/r))} \qquad \text{(Equation 1)}$$

Where: E = Voltage stress (in volts/mm)

V = Voltage potential between the two conductors being evaluated

r = Radius distance (in mm) of the conductor

d = Distance (in mm) between the two conductors

ln = Natural log

It is no surprise that the voltage stress increases with an increase in the voltage potential between the two conductors, or that the distance between them is an important factor in whether or not discharge occurs between them. What this equation demonstrates is that the radius has a significant impact on voltage stress between two conductors.

The voltage stress increases in proportion to the voltage, but the radius has the greater influence. Table 2-58 shows the results of calculations that were done using the same voltage and distance but with varying radii.

TABLE 2-58: VOLTAGE STRESS IN PROPORTION TO RADIUS AND VOLTAGE

Radius (r)	3 mm (0.118”)	0.7 mm (0.028”)	0.5 mm (0.020”)	0.2 mm 0.008”)	0.1 mm (0.004”)
Voltage (E)	1644	2722	2885	4343	6676

Calculations are based on a voltage potential of 1000 volts at a distance (d) of 0.5 mm.

CHANCE OF ARCING

If the voltage stress exceeds 3000 V/mm, PD (partial discharge) is likely to occur. Therefore the closer a live conductor is to ground, or the closer together two conductors are, the greater the chance of arcing. But the presence of a sharp radius such as a corner plays a much larger role in raising the voltage stress that can initiate an arc.

Two parallel strands of magnet wire have moderately low voltage stress. The same two strands, crossing at a right angle, have voltage stresses that are several times greater. That can be seen by considering the two conductor paths in two-dimensions. While they are not flat plates, the rounded edges are less likely to initiate an arc than two knife-edges. And the closer the intercept is to a right angle, the smaller the effective radius presented.

PHASE INSULATION IS ESSENTIAL

Consider top coil sides that cross bottom coil sides, forming something close to a right angle. While the voltage stresses are certainly higher for the phase coils, the sharp crossing angle also increases the voltage potential between the conductors. Therefore the presence of phase insulation is essential. When a winding has maximum circuits, and a delta connection (with its higher phase voltage), the voltage potential is increased.

When dismantling motors, repairers sometimes observe a place where the winding arced to ground. Invariably, this occurs at a bolt or a protruding corner on the frame or end bracket. Once again, the smaller radius raises the potential voltage stresses. With DC machines, it is common to find flashover damage to the corner of a brush box or the square corner at the end of the commutator. Many repairers lightly file such corners, providing a small chamfer that reduces voltage stress at the very place where many flashovers begin.

Winders avoid making sharp points when brazing a connection joint, not just because sharp points (small radius) might puncture the insulation, but also because they can dramatically increase the potential voltage stress between those points and the nearest potential conductor–whether that is to ground or another conductor.

POTENTIAL FOR PD DAMAGE

Finally, those who repair machines rated over 6 kV are accustomed to using conductive material on the straight section of the coil, with gradient (semi-conductive) material overlapping the ends of the conductive material and extending for several inches. Absent that semi-conductive gradient tape, the abrupt end of the conductive material becomes a sharp radius, greatly increasing the potential for PD damage to the coil insulation at the edge of the conductive tape.

Plug the 7-mil (1.8 mm) thickness of the conductive tape, and 6900V phase voltage for a wye-connected 13kV winding, into Equation 1. The resulting voltage stress of 19200V with d = 0.5 mm (0.020”) is extremely high. No wonder that we find PD damaging the ground-wall insulation of the coil sides.

Rewinding inverter duty motors

By Richard Huber
BC Hydro
Burnaby, BC Canada

The widespread use of adjustable-speed drives (ASDs) has resulted in motor failures, some of which are premature. The predominant problem has been failure of motor windings. Though less common, various types of mechanical failures have also occurred.

Motor and ASD manufacturers, wire suppliers and service centers have all tried to improve their products and procedures to minimize or overcome ASD-related motor failures. In fact, the resulting new products, materials and processes have reduced the failure rate.

This article briefly describes some of the common failure mechanisms and their causes, as well as repair methods and materials.

WINDING FAILURES

Of the many papers written on this subject, most trace the motor failures to the onset of electrical partial discharge activity (PD or "corona") within the motor winding. This problem is more prevalent in motors connected to ASDs using pulse width modulation (PWM) as a method of varying the energy supplied to the motor. These drives invariably use insulated gate bipolar transistors (IGBTs) in the output stage that have a very fast pulse rise time–about 0.1 microseconds.

This fast pulse rise time, combined with many other factors regarding the motor and the installation, can cause motor windings to fail prematurely. Some of the factors that determine the severity of these fast rise time pulses are given below.

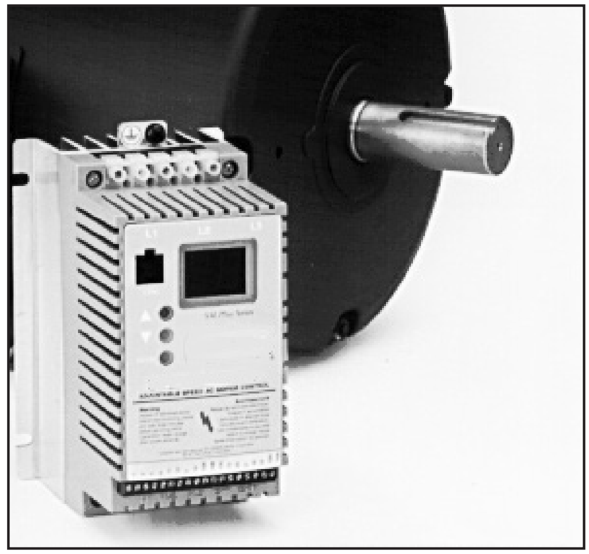
CONNECTING CABLE

Surge impedance of the cable. In general, the lower the surge impedance of the cable connecting the ASD to the motor the greater the amplitude of reflections at the motor terminals. This is due to the large mismatch in impedance between the cable and the motor. The amplitude of the pulses, which can increase by a factor of two (or more) at the motor terminals, is commonly called "voltage doubling."

Typical surge impedance for cables connected to electric motors is less than 100 ohms. For comparison, the surge impedance of motors can range from 1500 ohms for a 25 hp (20 kW) motor to 94 ohms for a 400 hp (300 kW) motor.

Cable length. Similarly, the length of the cable can contribute to "voltage doubling." The longer the cable, the larger its capacitance; hence the lower its impedance and the greater the mismatch at the motor terminals. The critical cable length can be as short as 50 feet (15 meters) and as long as 300 feet (90 meters), depending on the frequency of the pulses and propagation velocity of the cable. Shorter cables generally are considered to present lower risk.

On the other hand, the length of the cable connecting the ASD to the motor increases the electrical resistance between



the ASD and the motor. The farther the pulses must travel, the more they are attenuated (reduced) by the resistive losses in the cable.

Usually the capacitive characteristics of the cable dominate the effect on pulse amplitude at the motor terminals.

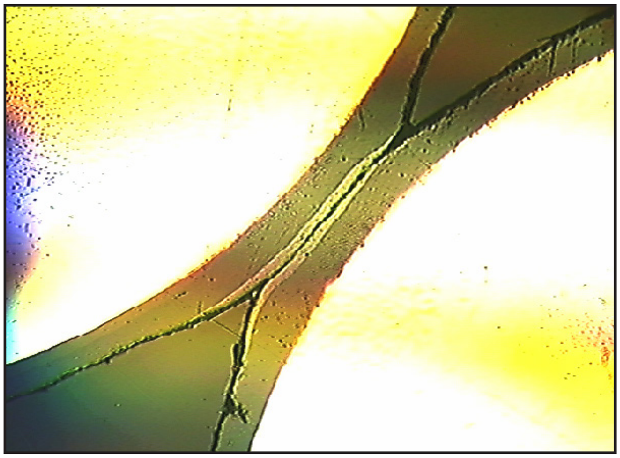
Cable diameter. Large diameter cables tend to have lower impedances than those with smaller diameters, so using oversized cables unnecessarily will increase the impedance mismatch between the motor and the cables. This too will increase the pulse amplitude at the motor terminals.

Shielded cable. In general, shielded cable does not attenuate fast rise time pulses as much as unshielded cable. If shielded cable is used, the amplitude of the pulses arriving at the motor terminals can be controlled somewhat by grounding at the motor rather than at the ASD. Grounding the cable at the motor also prevents any ground potential rise along the cable.

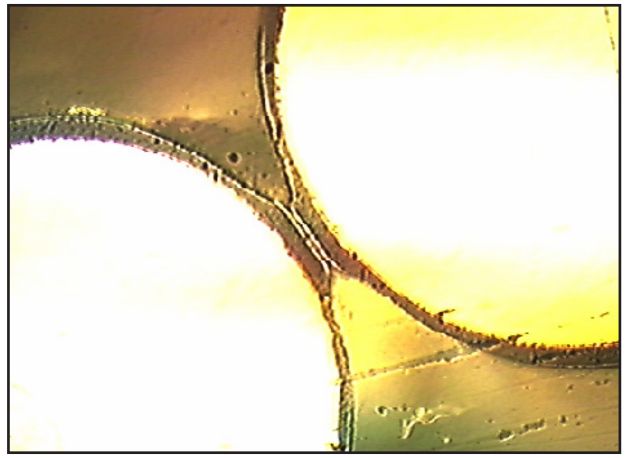
ASD DESIGN

As mentioned earlier, the latest types of PWM ASDs, when combined with the latest IGBT electronics, produce very fast rise time pulses–some as short as 0.1 microseconds. These drives are in common use today, especially with motors under 200 hp (150 kW). In addition to "voltage doubling" that may occur at the motor terminals, the fast rise time pulses affect the voltage distribution in the motor winding. Most of the voltage will be impressed across the first turn in the motor coil.

The carrier frequency used in PWM drives varies from a few kilohertz to 20 kilohertz. The drives with the higher



Corrosion occurs from the production of ozone and nitrous oxides in the voids between conductors.



Photos courtesy of Essex Wire

Cross-sectional view shows degradation of film coating prior to failure due to partial discharge ("corona") and ionization of gases in the voids.

frequency stress the motor insulation many more times per second, so they can shorten the life of the motor windings.

So far the discussion has focused on PWM ASDs, which produce voltage pulses that can damage motor windings. Another type of ASD that can cause motor problems is the current source inverter. Often used on larger motors, current source inverters distort current, giving the power supply a much larger harmonic content than PWM drives typically deliver. This produces more heating in the machine due to resistive losses. Once again, this can shorten the life of the motor.

MOTOR AND WINDING DESIGN FEATURES

Shaft resonance. The motor shaft has a resonant frequency above or below synchronous speed, depending on the design. When used without an ASD, this usually does not present a problem, as operation at the resonant frequency occurs only during start-up for the case where the resonance is below synchronous speed. However, if the motor is powered with an ASD, it is possible to operate the motor for extended periods at the resonant frequency, above or below rated speed. Vibration may increase dramatically, and in some cases the shaft will actually break. Some drives have a "skip frequency" feature that bypasses resonant frequency speed ranges. That is, the drive rapidly passes through these speed ranges and cannot operate within them.

Cooling. Motors are designed to operate at a synchronous speed that allows the cooling fan to circulate sufficient air to cool the motor. If the motor is operated too slowly to provide adequate air flow, it will overheat.

Air gap. Induction motors are designed with small air gaps. This creates a capacitive voltage divider between the stator winding and the rotor. Fast rise time pulses entering the stator will be capacitively coupled to the rotor. This can create a voltage potential on the rotor of several hundred volts. If not properly controlled, this voltage can break down the grease film in the bearings, causing bearing failure.

Wire size and insulation. The wire size used in the winding will affect the voltage at which partial discharge will occur. Discharges will occur at lower voltages on wires with small diameters than on wires with larger diameters.

The thickness and uniformity of wire insulation are also important in determining the ability of the insulation to withstand high amplitude pulses. Also important, voids or nicks in the insulation will reduce its ability to withstand high voltage pulses.

The insulation material can also affect the ability of the wire to withstand high-voltage pulses. Film-coated wire generally breaks down at lower voltages than either glass-served or mica-insulated wire.

In form-wound coils, it is not uncommon for the coil to be designed without dedicated turn insulation. This can result in turn-to-turn faults when the winding is exposed to fast rise time pulses.

The ground insulation and phase insulation are also important in determining the ability of the motor to withstand partial discharges and fast rise time pulses during operation with ASDs.

PREVENTING OR REDUCING MOTOR FAILURES

The following courses of action are available to the EASA service representative to prevent or reduce motor failures associated with ASDs.

Investigate. First, perform rigorous failure analysis on motors that arrive for repairs. The intent is to locate the failure and identify the cause. In addition, it is helpful to note existing features of the motor or winding that could easily be changed to improve its resistance to damage by fast rise time pulses.

At this point, it is good practice to discuss the motor-drive system with the customer to gain as much information as possible about the operating conditions. Gather details about cable size and length and determine whether it is shielded or not. Is the cable grounded, and if so, at which end? What type or vintage is the ASD? Is motor over-temperature a problem?

Reduce or eliminate pulses or reduce pulse amplitude. The best course of action is to reduce or eliminate the source of the problem by installing line filters or reactors. These can be installed at the motor terminals, but placing them at the drive output terminals provides the added benefit of preventing high-magnitude pulses from entering the cable.

THE REWIND

When a motor is rewound, specific things can be done to improve its resistance to failure due to fast rise time pulses. Note, however, that the following recommendations need not be applied to all motors–only to those suspected of failing because of exposure to fast rise time pulses from ASDs.

Magnet wire. The first consideration should be the insulation on the wire. Use wire that has thicker film, such as quad-film wire. Alternatively, use wire that is coated with a high dielectric strength film.

Major wire manufacturers have also developed new "inverter-duty wire" products for this purpose in which the insulating film is about the same thickness as that on heavy-build wire. The insulation material is specially formulated to resist deterioration by fast rise time pulses.

If overheating of a standard efficiency motor was the problem, install insulating materials that have a higher temperature rating. Just make sure the customer knows that this does not justify operating the motor at a higher output. Additional solutions for severe overheating might include installing a filtering device at the ASD output, replacing the rotor and stator steel, attaching an external fan to keep the motor cool, or even derating the motor.

Wire diameter. Larger diameter wire sizes are preferred over smaller ones, because as discussed previously discharges will occur at lower voltages on wires with small diameters.

Phase and ground insulation. Next, consider using thicker or dialectically stronger materials for the phase and ground insulation. For added protection, some service centers also apply sleeving over the first turn at the line end of the motor winding.

Testing. Additional testing can help ensure that the materials and methods chosen for the rewind will achieve the desired result. This must be balanced against the increased risk of failure as the number of tests increases. One example is to increase the number of surge tests on the coils by testing them prior to installation, after installation and wedging, and after connecting but before VPI treatment.

Resin treatments. VPI treatment (vacuum pressure impregnation) is preferred as it tends to fill small voids better than dipping. However, if VPI treatment is unavailable, additional varnish dips will help fill the space between conductors.

Bearings. If bearing failure due to electrical causes was the original problem, the motor can be reassembled using an insulated bearing. Alternatively, a shaft grounding brush may be provided to prevent the buildup of dangerous shaft voltages. Another option is a hybrid ceramic bearing with steel inner and outer races and ceramic rolling elements.

Motor speed-torque characteristics. NEMA design C and D motors tend to overheat when used with a PWM ASD. The rotor windings in these motors have higher resistance and therefore greater rotor losses than those of NEMA design A and B motors. Use only NEMA design A or B motors with ASDs.

OTHER CONSIDERATIONS

It may not be possible in a particular repair to make every change mentioned. However, it may be helpful to consider the following items when assessing the ability of a motor to operate successfully with ASDs.

If laminations in a stator or rotor require replacement, new ones can be manufactured from special steels that reduce leakage flux and eddy current losses in the stator and rotor. This will reduce any over-temperature problems.

When a motor is coupled to an ASD, the high frequency pulses and carrier signals can produce "skin effect" heating that increases exponentially with frequency. In repairs where laminations must be replaced, the geometry of the stator and rotor slots can be redesigned to improve heat dissipation and reduce "skin effect" heating.

In larger motors, shafts can be redesigned so that the critical speeds are above rated speed, rather than below rated speed as is typical. This prevents prolonged operation at critical speeds.

The fifth and seventh harmonics that can be generated by ASDs can cause pulsations in shaft torque. This phenomenon, if combined with mechanical resonance, can damage shafts, gears, and couplings. If damage of this type is encountered and the motor is connected to an ASD, check for possible resonance conditions.

If a motor is to be operated regularly at above rated speed, different bearings may be required to cope with the higher shaft speed. In addition, the rotor design may have to be changed to withstand the higher centripetal forces. In any case, consult the motor manufacturer about the suitability of the motor for this application.

There are NEMA, IEEE and IEC standards that apply to motors that operate with ASDs. At present, these standards only imply that the motor will operate satisfactorily when exposed to fast rise time pulses. They do not suggest a test method that will confirm whether a motor can withstand fast rise time pulses.

SUMMARY

The operation and repair of motors exposed to fast rise time pulses is complex. Available methods and materials can be used to mitigate the damage caused by this type of exposure. Hopefully, in the near future other products and techniques will be made available to further enhance a motor's ability to operate in this harsh environment.

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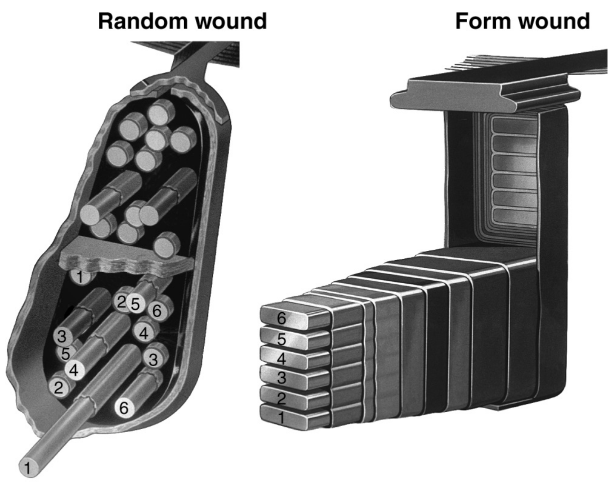
Rewind tips for 2300-volt, random-wound motors

By Chuck Yung, EASA Senior Technical Support Specialist

When rewinding a motor, the service center is restricted by the original design. Sometimes, it encounters a motor design it wishes had never been developed. Many winders would agree that the random-wound, 2300-volt motor design falls into that category. Most service centers would prefer to see medium voltage (2300-4160 volt) machines built exclusively using form coils (Figure 2-125). The form coil winding assures uniform volts/turn stresses, and reliably seals the windings against hostile environments.

FIGURE 2-125



Voltage stress between adjacent turns is uniform for the form coil (right), while the voltage stresses for the random-wound coil may potentially equal coil voltage.

From the manufacturer's perspective, a random-wound, 2300-volt motor represents a substantial reduction in manufacturing cost. And competitive pricing is important if they want to sell motors. The great challenge to the service center is in successfully rewinding this design while maintaining profit.

PROCEDURES FOR ENHANCING SUCCESS

Here are some tips learned from service centers with good track records in random-wound, 2300-volt motors that should enhance the success rate with these challenging rewinds.

First, the use of glass-over-film wire increases the turn separation, reducing the chance of failure between turns. Turn insulation is more critical with a random-wound motor, where the voltage between turns could equal the voltage per coil.

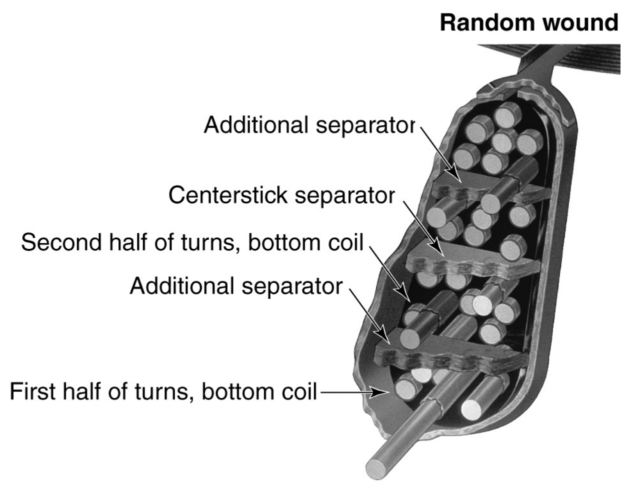
Doubling the slot liner helps protect against ground failures, and the use of Nomex®-Mylar®-Nomex® laminates combines the mechanical strength of Mylar® with the temperature resistance of Nomex®. Voltage creep distance increases in proportion to applied voltage, so slot liners should protrude at least 1 full inch beyond the end of the slot.

Phase insulation should also be doubled, with additional insulation between adjacent coils. Some winders tape every coil instead, while others use phase insulation between every coil. Taping coils improves resin retention.

REDUCE POTENTIAL VOLTAGE STRESSES

When practical, there are a couple of other ways to reduce the potential voltage stresses within each coil. First, divide each coil when looping coils. If a coil has 6 turns, loop and tie 3 turns before looping the remaining turns. During insertion: insert the first coil half; then install a separator (and phase insulation in the coil extension); see Figure 2-126. That reduces the potential voltage between turns to half of what it would be otherwise.

FIGURE 2-126



Insulation between phases should be doubled, and lacing should keep the wires tightly bundled without displacing phase insulation. Nomex® phase insulation has an advantage in that it absorbs resin.

Another concern is PD (partial discharge, or corona), which occurs when air adjacent to a conductor exceeds its dielectric strength.

A 0.040" (1 mm) void is large enough to permit partial discharge to occur. For this reason, multiple varnish treatments are strongly recommended, and/or the use of high-build resins. The goal is to create a void-free winding to reduce the risk of partial discharge. With round wires stacked in a coil, there are lots of opportunities for voids.

The use of high-build resins, and/or multiple treatments, minimizes the presence of voids that could contribute to premature winding failures. One major manufacturer even dips and bakes the winding first, then VPI processes it. Their goal is a void-free winding, especially through the slot section.

DETERMINE CIV OF WINDING

To determine the CIV (corona inception voltage–i.e., the voltage at which PD occurs) of a winding, perform this simple test for partial-discharge. Drape the stator with black plastic or a heavy tarp, and use a surge tester to energize the windings up to 1.5 times line voltage. Watch for visible arcing (evidence of partial discharge). Sometimes it is possible to hear the discharge, too. If the CIV is not well above line voltage, partial discharge may cause the winding to fail prematurely. Additional resin treatments should reduce the voids and raise the CIV.

REDUCING COIL MOVEMENT

Some service centers also spray the coil extensions using a two-part epoxy (normally a pour-through product) to further reduce voids between wires in the end turns. Others hand-tape each coil right up to the slot liner, to aid resin retention. That also increases the mechanical bond strength between coils, which should reduce coil movement. Coil movement can also be reduced by securely lacing a surge rope to each coil extension.

It is important to realize that these tips will help increase the chance of success; they do not ensure success. These motors are difficult to rewind, and the chance of failure is significantly higher than for a random-wound motor rated 480 volts. Warranty considerations should be discussed fully with the customer. They probably bought that random-wound motor because it was less expensive than a comparable form-wound motor and need to understand the tradeoff could be reliability.

Note: This article was originally published in *EASA Currents* (October 2001); it was reviewed and updated as necessary in August 2016.

Converting wound-rotor wave windings to lap windings

By David L. Gebhart, EASA Staff Engineer (deceased)

Since the development of the wound-rotor motor, much has been written about the wave windings that were used in the rotors of these machines for many years. Such information often explained the importance of recording the data accurately so that the proper connections could be made when these rotors were rewound. Articles also emphasized the extreme care required in soldering the clips on the end connections to prevent high resistance joints. With time, better methods of heating end connections were devised that helped reduce the possibility of high resistance joints. But making wave windings still required many hours of labor in forming copper straps, shaping ends for proper connections, inserting end clips, wedging, and soldering or welding. Today, however, improved materials and equipment make it possible to replace all wave windings and concentric windings with lap windings of either random-wound or strap copper coils.

Two basic formulas are used for making the winding conversions:

$$(1)\quad E_r = \frac{N_r \times S_r \times CF_r \times P_s \times K_r \times E_s}{N_s \times S_s \times CF_s \times P_r \times K_s}$$

$$(2)\quad N_r = \frac{N_s \times S_s \times CF_s \times P_r \times K_s \times E_r}{S_r \times CF_r \times P_s \times K_r \times E_s}$$

Where:

- N_r = Turns per coil in the rotor
- N_s = Turns per coil in the stator
- S_r = Slots in rotor
- S_s = Slots in stator
- CF_r = Rotor chord factor
- CF_s = Stator chord factor
- P_r = Parallel paths in rotor
- P_s = Parallel paths in stator
- E_r = Rotor volts between the rings
- E_s = Voltage across stator windings
- K_r = Rotor constant: 1.73 if wye connected; 1.0 if delta connected
- K_s = Stator constant: 1.73 if wye connected; 1.0 if delta connected

When replacing a wave winding, the calculations can be made from the original data or from the bare core. A concentric winding is best replaced by calculating from the bare core.

Most wave windings are wound with one turn per coil, two coil sides per slot, full pitch and single circuit. You could wind a rotor with a lap winding of one turn, but the coil would be quite large and impractical due to the great number of parallel wires that would be required. The cross-sectional area per turn of the coil can be reduced by the number of poles. This can be done by increasing the turns in the same ratio and connecting all the poles in parallel. It can be seen from formula (1) that an increase in rotor turns per coil (N_r) accompanied by a like increase in parallel paths (P_r) will not change the rotor voltage.

As an example, take a 125 hp, 900 rpm motor that has a wave-wound rotor of 144 slots, one turn per coil, full pitch of 1 to 19, connected single circuit wye, with a cross-sectional area of 62,800 circular mils. To wind such a coil with round wires, we would have to use twelve #13. This would be quite a job. With eight poles we have a choice of two, four, or eight parallel paths. If we choose an eight circuit wye connection, we will have eight turns with a circular mil area per turn of 62,800/8 = 7,850 circular mils. This gives us a coil of three #16 round wires.

We now have a simple formula for converting wave windings to lap windings.

$$\text{Turns per coil (lap winding} = \frac{\text{Turns per coil (wave winding) x Number of poles}}{\text{Number of parallel circuits (wave winding)}}$$

The number of parallel circuits for the lap winding now equals the number of poles. The same pitch and connection (wye or delta) is used for the lap winding as was used for the wave winding.

For lap windings:

$$\text{Coils per group} = \frac{\text{Rotor slots}}{\text{Phases x Pole}}$$

$$\text{Copper area per turn} = \frac{A_w \times N_w}{N_1}$$

Where:

- A_W = Wave winding area per turn
- N_W = Turns per coil (wave winding)
- N_1 = Turns per coil (lap winding)

If a shorter pitch is desired, the turns can be changed by the following formula:

$$(3)\quad N_n = N_o \times \frac{CF_o}{CF_n}$$

Where:

- N_n = Turns per coil after pitch change
- N_o = Turns per coil before pitch change
- CF_o = Chord factor before pitch change
- CF_n = Chord factor after pitch change

In our example, changing the rotor pitch from 1 to 19 to 1 to 14 would require a turns change to:

$$N_n = 8 \times \frac{1.0}{0.906} = 8.84 \text{ turns}$$

We can use nine turns as this would only cause a two percent increase in the rotor voltage (9/8.84 = 1.02).

It is essential to keep the rotor voltage within ten percent of its nameplate value. If this is not done, the controls may have to be changed.

Now let's convert a rotor to a lap winding using the bare core method. To do so we must know the stator data. The original winding can be either wave or concentric wound.

Assume that the motor is a 50 hp, 1200 rpm, 220/440 volt, TEFC motor. The stator data is: 72 slots, 14 turns, pitch 1 to 11 (chord factor = 0.966), connected 3 and 6 circuit delta. The rotor data is 314 volts, 74.6 amps, 90 slots.

We will assume a single-circuit delta connection with a full pitch of 1 to 16. Using Formula 2:

$$N_r = \frac{14 \times 72 \times 0.966 \times 1 \times 1 \times 314}{90 \times 1.0 \times 3 \times 1 \times 440} = 2.58$$

Since this is impractical, let's change the connection to three-circuit delta, which would change N_r to 3 x 2.58 or 7.74 turns. By using eight turns per coil, the rotor voltage would become 8/7.74, or 1.035 times its original value or 325 volts. This can be left as is because the voltage stays within 10 percent. However, if we want to get closer to the original voltage, we can change the rotor chord factor. We need a chord factor of 0.968 (7.74/8 = 0.968). Now by checking the chord factor table (Page 2-203 of this manual) we find the chord factor nearest 0.968, 0.978, equal to a pitch of 1 to 14. From Formula 3:

$$N_n = 7.74 \times \frac{1.0}{0.978} = 7.9$$

By using 8 turns, pitch 1 to 14, 3 circuit delta, the rotor voltage becomes 314 x (8/7.9) = 318 volts.

If the original turns and wire size are known, calculate the new wire size by the formula:

$$CM_2 = CM_1 \times \frac{T_1}{T_2}$$

Where:

CM = Circular mils per turn

T = Turns

1 = Original

2 = New

If the original turns and wire size are not known, calculate the new circular mil area per turn from one of the formulas shown below. Select a value of circular mil per ampere from the chart at the bottom of the page.

Wye Connection

$$\text{Cir. mils per turn} = \frac{\text{Line amps x Cir. mils per amp}}{\text{Number of parallel paths}}$$

Delta Connection

$$\text{Cir. mils per turn} = \frac{\text{Line amps x 0.58 x Cir. mils per amp}}{\text{Number of parallel paths}}$$

When calculating wire size by these formulas, make and insert one or two test coils before winding all the coils. It may be necessary to increase or decrease wire size depending on the slot fill. For example:

$$\text{Cir. mils per path} = \frac{74.6 \times 0.58 \times 550}{3} = 7932$$

A coil of three #17 and one #18 wires has an area of 7770 circular mils.

Now that you know the calculations for changing a wave winding to a lap winding, remember to use common sense in deciding whether to use a random or strap copper winding. Keep in mind that a rotor is subjected to the strains produced while banding, as well as the strain due to centrifugal force.

If random-wound coils are used, the coil ends should be taped completely, or at least around the nose. It is best to build up the coil shelf to make it level with the bottom of the slots. When banding, do not use as much tension as with strap coils.

Be sure to plan your lead connections so that they can be folded under the coil ends. Tie them in securely. Be sure to leave the coil leads long enough to eliminate the addition of jumpers. The more parallel paths you use, the fewer connections are needed.

Our second example points out that for designs of rotors or stators in the large horsepower ranges the number of turns per coil is very seldom a whole number. It also shows how adjusting the span (chord factor) will affect the effective number of turns in a coil. Sometimes, in adjusting the chord factor, we cannot get the exact results we are looking for. In that case, we must decide on a definite chord factor. Next, we must determine if it is best to raise the ring voltage by increasing the effective turns, or lower the voltage by decreasing the effective turns. Be sure to recalculate to see exactly what has happened to the voltage after deciding on a chord factor.

Remember, you can also change the effective turns by changing the type of connection used. These methods of adjusting the effective turns can be applied to stators as well as rotors.

CIRCULAR MILS PER AMPERE CHART (APPROXIMATE VALUES)

Frame	Insulation class	Open dripproof	Totally enclosed
Pre-1960 motors	A	430	550
Present-day motors	B	330	450

Design and redesign of multispeed motors

By David L. Gebhart, EASA Staff Engineer (deceased)

SINGLE-PHASE MOTORS

Two-speed, single-phase motors are built with two running windings and one or two starting windings. The second running winding may be wound for a different number of poles and operated independently of the main running winding, or it may be wound for the same number of poles and connected in series with the main running winding.

The pole changing method is normally used for split-phase motors. The high-speed winding is connected in the conventional manner, but the low-speed winding is quite often connected for consequent poles.

In order for this type of motor to start on both speeds, two starting windings must be used. This has two distinct disadvantages. First, larger motors are required to produce a given horsepower output as the second starting winding takes up space in the slots and results in there being three dead windings in the motor under running conditions. Second, only one centrifugal switch is used, and it must be set to open on the slow speed. Therefore it opens below the usual opening speed on high-speed operation. This reduces the high speed accelerating torque.

Using only one starting winding makes it mandatory to start the motor on the high-speed connection. This may be accomplished by using a special type of centrifugal switch that closes the low-speed circuit when it opens the starting winding circuit. In this case, however, the main control switch must be manually turned from high to low after the centrifugal switch has opened the starting winding before the motor will run on the low-speed connection. There is also a special switching arrangement whereby the motor will automatically switch from high-speed to low-speed operation after starting if the controls are set for low-speed operation when the power is applied.

Two-speed, capacitor-start motors are manufactured similar to split-phase motors. Where two starting windings are used, two capacitors are also used. One capacitor is used with one starting winding.

The largest application for multispeed, single-phase motors is for driving shaft-mounted, air-moving equipment. The types of motors used most often for this application are the permanent capacitor and the shaded pole. For these types of motors, two or more speeds are obtained by the tapped winding method or by varying the voltage to the motor terminals.

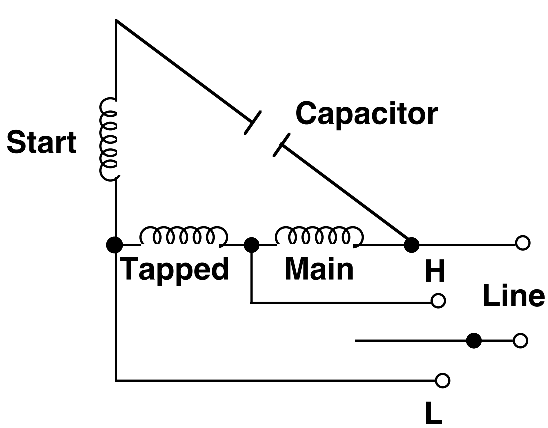
The tapped, or extended, winding method is the addition of turns to the original winding. The tapped winding is inserted in the same slots as the running winding and connected in series with it. It does not have the same number of turns and is wound with a smaller wire. A second tapped winding, if desired, can be added to obtain a third speed.

With a permanent capacitor motor, the windings may be connected "L" as shown in Figure 2-127, or "T" as shown in Figure 2-128.

The "L" connection can be used on 115 volts only. The reason for this is that the tapped winding is in series with, and becomes part of, the starting winding when connected for high-speed operation. This increases the voltage induced in the starting circuit, thereby increasing the voltage across the capacitor. With this type of connection, 230 volts applied to the motor terminals could raise the capacitor voltage to more than 500 volts. This does not happen on a T-connected motor, as the tapped winding is not used when the motor is operating on high speed.

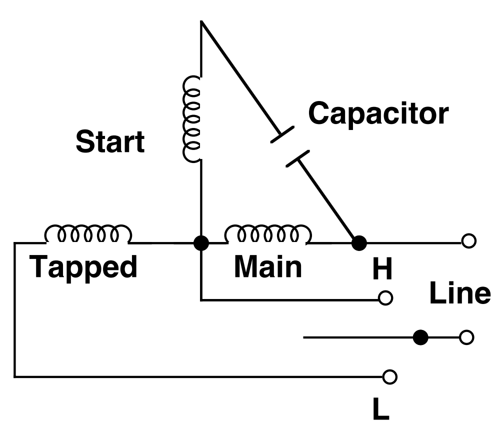
Tapped autotransformers is one method used to vary the voltage applied to the motor terminals. Reducing the voltage

FIGURE 2-127



L-connected windings.

FIGURE 2-128



T-connected windings.

weakens the motors, thereby reducing the operating speed. Any number of speeds may be obtained in this manner depending on the number of taps on the transformer. A variable resistance may also be used to adjust the motor speed. A method commonly used for speed changing of shaded pole motors is to insert a fixed resistance or resistances in series with the winding.

Quite often when operating on slow speed and driving air-moving equipment, these motors will be operating at a speed below that at which maximum torque occurs. This can cause a wide variation in the operating speeds of a given motor from a cold start to level-off temperature. It also can cause a wide variation in operating speeds for different motors of the same model when used to drive the same fan.

THREE-PHASE MOTORS

Three-phase multispeed motors are built in three different categories: constant horsepower, constant torque and variable torque. Most multispeed motors are built with one or two windings. With one winding, two speeds can be obtained. The speed ratio in this case is normally 2-to-1. In two-winding motors, two, three or four different speeds can be obtained. Any speed combination desired may be obtained with two-speed, two-winding motors. Three-speed, two-winding motors must have two speeds in a 2-to-1 ratio. Four-speed, two-winding motors must have 2-to-1 speed ratios for each winding. Motors with three windings have been built but are so rare they will not be discussed here.

Constant horsepower motors produce the same horsepower output at all rated speeds. Therefore the full-load torque must vary inversely as the speed changes. As an example, a 10 hp motor has 30 pound-feet load and locked-rotor currents also increase as the speed is decreased, but the ratio of change is much less than the speed change ratio. Some applications for constant-horsepower motors include large lathes, milling machines, production drill presses, winches and pug mills.

Constant-torque motors produce the same full-load torque at all rated speeds. This means the horsepower will vary as the speed. A 10/5 hp, 1800/900 rpm motor will have 30 pound-feet for its full-load torque on both speeds. The IEC equivalent would be a 7.5/3.75 kW, 1500/750 rpm motor whose full-load torque would be 48 newton-meters. IEC motors, however, do not have their output ratings in direct ratio to the speed change as do NEMA motors. Instead of 7.5/3.75 kW, IEC motors would have an output rating like 7.5/5 kW, 7.5/5.6 kW, 7.5/4.5 kW, and so forth. Full-load currents are generally less on the slower speeds, although there are designs for two-speed, one-winding motors where the currents are slightly larger on the slower speed. This condition usually occurs with intermittent duty motors where magnetic flux densities are high. Constant-torque motors do not have the same maximum and starting torques on all speeds. Some applications for constant-torque motors are conveyors, hoists, pumps, compressors, machine tools, and grinders.

For **variable-torque** motors, the full-load torque varies directly as the speed. This means the horsepower must vary as the speed squared. If the speed is cut to one-half of its original value, the full-load torque is also cut to one-half of its original value. The horsepower output, however, is cut to one-fourth of its high speed value. For IEC motors the output ratio may be more like 2.5 to 1 or 4.5 to 1. These motors are used mainly on fans, blowers, and centrifugal pumps.

TWO-SPEED WINDINGS

Windings that are reconnectable for use on two speeds (Dahlander connections) will have the same number of coil groups as a single-speed winding designed for use on the high speed. However, the coil span on the two-speed winding will be considerably shorter. The span should be as close to half pitch for the high speed as possible. That is, for a 4/8 pole, 48 slot motor, the coil span should be 1-7. This will give a chord factor of .707 for the high speed and 1.0 for the low speed.

NEMA motors with windings designed for two-speed operation require six leads numbered 1 through 6. Leads 4, 5 and 6 are the power leads for high-speed operation and 1, 2 and 3 for low-speed operation. IEC motors use 2U, 2V, 2W for high-speed leads and 1U, 1V, 1W for low-speed leads. The non-power leads are left open or connected together depending on whether the connection is delta or wye. A seventh lead is sometimes used when this type of winding is used in a two-winding, three- or four-speed motor. This seventh lead opens up one corner of the delta, thus preventing circulating currents when the motor is operating on the other winding.

Constant horsepower motors are connected series-delta for high speed and two-circuit wye for low speed. Constant-torque motors are connected two-circuit wye for high speed and series-delta for low speed. Variable-torque motors are connected two-circuit wye for high speed and series-wye for low speed. Multiples of these circuits may also be used in two-speed, one-winding motors.

Two speeds are obtained from one winding by reversing the polarity of every other coil group. High-speed operation is the same as the standard single-speed operation; that is, the number of north poles equals the number of south poles. The reversing of the polarity of every other coil group makes all poles have the same polarity. This causes poles of opposite polarity to be induced between the actual poles, which results in doubling the number of poles and cutting the synchronous speed in half. This type of operation is called consequent pole. Only 2-to-1 speed ratios are obtained with this method.

In designing windings for consequent-pole motors, it is well to remember that the chord factors and distribution factors are different for each speed. Chord factors for each speed and the distribution factor for the high-speed winding are determined in the same manner as for a single-speed motor. The distribution factor, however, decreases considerably for the low-speed connection. This factor is shown in the following table.

Coils per group	Distribution factor
1	1.000
2	0.866
3	0.844
4	0.837
5	0.833
6	0.831

The lines of flux per pole are always fewer for low-speed operation. For windings that have a chord factor of 0.707 for the high speed and 1.0 for the low speed, the flux per pole for the low-speed connection is approximately 94.5 percent, 71 percent and 41 percent of the high speed flux for constant-horsepower, constant-torque, and variable-torque motors, respectively.

The formula for calculating air gap and tooth densities is: (1.57 x Flux per pole x Poles)/Area. Thus it can be seen that the pole change is more rapid than the flux change on constant-horsepower and constant-torque motors. This results in higher densities in the air gap and teeth for low-speed operation. These densities, however, decrease on variable-torque motors. Since the back iron density is not related to the number of poles [Flux per pole/(2 x Area)], it will always decrease at the same rate as the flux per pole decreases.

TWO-WINDING MOTORS

Two-winding motors are generally built to the same standard types as one-winding motors but, since each winding operates independently, they can be designed for any speed ratio and horsepower ratio desired. It is advisable, however, to always make the high-speed horsepower equal to or greater than the low-speed horsepower. This is necessary to accelerate the rotor to the higher speed in a reasonable length of time.

As an example, I was once called upon to design a motor for an application that required a 3 hp output at 3600 rpm and a 5 hp output at 600 rpm. The motor was to change speeds three times during each cycle. In order to accelerate and brake rapidly enough the motor had to be designed for 15 hp at 3600 rpm and 7-1/2 hp at 600 rpm.

The most common speed ratios used in two-winding motors are 3-to-2, 4-to-3, 3-to-1, and 4-to-1. This necessitates a compromise of the motor constants between the two speeds and reduces the efficiency of both speeds. Normally the bore diameter is the same as that used for a single-speed motor of the lowest speed. The number of stator slots usually will allow even coil groupings for both speeds. A stator-rotor slot combination must be chosen that will be suitable for both speeds. (See Page 2-214 of this manual.) Stator slots are normally wider and deeper than those used in a single-speed motor. The space occupied by each winding ranges from 50/50 percent for variable-torque motors to 35/65 percent for constant-horsepower motors, with the low-speed winding occupying the most space. For motors of the three standard types, air gap and tooth densities will increase as the speed decreases (except for some variable-torque motors), while core densities will decrease with a decrease in speed.

Two-speed, two-winding motors are also built with a 2-to-1 speed ratio. These motors, however, are larger and therefore more costly than two-speed, one-winding motors of the same ratings. This cost is offset somewhat by the increased cost of the controls for a one-winding motor over a two-winding motor.

The high-speed winding should always be inserted first. The motors should be connected wye, if possible; however, a delta connection may be used if an extra lead is brought out to open one corner of the delta and prevent circulating currents. A series circuit must always be used with odd coil grouping. Multiple circuits may be used with even coil groupings for certain speed ratios. For more information on this, see Page 2-212 of this manual.

Designers always attempt to approach the NEMA current and torque values of single-speed motors. Maximum torque is usually obtainable; however, starting torque is usually slightly low and starting current slightly high.

For two-speed, two-winding motors, the leads are tagged 1, 2 and 3 for low speed, and 11, 12 and 13 for high speed. For four-speed, two-winding operation, the leads are tagged 1 through 7 for low speed (1200/600 rpm winding of an 1800/1200/900/600 rpm motor), and 11 through 17 on high speed (1 through 6 and 11 through 16 for variable-torque motors.)

The numbering system for three-speed, two-winding motors depends on which winding is used for obtaining the two speeds. If the high-speed winding is used, such as 1800/900 on a 1800/1200/900 rpm motor, the leads are tagged 11 through 17 for 1800/900, and 1, 2 and 3 for 1200 rpm. For a 1800/1200/600 rpm motor the tagging is 11, 12 and 13 for 1800 rpm, and 1 through 7 for 1200/600 rpm. Dual-voltage, multispeed motors are very seldom built because they require a very large number of leads and, since they are special motors, the supply voltage is generally known.

PAM MOTORS

PAM (pole-amplitude modulation) motors were developed in England in the late 1960s. They are two-speed, one-winding motors designed for speed ratios other than 2-to-1. They can be close ratios like 4-to-6, or wide ratios like 8-to-32. It takes only six external leads to connect them, just like any two-speed, one-winding motor. A constant-torque motor is still connected 2-wye, 1-delta, and the variable-torque motor has a 2-wye, 1-wye connection.

The basic principle of pole-amplitude modulation is similar to the principle of frequency modulation. If a frequency of 60 hertz is modulated by a frequency of 2 hertz, two new frequencies of 58 and 62 hertz are produced. In a PAM motor, if an 8-pole field is modulated with a 2-pole field, a 6-pole field and a 10-pole field result.

For an 8-pole field modulated with a 2-pole field, proper spacing of the "B" and the "C" phases with respect to "A" phase eliminates the undesired field. If in this case "B" phase and "C" phase start 120 and 240 mechanical degrees, respectively, ahead of "A" phase, the 6-pole field is eliminated, producing an 8/10-pole motor. Placing "B" phase and "C" phase the same distances behind "A" phase cancels the 10-pole field, leaving us with a 6/8-pole motor.

The modulating field is obtained by reversing half of each phase. This is the same method that is used for the normal two-speed, one-winding motors with a 2-to-1 speed ratio. However, the coil grouping as well as the internal jumper connections are different.

For some PAM windings the coil grouping may give the appearance of disorder, but for others the grouping appears quite manageable. For example, a 4/6-pole, 24-slot motor has 12 groups of 1 coil and 6 groups of 2 coils. The grouping, 1-1-1-1-1-1-2-2-2, is repeated. The 6/8 pole, 24-slot motor has 16 groups of 1 and 4 groups of 2 coils. The grouping is 2-1-1-1-1; it is repeated 3 more times.

Some coil grouping, however, can get quite complicated. Take, for example, a 4/6-pole motor with 54 slots and 20 groups of coils. There are 6 groups of 1, 6 groups of 2, 2 groups of 3, 2 groups of 4, 2 groups of 5, and 2 groups of 6 coils. The following table shows the coil grouping, its phase relationship, and polarity for both speeds. Note that each phase has the same number of coils.

Group #	Coils/ group	Phase	High speed polarity	Low speed polarity
1	4	C	S	N
2	2	B	S	S
3	2	A	N	N
4	1	B	S	S
5	3	C	N	S
6	1	B	S	N
7	2	C	N	S
8	6	A	S	S
9	5	B	N	S
10	1	A	N	N
11	4	C	S	S
12	2	B	S	N
13	2	A	N	S
14	1	B	S	N
15	3	C	N	N
16	1	B	S	S
17	2	C	N	N
18	6	A	S	N
19	5	B	N	N
20	1	A	N	S

As the table shows, the phase sequence is not A-B-C. Also note that in some cases groups of the same phase combine to form one pole, even though they are not next to one another. At other times, consequent poles are set up.

When rewinding a PAM motor, be sure to record the coil grouping and the internal connections accurately. If the coils of the new winding are incorrectly grouped or connected, the motor will not operate properly.

EASA has some diagrams for internal connection of PAM motors on file.

Note: The article was originally published in *EASA Currents* (May 1984); it was reviewed and updated as necessary in August 2016.

Two variations of form-wound coils

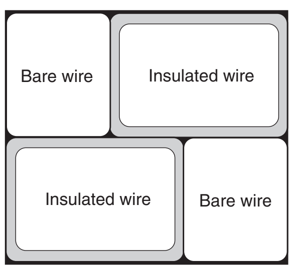
By Cyndi Nyberg
Former EASA Technical Support Specialist

It is very important to take accurate data when you rewind a form-wound motor or generator, especially if the coils will be made by an outside coil manufacturer. For this reason, it is helpful to know about a couple of variations to the standard coil design that are not common, but that you may come across from time to time.

BRICK DESIGN

A "brick" winding uses two different wire sizes arranged as shown in Figure 2-129. Instead of one large rectangular wire for each turn, this example uses four smaller wires. The larger ones are insulated (glass, film, mica, glass-over-film, etc.), and the smaller ones may be bare copper, with the same total height as the insulated wire.

FIGURE 2-129



Cross-section of one turn in a brick winding.

Normally, when more than one conductor is used, each of them must be insulated. As Figure 2-129 shows, the brick design achieves the required separation without insulating every wire.

One benefit of this winding configuration is to reduce eddy current losses within the turn of the coil. The brick design also can increase efficiency and cooling, based on design requirements. Each strand of wire is separated by the insulation, and the bare copper wire maximizes the copper content in the slots.

TERRACE DESIGN

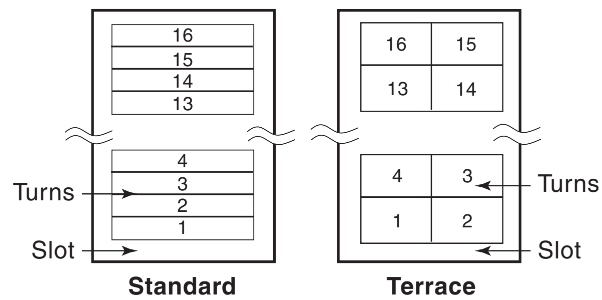
A second type of coil, called "terrace wound," is normally used when there is a high number of turns per coil. Instead of a very thin wire that is the width of the slot, this design uses a thicker, half-width wire that is staggered in the slot. Figure 2-130 shows a comparison of the standard coil and the terrace-wound coil.

When you're taking data on terrace-wound coils, it is easy to miss the number of turns and the wires in hand. Normally, when you see a coil with two vertical columns, you assume that there are two wires in hand, with the number of turns equal to the number of conductors in the "stack."

The way to tell that the coil is terrace-wound and has only one wire in hand is to look at the coil lead and confirm that there is only one wire in hand. If you routinely calculate the flux densities for your designs, the incorrect data will result in double the densities and double the circular mils per amp that you would normally expect.

One reason for using terrace-wound coils is that the thicker wires are easier to work with than a very thin wire. The drawback is that the volts per turn (V/T) are higher between some of the turns in the terrace-wound coil. In Figure 2-130, for example, the V/T between turns 1 and 4 equal the sum of the V/T between 1&2, 2&3, and 3&4.

FIGURE 2-130

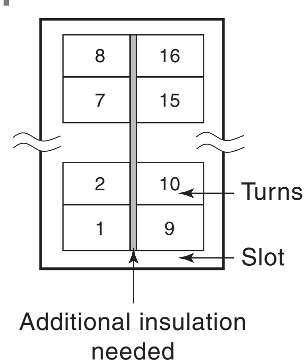


Cross-sections of standard and terrace-wound coils.

Unfortunately, most of these designs use a 1-circuit connection. If the connection had 2 circuits originally, a new coil with the incorrect data could be changed to a 1-circuit connection. But if the connection was only 1-circuit, new coils would be needed.

Note: Some coil manufacturers make replacement coils with two wires in parallel, and connect the two columns in series (Figure 2-131). It is important that in these cases, the two columns be insulated from one another since the volts per turn between the turns can be quite high.

FIGURE 2-131



Note: This article originally appeared in *EASA Currents* (July 2001); it was reviewed and updated as necessary in August 2016.

Taking data on form-wound motors and generators

By Manuel Garcia, Jr.
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To perform a quality rewind on a form-wound, three-phase motor or generator, it is important to take accurate winding data. Most service centers now purchase form-wound coils rather than making their own, so they can no longer fine tune winding machine and spreader setups to get coils to fit properly. To hold costs down, assure timely service for their customers and obtain coils of the highest quality, service centers must provide coil manufacturers with complete, precise winding data with their orders. The following procedures explain how to accomplish this, using EASA's *AC Stator Form Coil Data* sheet as a guide (Page 2-257).

MEASURING TOOLS REQUIRED

The tools required to take accurate data on form-wound coils include:

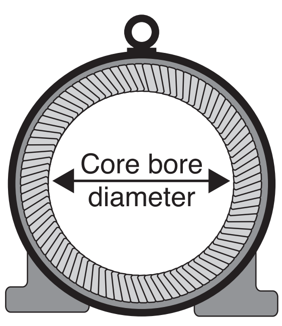
- Steel ruler (12 inch or 300 mm)
- Steel ruler (3 foot or 1 meter)
- Measuring tape
- A combination square (12 inch or 300 mm)
- Adjustable parallels
- Vernier calipers (6 inch or 150 mm)
- Set of micrometers (0 to 2 inches or 0 to 100 mm)

Remember that accurate data will enable the coil manufacturer to provide a set of coils that fit properly the first time.

TAKING STATOR DATA

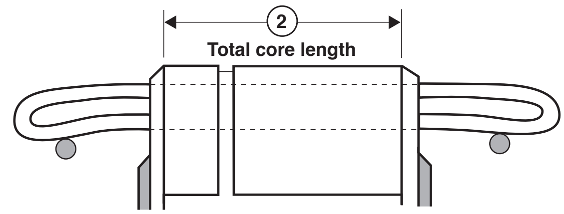
Note: The following procedures are numbered to correspond with the numbering scheme used on EASA's *AC Stator Form Coil Data* sheet. Perform Steps 1 - 17 before burning out or stripping the stator.

1. **Core bore diameter.** The bore diameter is the distance from any point on the inside edge of the stator iron to a point diametrically opposite it (i.e., 180° around the inside of the bore). To measure this dimension, hold one end of the tape measure stationary on the inside edge of the bore while scribing a small arc over the opposite inside edge. Record the largest measurement (to nearest 1/16" or 1 mm*).

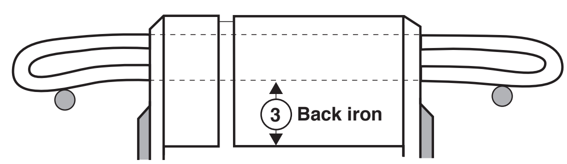


* Metric dimensions in this article represent practical tolerances, not exact equivalents of English units.

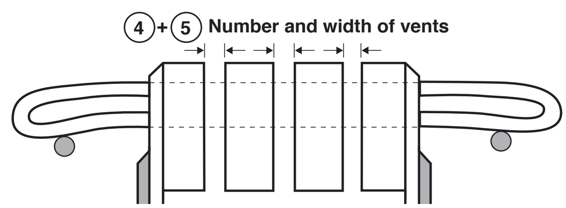
2. **Total core length.** This is the length of the iron excluding the finger plates (see No. 6 below). Some of the laminations on the ends of the core may be damaged or flared, so be sure to take measurements in the best areas. To assure an accurate dimension (to nearest 1/16" or 1 mm), take measurements in several places around the core, being careful to measure in a straight line.



3. **Back iron.** This is the distance from the bottom of a slot to the outer edge of the stator iron (near the frame). Measure with the calipers at several locations along the length of the slot. If the back iron dimensions vary, record the maximum and minimum dimensions (to nearest 1/16" or 1 mm).

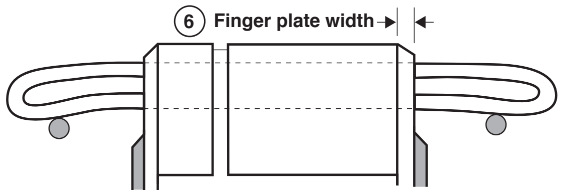


4. **Number of vents.** Vents are periodic breaks in the stator iron that allow for air circulation. Count and record the number of vents.
5. **Width of vents.** Using a Vernier caliper, measure the width of one vent (i.e., the gap between two packs of lamination). To do so, insert the jaws of the caliper into the vent and adjust it until the jaws touch the iron on both sides. Record this dimension (to nearest 1/16" or 1 mm). If the vents vary in size, measure each one, indicating the number, width and location of each size.

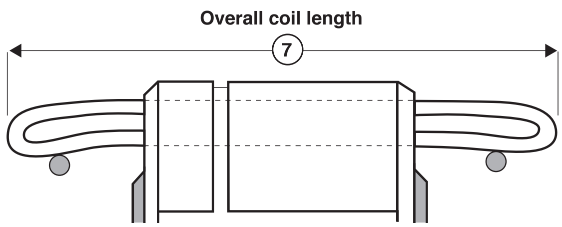


6. **Finger plate width.** Finger plates are pieces of heavy metal that apply pressure to the stator laminations. Using a small ruler or Vernier caliper, measure and record the

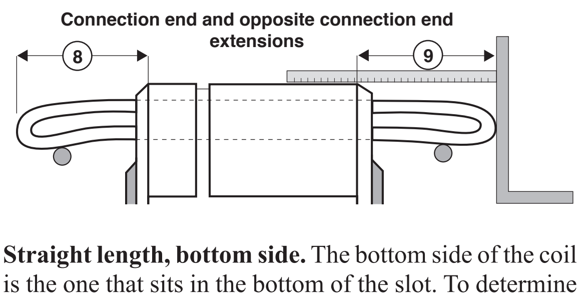
width (depth) of the plate from the end of the core (to nearest 1/16" or 1 mm). Do not include any laminations in the measurement. If the stator has no finger plates, indicate this on the coil data form.



7. **Overall coil length.** This is the overall length of a coil, measured (to nearest 1/16" or 1 mm) from the outer edge of one knuckle to outer edge of the opposite knuckle while the coil is still in the stator. Do not include the connection in this measurement.

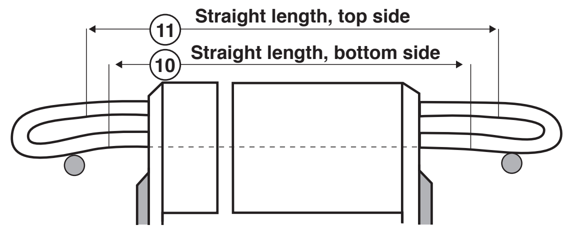


8. **Connection end extension.** This is the distance from the stator iron to the outer edge of the coil knuckle on the lead end. To measure this dimension, position the combination square so that it touches the outside of the knuckle, with the ruler facing up and perpendicular to the stator bore. Then lay the 3-foot steel ruler on the iron in the stator bore, extending it out over the coil end far enough to touch the rule on the combination square. Record the dimension (to nearest 1/16" or 1 mm). Be sure to measure from the end of the knuckle to the core iron (not to the finger plate).
9. **Opposite connection end extension.** Follow the same procedure as above to determine the length of the coil extension on the end opposite leads.

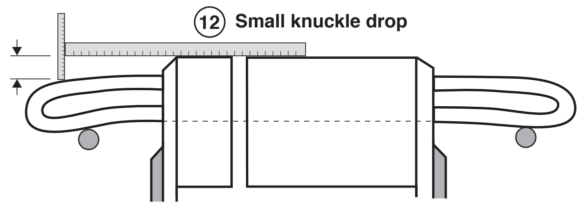


10. **Straight length, bottom side.** The bottom side of the coil is the one that sits in the bottom of the slot. To determine this dimension, place one end of the tape measure at the point where the straight edge of the coil just begins to turn towards the knuckle or diamond. Now measure in the opposite direction along the inside of the straight part of the coil to the point where the coil end starts turning towards the knuckle or diamond. Record this dimension (to nearest 1/16" or 1 mm).

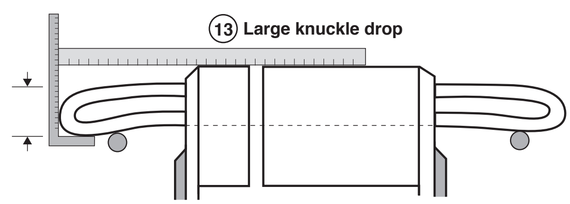
11. **Straight length, top side.** Using the method described above, measure the straight portion of the top side of the coil.



12. **Small knuckle drop.** To determine the small knuckle drop, place the small rule perpendicular to the coil side at the point where the knuckle (outside round nose) just begins to take shape. Then lay the 3-foot rule against the iron in the stator bore as shown, extending it over the coil extension to the small ruler. Take the reading (to nearest 1/16" or 1 mm) where the two rulers intersect. Measure and record the small knuckle drop on both ends of the coil.

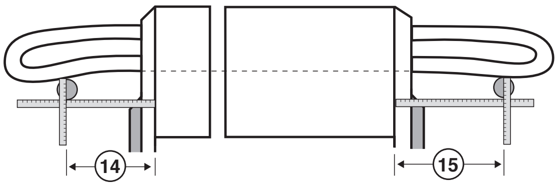


13. **Large knuckle drop.** Place the 12-inch combination square under the lowest point of the coil extension with the rule reaching upward past the coil knuckle toward the bore. Place the 3-foot rule against the iron in the stator bore, extending it over the coil extension to the rule on the combination square. Take the reading (to nearest 1/16" or 1 mm) where the straight edge meets the rule. Measure the large knuckle drop on both ends of the coil.

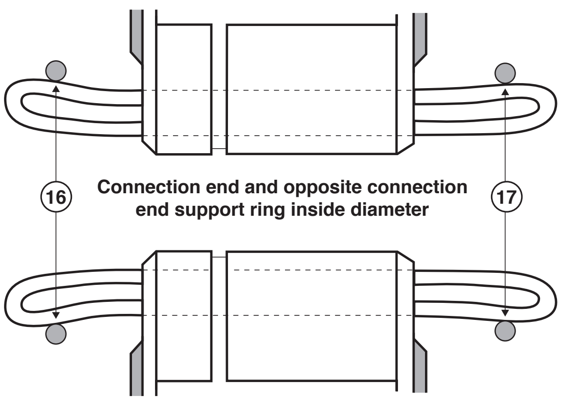


14. **Connection end support ring from core.** To measure this dimension, place a straight edge on the centerline of the ring such that it is parallel to the end of the core. Then place the 3-foot ruler against the straight edge and extend it back to the stator iron. Take the measurement where the rulers intersect the stator iron. If there are several front support rings, sketch their locations on the data sheet and indicate the distance to each one (to nearest 1/16" or 1 mm).
15. **Opposite connection end support ring from core.** Follow the same instructions as given above for the connection end.

Connection end and opposite connection end support ring

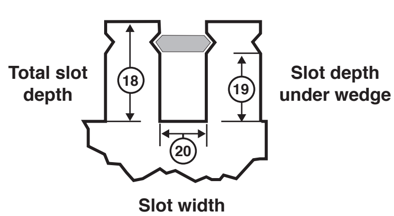


16 & 17. Connection end and opposite connection end support rings inside diameter. It is often easier to measure the inside diameter of a support ring after the motor has been stripped. First, make sure the ring is in the proper position. Then hold the end of the tape measure against the inside of the ring on one side and extend the tape to the opposite side of the ring. Strike an arc or move the tape to several points and measure each distance. The point on the ring with the largest diameter is the ID of the ring (to nearest 1/16" or 1 mm).



18. Total slot depth. The total slot depth is the distance from the top of the tooth to the bottom of the slot. To measure this dimension, insert the depth gauge of the Vernier caliper into the center of a slot, pushing the slide down until the gauge touches the bottom. Make sure the top portion of the depth gauge is on top of the stator tooth and record the reading (accuracy 0.001" or 0.03 mm). For accuracy, measure 5 percent of the slots.

19. Slot depth under wedge. This is the area that the coil actually occupies. To measure this dimension, first insert a wedge in the wedge groove. Using the inside section of the Vernier caliper, adjust the jaws so that they touch the bottom of the wedge and the bottom of the slot. For accuracy, measure and record this dimension for 5 percent of the slots (accuracy 0.001" or 0.03 mm).



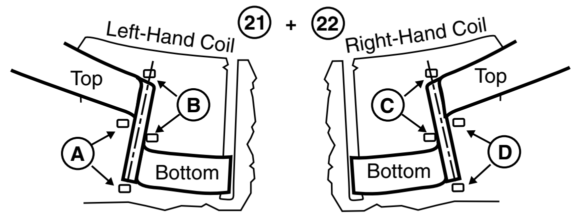
20. Slot width. Using adjustable parallels, select the correct size and loosen the set screw with a small screwdriver. Next, insert the parallels into the bottom of the slot and slide the two halves away from each of other until they fill the width of the slot but can still move. Then tighten the screw and remove the parallels. To assure accurate measurement, insert the parallels into several different slots. Finally, measure the width of parallels with a micrometer and record the dimension (accuracy 0.001" or 0.03 mm).

21. Lead location. Facing the connection end of the stator, note where the coil leads come out and record this on the data sheet.

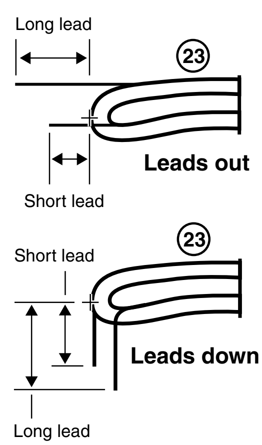
- **A or D** Start and finish leads come out of the center of the coil and the bottom nearest to the support ring.
- **B or C** Start and finish leads come out of the coil connection end on the top and near the bore and center of the knuckle.

22. Coil type. Face the coil connection. If the top coil side is on your left, it is a **left-hand coil**. If the top coil side is on your right, it is a **right-hand coil**.

Coil type



23. Coil lead length and number. Indicate whether the leads come out straight or bend down. Measure and record the lengths of both long and short leads from the midpoint of the knuckle (to nearest 1/4" or 6 mm). Then count and record the number of coils with one long lead and the number of coils with two short leads.



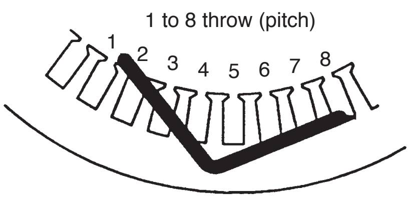
24. Jumper. Determine and record the internal connection of the coil group (e.g., 1-4 or 1-7).

25. Connection. Determine and record the connection of the stator windings: wye or delta.

26. Number of circuits. Determine and record the number of parallel circuits.

27. Number of slots. Count and record the number of stator slots. This will also be the number of coils needed unless indicated otherwise.

28. Coil pitch (throw). This is the number of slots that a coil spans, counting from the bottom side of a coil to the top side of the same coil. When counting the coil pitch, be sure to include the slots that actually hold the bottom and top sides of the coil. (Span is the number of teeth enclosed by the coil.)



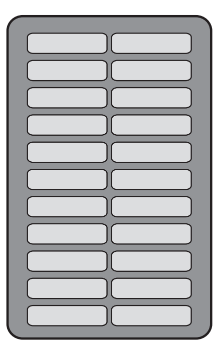
28 **Coil throw (pitch)**

29. Turns per coil. Turns per coil describes the number of times the wire is looped in a coil conductor. To determine this, cut through the coil extension of a good coil (near the slot or the knuckle) on end opposite the connection and count the wires in the cross section. Then count the wires in parallel (or "in hand") in one of the coil leads. To get the turns per coil, divide the number of wires in the cross section by the number of wires in parallel.

$$\text{Turns per coil} = \frac{\text{Wires in cross section}}{\text{Wires in parallel}}$$

Follow the same procedure on several consecutive coils, since some windings have coils with different numbers of turns per coil. (Note: Verify the wire size in the coils with different turns; the wire sizes in such coils are sometimes different from the rest.)

29 **Turns per coil**



30. Total wires in parallel. The wires brought out together in one coil lead are called wires "in parallel." Sometimes termed wires "in hand," these wires are the total conductors for each turn.

31. Wire sizes. Wire size must be determined from the bare copper. Being careful not to distort the wire, remove all insulation from the portion of each strand to be measured. Once insulation has been removed, clean the copper with steel wool. Now measure the width and height of each strand with a micrometer (accuracy 0.001" or 0.03 mm). Strands are often different sizes, so measure several strands of the coil and compare the dimensions with those obtained from other coils to assure correct wire size.

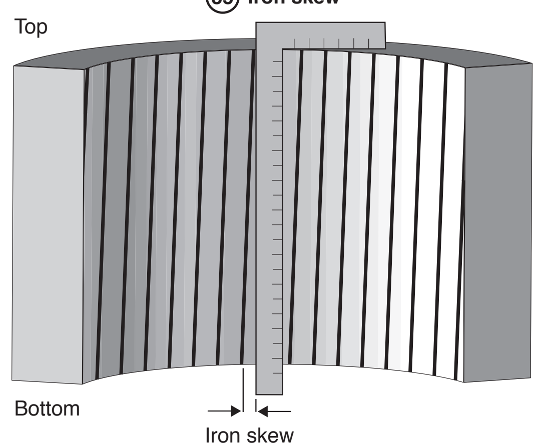
32. Strand insulation. Determine which type of insulation is used on the wire and note this on the data form. Examples are glass, film, mica, glass-over-film and bare.

33. Coil weight. Weigh one coil (preferably with the insulation removed) and record the weight on the data form.

34. Groups of coils. Determine and record the number of coil groups and the number of coils in each group. Note that with unequal grouping there will be two sets of coil groups.

35. Iron skew. If the stator slots are not parallel with the shaft, the iron is skewed. To determine the amount and direction of the skew, place a square of the appropriate length in the stator bore, laying it flat against the core and at right angles to the ends of the bore. Call the end where you are standing the "Bottom End" and the opposite end the "Top End." With the ruled edge of the square touching the left inside edge of the chosen slot at the Top End, measure the distance from the same ruled edge to the left inside edge of the same slot at the Bottom End (to nearest 1/16" or 1 mm). Record the measurement, noting whether the slots are skewed right or left.

35 **Iron skew**



Note: This article was originally published as *EASA Tech Note 33* (June 2000); it was reviewed and updated as necessary in August 2016.

Guide for procuring form wound coils for motors and generators

By Manuel Garcia, Jr.
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This guide applies to procurement of form wound coils for medium-voltage motors and generators up to 7 kV.

Since each original equipment machine manufacturer has its own design criteria, only certain parameters can be assumed from the existing winding.

When ordering a set of form wound coils, it is most important to provide the coil manufacturer with accurate and complete winding data (see *Taking Data on Form Wound Motors and Generator*s on Page 2-233). Record the winding data on EASA's *AC Stator Form Coil Data* sheet (Page 2-257), and send it to the coil manufacturer along with your requirements.

Make certain that the coil manufacturer you choose agrees to follow the guidelines listed below, and that you be made aware of and agree on any suggested changes.

VERIFY THAT A QUALITY SYSTEM IS USED

Confirm that the coil manufacturer has a quality system in place, such as ISO 9000.

You should also ask:

- What materials it uses for each type of coil
- Which type of coil will be provided for your order
- What specific test procedures it follows
- What test voltage it recommends for green coils

COIL INSULATION SYSTEMS

Each coil manufacturer has different names for its coil insulation system, depending on the impregnation process. Specify the type of processing that you will use after rewinding [e.g., vacuum pressure impregnation (VPI), dip and bake, spray (overcoating) and bake], and the type of resin or varnish you will use. Also, specify that the coil insulation system be compatible with the process and the resin or varnish you will use.

Coil insulation systems include:

- VPI (global impregnation) green (untreated) coils, hermetic, conventional
- Dip-and-bake fully-cured coils, sealed system, conventional dip-and-bake
- Hot press coils, fully-cured straight section and green ends (may be covered in a future edition of this guide).

Specify the coil insulation system you want (e.g., class F or class H).

COIL INFORMATION AND BASIC SPECIFICATIONS

Provide information about coil materials and basic specifications.

Wire dimensions. Identify the bare wire width and thickness, measured to 0.001" (0.025 mm) accuracy, for each copper conductor. Specify that you must approve any reduction in the original conductor area.

Conductor insulation. The conductor's insulation is important because of steady-state and transient voltage withstand requirements. Types of conductor insulation include:

- Enamel (single, heavy, triple and quadruple film)
- Glass (single or double) or polyester (fused or not fused)
- Glass or polyester over enamel or Kapton
- Fused Mylar strand insulation
- Kapton
- Mica tape
- Nomex®
- Polyester film tape and Nomex
- Polyester film tape and mica tape

Turn insulation. Determining the correct turn insulation is critical, since not all the parameters of the original design are known. To do so, the coil manufacturer must have the complete nameplate information and the winding data, including:

- Maximum operating voltage
- Connection type (wye or delta)
- Number of coils, circuits and turns per coil (for calculating the volts per turn to determine if turn insulation is required).

You should also provide the coil manufacturer with information about any winding failures associated with transients (e.g., from vacuum starters, reclosures or lightning strikes).

Ground-wall insulation. Some coil manufacturers use tape for ground-wall insulation. Others use layers of tape over the conductor and then a wrapper or tape, depending on the voltage and space available in the slot. Whichever system is used, it should include sufficient layers of appropriate tape or sheet wrap material to produce a final wall thickness after pressing that meets the operating voltage requirements.

Note: The critical concern with ground-wall insulation is the voltage stress in volts/mm or volts/mil (0.001") between the copper and the slot side. In some instances the conductor insulation is considered in this calculation. The differences in voltage stress capabilities of various insulation materials (e.g., mica versus fiberglass) are also factors.

For VPI process coils, a porous mica tape or wrapper should be used. Ask the coil manufacturer to verify that the mica-paper tape or wrapper they use will not reduce resin penetration of VPI coils.

For dip-and-bake or fully-cured coils, a mica-paper tape or wrapper is commonly used.

Table 2-59 is a general guideline for the ground-wall insulation thickness for some medium-voltage coils that you may expect from a coil manufacturer.

TABLE 2-59: TYPICAL GROUND-WALL INSULATION THICKNESS FOR MEDIUM VOLTAGE COILS

	2.3 kV	4 kV	6.9 kV
Per side	0.060” (1.5 mm)	0.070” (1.8 mm)	0.090” (2.3 mm)
Total	0.120” (3.0 mm)	0.140” (3.6 mm)	0.180” (4.6 mm)

Some coil manufacturers may use more insulation, and others less, depending on the voltage withstand capability of the materials in their specific insulation system.

Some original equipment manufacturers use a relatively high voltage stress level for their insulation system, so their ground wall is thinner than that of many aftermarket coil manufacturers. In that case, any increase in insulation thickness and consequential reduction of copper area by the coil manufacturer would reduce heat transfer and increase copper losses, resulting in higher operating temperature.

A slot liner may also be considered part of the ground-wall insulation. Specify if you will use a slot liner (usually not recommended above 4.2 kV).

Insulation on the overhang. The overhang or diamond of the coil should be insulated with mica tape. Generally less insulation will be used in this area than in the slot section, since there is no direct contact to ground. Some coil manufacturers use more insulation on the lead end coils of each group.

Coil lead insulation. The coil lead insulation should be at least as thick as the coil endwinding insulation. If the coil manufacturer uses a sleeving instead of mica tape, verify the voltage rating of the sleeving is at least double the rated line voltage of the machine, and that the sleeving is doubled.

Armor tape. A protective or armor tape should be applied over the wrapper or mica tape to protect it during winding and handling. Of the several tapes for this, the most popular are polyester Dacron® and fiberglass tapes.

Corona (partial discharge) protection. Specify to the coil manufacturer if you require corona protection and/or grading protection.

There are two elements to corona protection:

- Conductive corona tape (or paint) is used on the coil cell along the slot section.
- Grading tape (or paint) controls passage of the discharge current from the endwinding to ground.

Some motor and generator manufacturers only use this protection above 7 kV, while others use it on 6 kV and above. (Note: All VFD-fed, medium-voltage windings should have corona protection.) Ask the coil manufacturer for their specifications on this protection.

Note: If corona protection is used, it must make good contact with the stator iron; therefore no insulated slot liner should be used.

Additional winding materials. Specify any additional winding materials needed (e.g., connectors, wedges, bracing).

HIGH POTENTIAL (HIPOT) AND SURGE TESTS

Testing of coils varies with each coil manufacturer. The voltage stress to ground and the surge test should follow:

- NEMA MG 1
- IEC 60034-1
- IEEE 522
- IEC 60034-15

Agree with the coil manufacturer on the hipot test voltage that should be used, whether AC or DC. Green VPI coils should be tested at lower values than for fully cured coils. If you are going to final test the stator at twice rated voltage plus 1000 for AC (or 1.7 times that for DC hipot), the coil manufacturer should test at a 15% higher voltage.

In addition, if the coil manufacturer does not hipot test all the coils (preferred), make certain you are advised of and agree with the percentage of coils tested.

Most coil manufacturers have their own turn insulation test criteria. Make certain that these criteria meet or exceed the IEEE 522 or IEC 60034-15 test requirements.

DELIVERY OF THE COILS

The coil manufacturer should package the coils so as to minimize movement and protect against moisture during transportation.

The coil manufacturer should also provide a report with each coil shipment that lists the coils tested and the type of test performed on each coil (e.g., hipot, surge, etc.).

When you receive the coils, use a micrometer to measure the width and height in 3 or 4 equally-spaced sections of the straight portion of about 5 to 10% of the new coils. Any variations of more than 10 mils (.25 mm) from specified dimensions may be due to insufficient or excess insulation on the straight portion of the coil. This may be the result of irregular taping of the coil.

Note: This article was originally published as *EASA Tech Note 44* (June 2008); it was reviewed and updated as necessary in August 2016.

Rewinding form-wound motors and generators up to 5 kV

Prepared by the Technical Services Committee

INTRODUCTION

In rewinding form-wound motors and generators, the first and most important step is to take accurate data. Commonly referred as "reverse engineering," this procedure is essential for getting a satisfactory set of coils from the manufacturer (see Page 2-233, "Taking Data on Form-Wound Motors and Generators"). Another critical step is to test the stator core *before* and *after* the burnout process to ensure that losses have not increased. This article covers the remaining procedures for rewinding form-wound stators up to 5.0 kV, including: how to check new coils, how to prepare the stator and how to insert, wedge, block, connect and test new coils.

INSPECTION OF NEW COILS

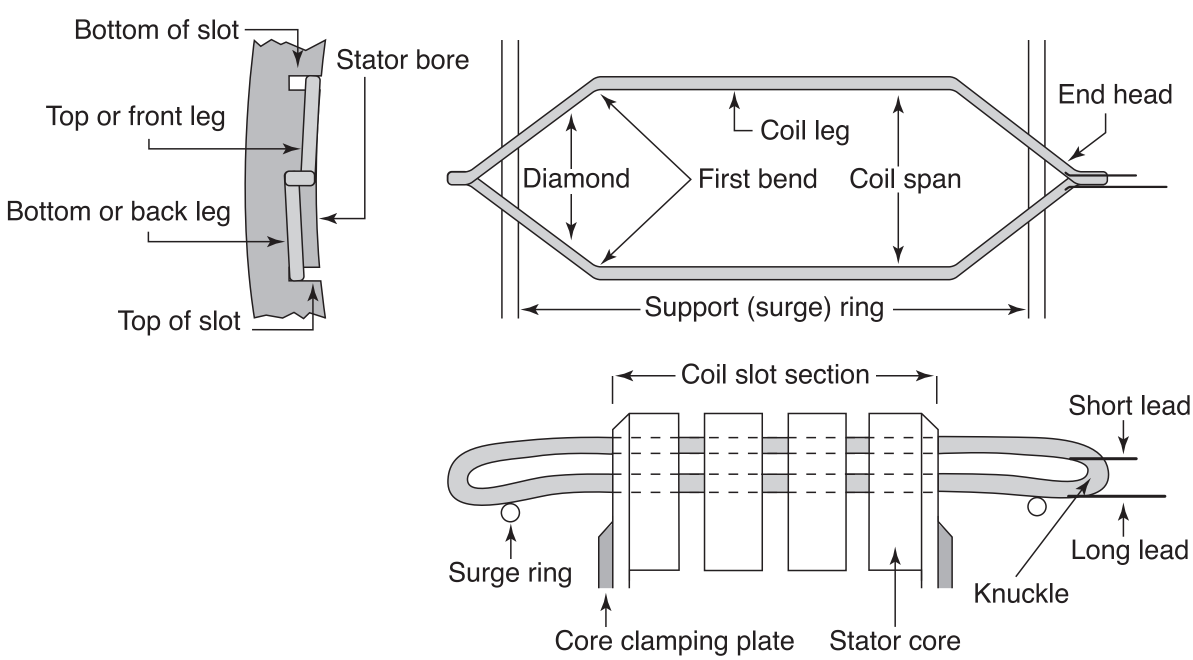
To assure quality and avoid costly warranty work, carefully inspect all newly manufactured coils when they are received. Use the following checklist to be sure every coil is in acceptable condition (Figure 2-132).

- Check contents of the shipment against the packing slip and the original order to ensure that it contains the correct number of coils with long and short leads.
- Inspect all coils for damage, making sure they are smooth and straight through the slot section.
- Make sure the small and large knuckle drops are correct and consistent on every coil.
- Measure the span of each coil to make sure it is correct and consistent from coil to coil.
- Check the mechanical dimensions of each coil against those on the data sheet.
- Make sure the positions of the start and finish leads on each coil match those specified in the order and are consistent from coil to coil.
- After the coils have been inspected and tested, store them in a clean, cool and dry location.

STATOR CORE PREPARATION AND CHECKS

- Before inserting any coils, core test the stator with a core loss tester or use EASA's stator core testing procedure (*EASA Technical Manual*, Section 7: Electrical Testing). Compare the results with those from the core test taken prior to burnout to confirm losses have not increased. **Note:** The stator winding should be removed following the guidelines on Page 2-98, "Guidelines for Maintaining Motor Efficiency During Rebuilding.")

FIGURE 2-132



Elements of a coil.

- Check the stator for a loose core, loose laminations, loose finger plates (clamping rings) and loose fingers. Sometimes these are individually spot-welded, so inspect all welds for cracks.
- Check for smeared or rubbed laminations.
- Check slots for high or shifted laminations.
- Check for foreign particles in the slots.
- Clean the slots and air ducts with a nonmetallic bristle brush, removing any remaining dust and debris with a vacuum.
- Make sure all air vents are clean and open. Be sure, too, that none of the vent beams are loose or missing.
- Referring to the original data sheet, mark the stator to indicate the coil pitch, start and finish slots and location of RTDs.

Coil support rings

The coil support rings (also called surge rings or bull rings) hold the coil end turns in place. This function is very important during start-up and any locked-rotor condition. Some smaller machines have "floating" coil support rings that are lashed to the coils. Larger machines usually have one or more support rings on each end that are held in place with brackets.

- Make sure the coil support rings are concentric with and securely fastened to the stator frame (unless "floating" rings are used).
- Confirm that all metal rings mounted on insulated brackets are grounded.
- Temporarily insert 4 to 6 coils at various locations around stator to confirm that they fit correctly and that the support rings are located properly.
- Check the coil fit at the support ring to ensure that sufficient space is available. Depending upon coil size, clearance between the coils and the support rings should be at least 1/8" to 1/4" (3 mm to 6 mm) once the rings have been insulated. This provides room to insert felt pads under the coil knuckles, allowing the coils to rest in the bottom of the slot with no stress on the slot portion (Figure 2-133).

TABLE 2-60: MINIMUM HALF-LAP SERVINGS OF TAPE NEEDED FOR COIL SUPPORT RING

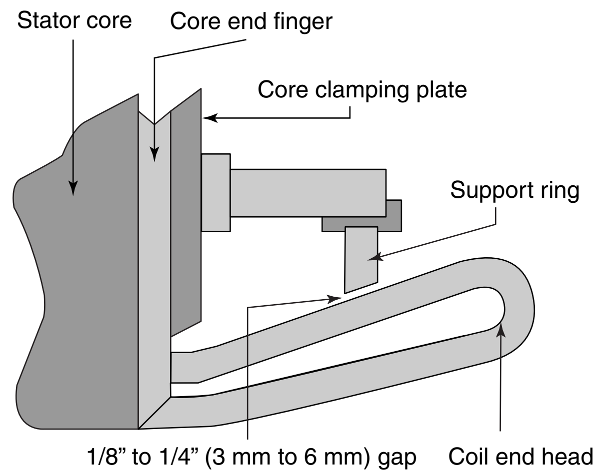
Up to voltage	Servings of mica tape (0.007" or 0.18 mm)*
1000	1
3300	3
4200	4
5000	5

* Apply one layer of armor tape over mica tapes.

Slot liners

Some service centers use a slot liner with form coils rated lower than 5 kV. While this can be done successfully for this voltage class of machines, it is not considered best practice and has been known to cause difficulty with impregnation in the absence of well-established process controls. When ordering form coils, always let the coil manufacturer know whether or not slot liners will be used.

FIGURE 2-133



Coil fit at the support rings.

Slot fillers

The bottom spacer can be as thin as 0.009 inches (0.2 mm) as its function is primarily to protect the coil surface from lamination stack irregularities.

The center spacer thickness is primarily a function of machine rated voltage and desired separation between phases. See Table 2-61 for typical center spacer values. Also, it is common for a properly fitted RTD to serve as the center spacer where used.

TABLE 2-61: SLOT FILLERS

Up to voltage	Thickness, in (mm)
2300	0.030 (0.8)
3300	0.040 (1.0)
4200	0.060 (1.5)
5000	0.080 (2.0)

Adequate space in the top should be left to accommodate variance in coil height and slot depth. For this class of machine, 0.040 in (1.0 mm) is typically reasonable. The top spacer also protects the coil surface while driving the wedge.

COIL INSTALLATION

- Wind the stator in a clean, dry area.
- To ensure good heat transfer from the coil to the stator, make sure the side fit of both dip-and-bake and VPI coils is approximately 0.010" to 0.015" (0.25 mm to 0.38 mm) loose.
- Do not bend, twist or distort the coils unnecessarily when handling or inserting them. It is critically important to keep external forces to a minimum during coil installation.
- Use thin polyester sliders to prevent coil damage when inserting the coils into the slots. Once the coil is in position, remove the slider.
- When placing the coil in the slot, make sure the coil extensions match the dimensions on the data sheet.

- If the coils are tight in the slot, place a long micarta board (the length of the slot) on the coil side and tap lightly with a rubber-faced mallet until the coils are fully seated. Be extremely careful not to bend the slot portion of the coil.
- If a coil is damaged in any way during installation, repair or replace it.
- Check the position of the coils to make certain there is no mechanical interference with end bells, air deflectors, and so forth. Be sure, too, that the coil end turns are not touching one another, and that coils are not in contact with the support rings or the finger plates.

Pre-lifting coils

Coils that must have their top sides lifted in order to install the bottom sides of the final coils of the winding are commonly called "span coils." Unless properly supported, the top legs of these coils can be distorted while the coils beneath them are being inserted (especially on 2- and 4-pole stators). Span coils may be supported with a padded ramp as they are inserted, or by tying them to the opposite side of the bore.

Resistance temperature detectors (RTDs)

- Make sure the RTDs are the correct type (copper, platinum, etc.) and resistance/reference temperature before beginning to install the winding.
- Measure the resistance of RTDs before installing them and after wedging the stator coils to make certain no damage has occurred.
- Most machines will have two equally spaced RTDs per phase. It is a good practice to install one more RTD per phase than required in case one of them becomes defective.
- RTDs are typically placed in the center filler location and may also serve as a stand-alone center spacer or be embedded in a machined center spacer.
- Bring the RTD leads out of the slot straight towards the back iron and attach them with clips around the stator; do not attach them to coil jumpers or connections. Keep RTD cabling away from coil jumpers and connections.
- Sleeve the RTD cables with acrylic sleeving or use armored cable.

Wedges and slot fillers

- Magnetic wedges are becoming increasingly common. Before removing stator windings, always check for magnetic wedges using a magnet. To help maintain the machine's original performance, replace magnetic wedges only with magnetic wedges.
- Conventional dip-and-bake windings (non-VPI) require a tight wedge fit (vertically). One check for adequate slot fill is whether the filler strip can be easily pulled out from under the wedge. Global VPI windings should have snug wedging but can accommodate more looseness than dip-and-bake windings due to the VPI process.
- For easy insertion, use wedges 6" to 8" (15 cm to 20 cm) long.
- On stators having wedges with air flow grooves, it is important that replacement wedges have these same vent grooves. Otherwise, reduced air flow will increase stator heating.
- Partial or "skip" wedges should be used only if the original winding employed this system.

In-process testing

Strand insulation

Coils manufactured with multiple parallel strands per turn should have the strand to strand insulation integrity verified in-process after manufacturing using 120 VAC or other agreed upon test level. Best practice is to have this test repeated on-site after wedging and bracing

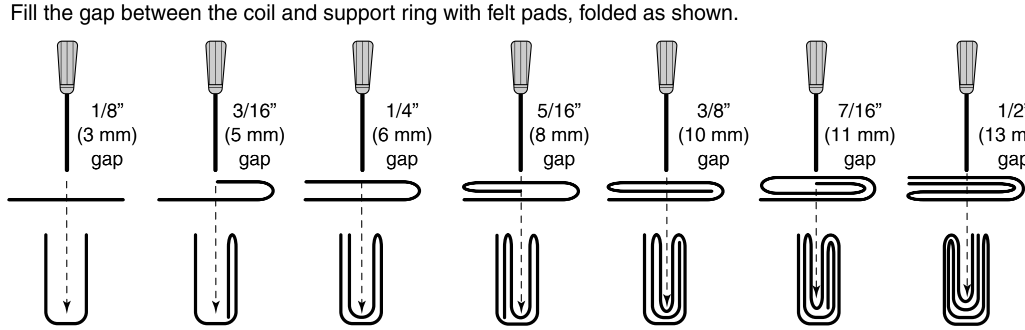
Turn insulation

The surge withstand capability of the winding should be verified at one or more of the following steps of manufacture: (a) individual coils before installation in slots, (b) individual coils after installation but prior to connection, with wedging and bracing in place, and (c) on the completely wound and finished stator. Best practice is to do testing at steps (a) and (b) and an additional reduced voltage test after connection but before processing. The reduced voltage test can provide some assurance that the connection is correct.

The test levels should be agreed upon in advance by the

FIGURE 2-134

Fill the gap between the coil and support ring with felt pads, folded as shown.



After insertion between the coils, the felt pad will look like this ...

Folding of felt pads.

coil manufacturer, service center, and in some cases, the customer. Depending on the application and design of the insulation system, typical values for fully-cured coils (100%) and "green" or uncured coils (60%) are shown in Table 2-62 for some common machine voltages. The test values shown are consistent with IEEE 522 and IEC 60034-15, although the standards also allow for different test parameters as well. EEE 522 refers to 3.5 p.u. as a standard withstand voltage and 2.0 p.u. as a reduced voltage test used for windings that are not likely to see high-magnitude, fast-fronted surges. NEMA MG-1 takes the opposite approach, referring to 2.0 p.u. as the standard test voltage and 3.5 p.u. as a test level for windings designed for higher surge capabilities.

Repeating the factory coil test after wedging and bracing ensures that the installation process did not cause or expose a turn-to-turn short. Surge testing of completed form windings can help identify connection errors, but it is not very effective for testing turn insulation of the complete winding.

TABLE 2-62: CALCULATED TEST VALUES FOR SOME COMMON MACHINE VOLTAGES

Rated voltage (V)	IEEE 522[1] 2.0 p.u. (kV) 0.1 μs front rise		IEEE 522[1] 3.5 p.u. (kV) 0.1 μs front rise		IEC 60034-15[2] 0.65 U_p 0.2±0.1 μs front rise	
	100%	60%	100%	60%	100%	60%
400	0.7	0.4	1.1	0.7	4.3	2.6
460	0.8	0.5	1.3	0.8	4.4	2.7
575	0.9	0.6	1.6	1.0	4.7	2.8
2300	3.8	2.3	6.6	3.9	9.2	5.5
3300	5.4	3.2	9.4	5.7	11.8	7.1
4000	6.5	3.9	11.4	6.9	13.7	8.2

[1] 1.0 p.u. = $V_{L-L}\sqrt{(2/3)}$ kV
[2] 1.0 U_p = $4 \cdot V_{L-L} + 5$ kV

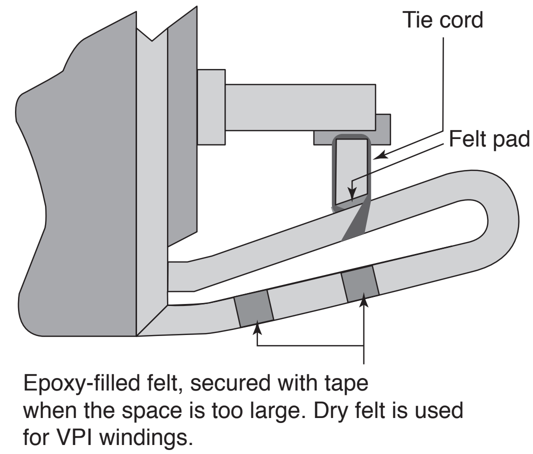
Ground insulation

The ground insulation integrity is sometimes verified in-process after manufacturing. Repeating this process after wedging and bracing on individual coils or groups of coils can prevent a tremendous amount of rework in the event a coil is damaged during transport, handling or installation. Insulation resistance testing can be performed to verify there are no severe defective conditions that may be correctable prior to high potential testing. Common practice is to test fully-cured coils in-process at a value between 100-110% of the final test voltage to ground ($2V_{L-L}$+1 kV AC or 3.4 V_{L-L}+1.7 kV DC). For "green" uncured coils intended for global VPI processing, the in-process testing is typically DC and not in excess of rated machine line-to-line voltage. A similar reduction in test voltage can be made for coils with uncured, resin-rich turn insulation.

Tying and blocking

- Do not force the coil to the support ring.
- Fill the remaining space [1/8" to 1/4" (3 mm to 6 mm)] with felt as shown in Figure 2-134. This will be saturated with epoxy for coils that have already been dipped and baked. Use "green" or dry (not saturated) felt with VPI coils.

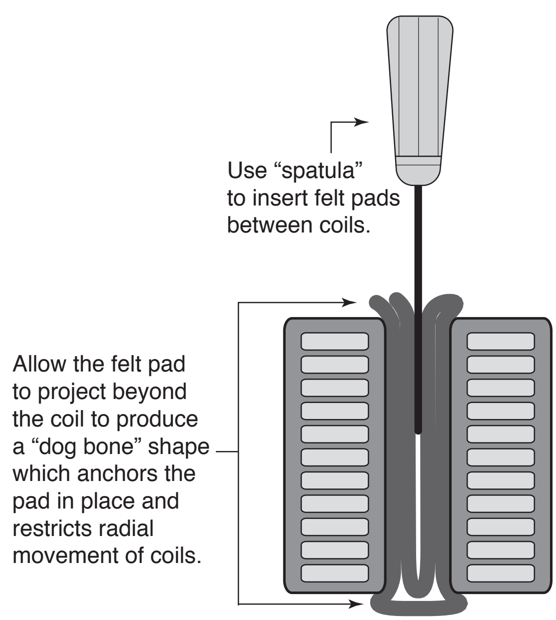
FIGURE 2-135



Example of blocking and tying.

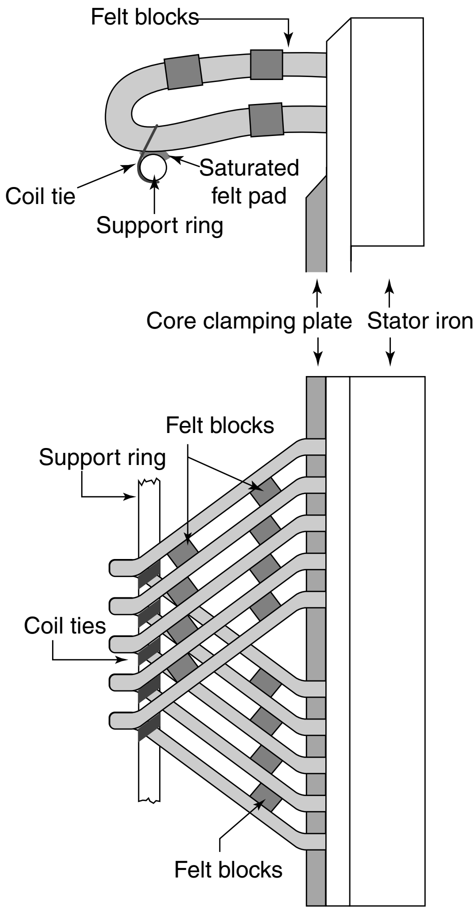
- Make sure the slot portion of the coil rests on the bottom of the slot so that no stress will be placed on the coil when it is tied to the support rings.
- Do not tie coils to support rings with cord that will shrink more than 5%. Doing so may distort the coils and crush the insulation (Figure 2-135).
- Coil bracing should be equal to or better than the "as found" condition, or as specified in the OEM standards. (Refer to data taken prior to stripping.)
- Do not eliminate support rings or coil blocking. If in doubt, add more blocking. Be careful, however, not to obstruct air flow with too much blocking.

FIGURE 2-136



"Dog bone" block.

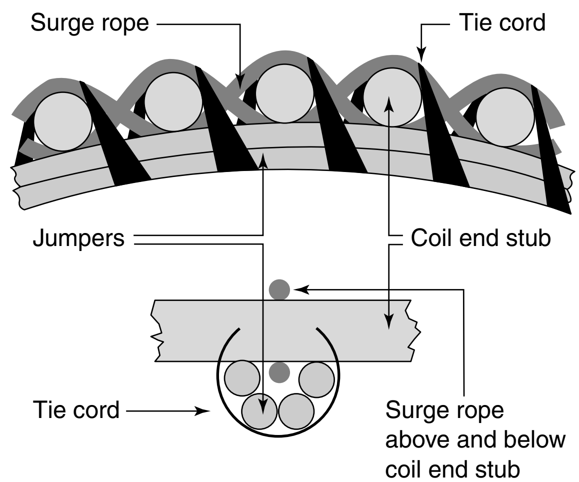
FIGURE 2-137



Blocking and tying.

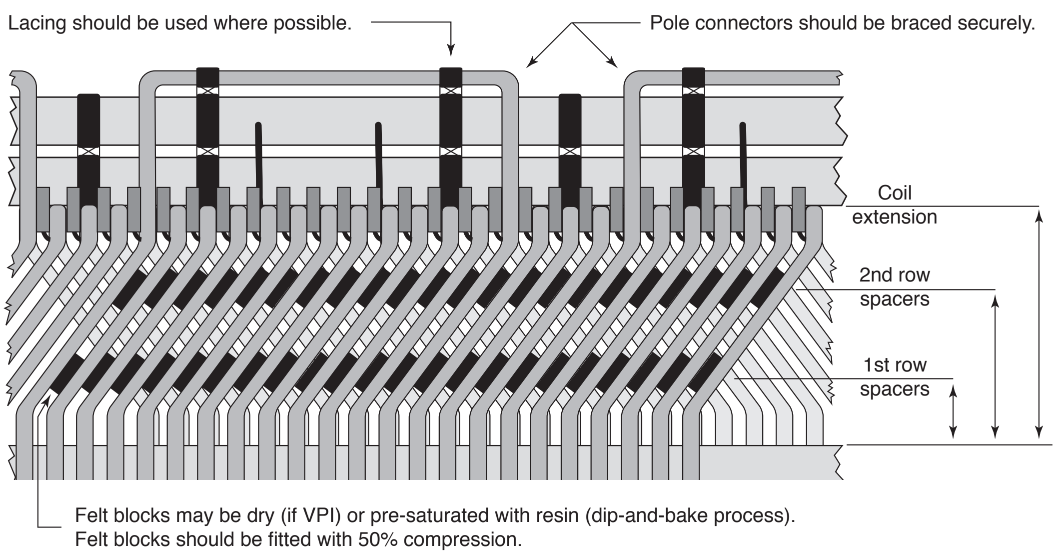
- If the space between coils is too large, tie the blocking in place. Figure 2-136 shows how felt can be folded to form a "dog bone" block that will not fall out after impregnation.
- Figure 2-137 illustrates one way to tie a coil to a support ring.
- If a steel support ring is not reusable, replace it with a resin-saturated ring or surge rope (non-VPI motors), or with a non-saturated surge rope (VPI windings).
- Windings with U-shaped connections have multiple rows of pole jumpers that normally must be interlocked and tied after they have been insulated (Figure 2-138).
- If stub connection is preferred, space the jumpers and connections neatly around the outer diameter of the connection circle, bracing the jumpers as shown in Figure 2-139.

FIGURE 2-139



Reinforcing stub connections.

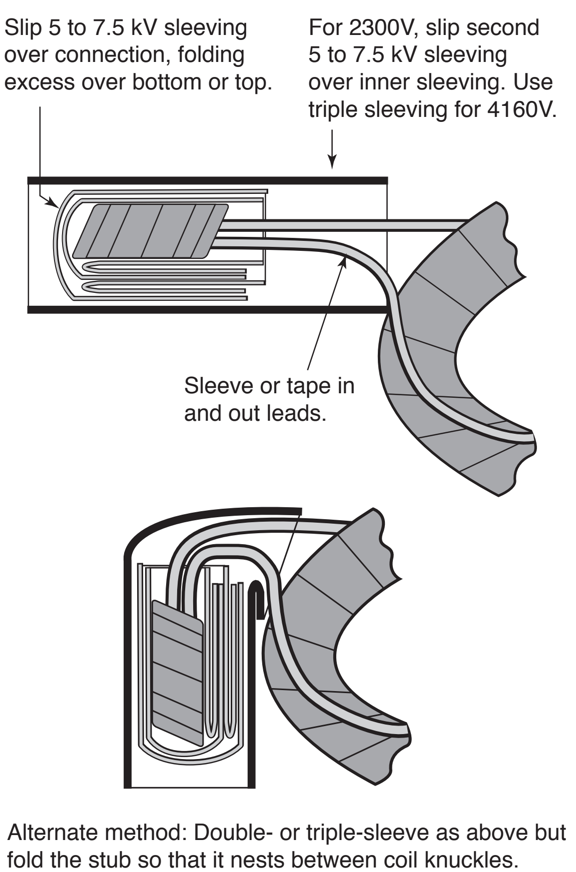
FIGURE 2-138



U-shaped connections with multiple rows of pole jumpers.

- Reinforce stub connections using a 1/4" (6 mm) surge rope tied in a "figure 8" around each stub (Figure 2-139). Then lay the jumpers and leads underneath the stub connections, inserting thin pieces of felt between the connections and jumpers. Once the jumpers are laid in, tie all together with shrinkable tie cord. Finally, tie between each stub connection as also shown in Figure 2-139.
- An alternate method is to bend series stubs over, so that they nest neatly between the coil knuckles (Figure 2-140).

FIGURE 2-140



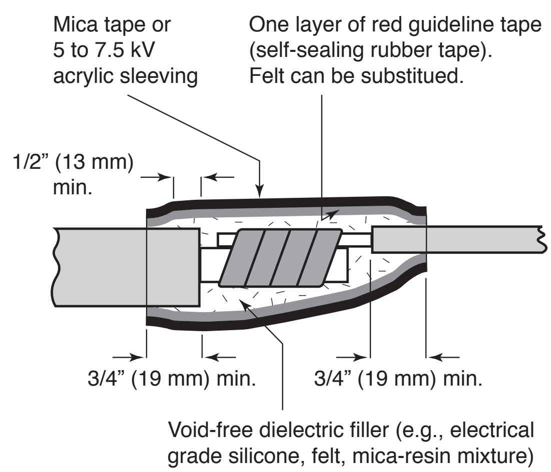
Insulating stub connections.

- If a steel ring is not reused or the original ring was a surge rope, tie a surge rope on both the inside and outside of the coil knuckles in addition to other bracing. Reinforce the blocking on 2- and 4-pole motors. Additional blocking is beneficial for applications involving frequent starts or across-the-line starting of high inertia or high torque loads with one row of blocking every 4" (100 mm) typically acceptable.
- Make sure the clearance to end brackets and air deflectors is sufficient before making the coil and jumper connections.

CONNECTIONS

- Overlap the two or more conductors by at least 3/4" (19 mm).
- Braze all coil connections with a torch, carbon tongs or induction brazing units. *Do not use flux when brazing*.
- Be careful not to not damage or distort the insulated portion of the coils during the heating process. Use small metal shields around coil and wet strips of felt, cotton fabric or equivalent to contain the heat. The use of heat isolating putties may also be beneficial.
- File off any burrs or sharp points from brazed joints before applying the insulation.
- Use a shrink sleeving or self-sealing rubber tape over the joints. Make sure the sleeving or tape extends at least 3/4" (19 mm) beyond the stripped area on each side of the connection (Figure 2-141).

FIGURE 2-141



Lead connections.

- Tape series connections and jumpers as indicated in Table 2-63.

TABLE 2-63: MINIMUM HALF-LAP SERVINGS OF TAPE FOR SERIES CONNECTIONS AND JUMPERS

Up to voltage	Servings of mica tape (0.007" or 0.18 mm)*
1000	1
3300	3
4200	4
5000	5

* Apply one layer of armor tape over mica tapes.

Stub connections

If a stub connection is preferred for VPI process, slide 5 kV VPI sleeving over the connection and as far into the joint as possible, making sure no copper is showing. Fold the excess sleeving over the top or bottom side, depending on how the coil stub will be tied.

Figure 2-140 shows the excess sleeving folded towards the bottom where the stub connections will be tied to the jumpers. This provides ample room for insulation between copper conductors. Finish insulating 2300V stub connections by pushing a second piece of sleeving over the first, folding it as also shown in Figure 2-140. Use triple sleeving for 4160V applications.

An alternate method is to double- or triple-sleeve the connection as described above but fold the stub so that it nests between coil knuckles.

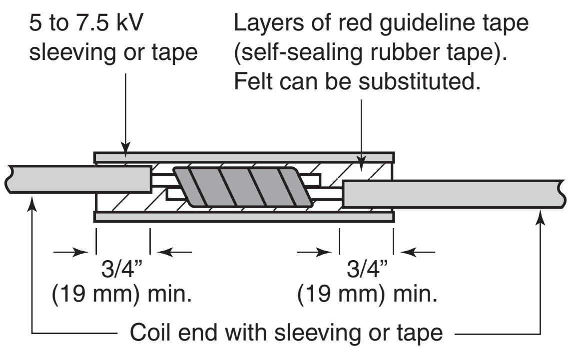
Lead connections

- Braze the lead connections as previously described.
- Seal the brazed connections with void-free dielectric filler (e.g., electrical grade silicone, felt, mica-resin mixture) to keep resin from wicking into the leads (Figure 2-141). If electrical grade silicone is used, it must be allowed to cure prior to impregnation. Unless protected in this way during impregnation, lead insulation may become brittle and crack once the resin cures.
- Apply one layer of red guideline tape (self-vulcanized silicone) for non-VPI applications.
- Insulate the lead connections with mica tape or acrylic sleeving.
- Apply sleeving or tape from coil ends.

Jumper connections

- Overlap the two or more conductors by at least 3/4" (19 mm).
- Braze the connection and file off all burrs and sharp corners.
- Use a 5 to 7.5 kV acrylic shrink sleeving or red guideline tape (self-sealing rubber tape) over the joints, extending it at least 3/4" (19 mm) beyond the stripped area on each side of the connection (Figure 2-142).
- Insulate the coil end with sleeving or tape.

FIGURE 2-142



Jumper connections.

VPI OR DIP-AND-BAKE PROCESS

- VPI and dip-and-bake processes differ significantly, so the winding must be prepared specifically for the method being used.
- Eliminate all stress points where the terminal leads exit the stator frame.
- Masking all machined areas with proper protectant before the impregnation process begins will make them easier to clean after baking. It sometimes saves time to remove the protectant from these areas before baking.
- Use Teflon paper or mylar sheets to protect the leads from damage during the impregnation and cure cycle.
- Be very careful with RTD leads that are protected with acrylic sleeving. Acrylic becomes very brittle after impregnation, so RTD leads may break easily if they are disturbed after the bake cycle.

FINAL TESTS OF COMPLETED WINDING

Turn insulation

The surge withstand capability testing previously mentioned can be performed on the finished winding. However, depending on the location of the fault, turn-to-turn failures may be very difficult to identify. This is why performing this testing on individual coils, under wedge and blocked, is more effective.

Ground insulation

Polarization index and insulation resistance testing should be performed in accordance with ANSI/EASA AR100. Acceptable windings are deemed suitable for high potential testing.

For form-wound machines, there are significant advantages in detecting defects when using alternating voltage tests whether done at power frequency or using a VLF (very low frequency) test set. The high potential test levels for the finished winding at power frequency, very low frequency (VLF) and direct voltage (DC) are shown in Table 2-64. Note: VLF testing is not addressed in NEMA MG-1, IEC 60034-1, or ANSI/EASA AR100. It is included here as a more effective tool than DC testing for finding faults in solid, micaceous insulation.

TABLE 2-64: HIGH POTENTIAL TEST LEVELS FOR THE FINISHED WINDING

Rated voltage (V)	AC[1] (50/60) Hz kV RMS, kV, 1 minute	AC (VLF) kV Peak, kV,1 minute	DC[1] kV 1 minute
400	1.8	2.9	3.1
460	1.9	3.1	3.3
575	2.2	3.5	3.7
2300	5.6	9.1	9.5
3300	7.6	12.4	12.9
4000	9.0	14.7	15.3

[1]NEMA MG-1, IEC 60034-1, ANSI/EASA AR100

IEEE 522 and IEC 60034-15 both include requirements for the ground insulation to withstand impulses or surges with rise times of about 1.2 µs. This is because impulses or surges with slower rise times than about 1.0 µs are known to stress the ground insulation. For this test, each standard prescribes test voltages that calculate to be roughly $4V_{L-L}$. This is not a routine test in most service centers, but if it is specified in a repair specification or purchase order, the coil manufacturer should be aware prior to manufacturing.

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Rewind tips for 5 kV and higher

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This article explains how to minimise risks when rewinding large AC machines, particularly the stators of large induction and synchronous machines used to drive compressors, pumps, fans or mills or as generators with ratings from 350 kW to 350 MW and voltages from 5 kV to 15 kV (HV). These machines may be constant torque, constant speed applications with mains power, or variable torque and speed applications with inverter drives.

A large machine rewind needs to use an insulation system which will survive the stresses experienced in service, in particular electrical stress to earth (ground) and between phases with good control of the effects of partial discharge activity (PD). The coil design must ensure the correct thermal performance as well as the correct electro-mechanical performance of the machine.

PROBLEMS ASSOCIATED WITH HIGH VOLTAGE (HV) WINDINGS

Electrical stress occurs between copper sub-conductors and earth (ground) and between conductors. The voltage stress [V/mm (V/mil) = $V_n/(\sqrt{3} \times d)$] between copper and earth in a modern HV machine will typically be between 1500 - 1900 V/mm (60 - 75V/mil), whilst an older conservative machine will have 1250V/mm (50V /mil) or less.

V_n is the nominal line voltage as stamped on the rating plate; and d is the radial thickness of ground wall insulation (from copper conductor to the outer surface of the coil) in mm or mil.

One problem associated with HV windings is the presence of voids within the insulation. The voltage drop across the void can be 5 times the voltage drop across an equivalent thickness of mica. This is because the voltage is distributed in proportion to the capacitance of the insulating materials between copper and ground. Voids generate discharge activity which can lead to insulation failure.

REQUIREMENTS FOR A SUCCESSFUL HV REWIND

For a successful HV rewind, the coils must have a good fit in the slot to ensure good electrical contact between the coil side and the core. PD activity within the slot is likely to cause premature failure of the insulation system. The coil endwinding must be adequately braced to minimise coil movement during starting or fault condition as well as in normal service.

When connecting the winding, care must be taken to ensure there are no sharp edges to act as points of electrical stress concentration or puncture insulation. All electrical insulation joints must have a scarf joint with a length appropriate for the operating voltage (V_n). All electrical insulation must be applied so as to minimise the voids within the insulation system.

To ensure the correct electro-mechanical performance of the machine, service facilities should follow the principles detailed with the *EASA/AEMT Rewind Study and Good Practice Guide to Maintain Motor Efficiency*.

REWIND PROCESS

When rewinding large machines, the better the preparation work the less likely there will be problems when the machine is returned to service.

To achieve this there are five basic steps to follow:

1. Record all relevant data from the old stator.
2. Investigate how the stator failed.
3. Review the data and coil design to eliminate known cause of failure.
4. Review facility capabilities in relation to work scope (e.g., experience of personnel and suitability of process and test equipment).
5. Plan the rewind and how it will be managed.

1. Record all relevant stator data

When detailing the stator, digital photographic records can be very useful. Record the full data for the existing winding even if the new winding will be modified. EASA's Form Coil Data Sheet (Page 2-257) or coil data sheets provided by coil manufacturers or in-house coil shops are the starting point, since they contain the minimum data required to manufacture a set of coils.

The rewind data needs to include much more information, including:

- Machine type
- Number of poles
- Enclosure
- Operating hours
- Number of starts
- Site operating conditions
- Winding type: lap, wave, concentric, single- or two-layer winding, and two- or three-tier concentric winding format
- Number of terminals
- Number of parallel paths
- Internal connections, including any unusual connections like equalisers
- Type of transposition and location

The winders need to check all of the coils in a parallel path in a phase or as a minimum two pole groups, in case the turns in each coil are different. When the number of slots per pole per phase is not an integer, the number of coils in each pole group, their sequence around the stator, and all circuit connections should be recorded in detail.

Full information on the slot packing and the coil size of the original winding should be recorded to assist the coil manufacturer. The slot width measurement must be accurate to the nearest 0.001" (0.025 mm); measure this critical dimension using a spacer block with precision milled parallel faces and a feeler gauge.

If the stator slot has a skew, this must be measured. This will generally be a 1 slot skew. Detail the direction of the skew in relation to the coil connections and record it on the coil manufacturer's data sheet.

When detailing the stator, accurately record any transpositions used to control stray losses caused by flux leakage across the slot. This can be a full 540° or 360° Roebel transposition, or a twisted conductor (turn) in the diamond coil (GE or Summers type transposition) or in coil-to-coil or group-to-group connections–e.g., a conductor transposition (top-bottom or bottom-top) in the connections (Westinghouse type transposition).

Generators >30 MW with stator half-bars will generally have either a Roebel transposition or coil-to-coil transposition. There are some older machines still operating with Kuyser transpositions, which were used before the Roebel transposition became the industry standard.

When detailing the slot wedges, accurately record the size and position of the fluting that assists ventilation through the radial ventilation ducts. If the fluting is not reproduced as on the original wedge, thermal performance can be compromised. This is most important when the fluting is only on one side of the wedge, where fitting the wedge with the fluting on the wrong side will significantly affect temperature rise. Wedge flutes must align with radial ventilation ducts.

When detailing the winding, record all relevant electrical clearances, not just the clearance between coil side in the endwinding but also the clearance between the endwinding and its connections to earth (ground) at the end of the core, core finger, core clamp plate and the winding cover or any other surface at earth potential (e.g., rotor fan blades).

The lengths of the straight coil sides projecting beyond each end of the core need to be recorded in case the straight length projections are not symmetrical.

If the knuckle or evolute of the coil is not at the centre of the slot pitch, its position must be measured, recorded and sent to the coil manufacturer, as does the measurement of any angle of the knuckle or evolute that is away from radial. Angled knuckles reduce endwinding projection length and increase gaps between coils.

When recording details of the bracing system, include the location of all blocking and the method of lashing (e.g., cord, tape or profile of block), as well as support and bracing rings, fixed or floating, and packing between top and bottom endwinding coil sides.

The packing and bracing will vary greatly depending on the manufacturer, application, method of starting and insulation/impregnation system.

Various coil data sheets are available to cover most winding formats, but there always are exceptions that necessitate the production of sketches and photographs to assist the coil manufacturer.

2. Investigate how the stator failed

Any failure investigation should follow the principles detailed in EASA's *Root Cause Failure Analysis*.

A generalised spectrum of the principle causes of stator failures includes the following defects:

- Wedge and bracing
- Earth (ground) fault
- Inter-turn
- Over temperature
- Contamination
- Partial discharge (PD) activity
- Other

Note: These failure mechanisms are for the stator winding only–i.e., not for the complete machine, where bearing and mechanical failure mechanisms predominate.

Stator winding over-temperature can be caused by loss of ventilation, machine overload, stall, operation at reduced voltage, loss of one or more phases, excessive voltage unbalance, excessive harmonic distortion, stator core failure and heat exchanger failure. The objective is to identify some of the causes but not necessarily all them.

Earth (ground) faults from insulation failure can be caused by excessive endwinding movement due to multiple starts, malsynchronisation, or re-starting a rotating motor out of phase. All of these cause current surges resulting in very significant forces between coil sides.

Earth faults can also be caused by winders when fitting the coils into the stator, by forcing formed coils into a new shape to fit a bracing ring, or by fitting inadequate bracing or using materials with a high shrink rate. These defects should generally be eliminated by electrical tests during rewinding.

Earth faults can also be caused by water ingress through inadequate ingress protection, air-water heat exchanger failure, chemical ingress attacking slot cell insulation, foreign body ingress or rotor-to-stator impact.

Longer term earth faults can be caused by ground wall abrasion (due to inadequate wedging and coil movement in the slot) or by electrical discharge activity in the slot cell.

Phase-to-phase faults can occur in the endwinding, where inadequate space between phase coils in a combination with PD activity and contamination can cause insulation failure.

Inter-turn faults generally result from voltage spikes from lightning, vacuum starters, mains harmonics, variable-frequency drives or occasionally as a result of damage caused during coil manufacture or winding.

Some failures will occur because the insulation system has reached the end of its design life, which with modern insulation systems is generally shorter than some of the older very conservative insulation systems.

3. Review the data and coil design to eliminate known cause of failure

Having identified the root cause of failure you now need to ensure that wherever possible that cause of failure is eliminated. This may entail changes to the coil design by the coil manufacturer, changes in the coil bracing, changes in machine operation, improvement in the machine protection, or whatever mitigating measures are appropriate to prevent the cause of failure reoccurring.

Coil design. The coil design is critical to a successful rewind. The coil must be able to withstand the voltage stress to earth and between phases, the voltage stress between turns and voltage pulses, and the mechanical and thermal stresses experienced during normal operation.

The coil must also withstand the voltages used to verify coil condition during coil manufacture and stator winding (a minimum of 2 times line voltage (V_n) plus 1,000V) and voltage transients experienced in service.

It is important that the insulation to ground is of uniform thickness and free of voids. To ensure uniformity of wall thickness, it is necessary to consolidate the conductor stack before applying the ground insulation.

In resin-rich insulation systems, the excess resin draining from the slot cell during the hot press facilitates the reduction of voids. In VPI insulation systems, correct processing with VPI resins in good chemical condition, and full curing of the impregnated coil with minimal drainage, facilitates the reduction of voids.

The inter-turn stress in normal operation is negligible but significant during starting and abnormal operating conditions such as transient voltages and lightning strikes. The inter-turn test, which can be up to 3 x line voltage, is carried out during coil manufacturing and during winding, ensuring the winding will be fit for service after the rewind.

In normal operation the coil has to withstand the normal flexing of the endwinding in service, at 2 x line frequency, as well as the abnormal movement which occurs during direct on line starting, mal-synchronisation, and restarting a rotating motor out of phase.

The thermal performance of the coil has to withstand its normal operating temperature and excess temperature caused by operating at reduced voltage, or with excessive voltage unbalance and/or harmonic distortion, as well as deliberate or accidental overloads.

There are many standards by which coils can be evaluated.

COIL EVALUATION STANDARDS

Coil test	Applicable standards
Voltage withstand	NEMA MG 1 IEC 60034 -1
Inter-turn voltage	IEEE 522 IEC 60034-15 EA 44-5 & EA 44-7 Tan Delta/Tip Up IEEE 286 EN 50209 EA 44-5 & EA 44-7
Voltage endurance	IEEE 1043 IEEE 1553 IEC 60034-18-32 EN 50209
Thermal endurance	IEEE 1310 IEC 60034-18-31

A further critical area is the accuracy of the coil dimensions. This has an impact on the fit of the coil in the slot, and therefore the resistance of the contact between the coil and the slot and the method used to control discharge currents from the endwinding to the coil slot conducting surface (i.e., the stress grading system).

Where delivery time permits, fitting a trial coil before the full coil set is manufactured can identify coil data sheet dimension errors and tailor the coil to make winding easier.

The radial slot wall thickness of typical coils will be in the order of:

RADIAL SLOT WALL THICKNESS OF TYPICAL COILS

Line voltage (kV)	Thickness–inches (mm)
6.6	0.071 (1.8 mm)
11.0	0.118 (3.0 mm)
13.8	0.150 (3.8 mm)

The length and type/application of stress-grading material beyond the overlap of the slot conducting surface and the amount of overlap are also proportional to the line voltage.

Although the above specifically refers to resin-rich coil insulation systems, resin-poor coils for VPI impregnation systems will have similar insulation thicknesses and corona control systems. The only difference is the resin content in the materials used.

4. Review facility capabilities, experience of personnel, and suitability of process and test equipment

Before undertaking a rewind you should review your capability to complete the rewind successfully. This should cover all aspects of the rewind process, from mechanical handling of the complete machine or stator to the capability to turn the stator to facilitate winding.

Do you have the equipment to strip the old winding, and in particular for a VPI winding, do you have access to a large enough controlled pyrolysis burnout oven?

Since the correct application of insulating materials is critical to insulation system performance, do your supervisors and winders have sufficient experience in HV rewinding, or do you need to hire an experienced supervisor? Do you have suppliers of the right insulating materials stored in the climate-controlled conditions specified by the insulation manufacturer, and do you have a suitable climate-controlled storage capability on site?

Is there a clean area with controlled environment where the stator rewind can be conducted, or do you need to produce a temporary enclosure with appropriate environmental control equipment? Winders dripping sweat on uncured insulation creates a low IR problem, increasing the time to dry out the winding before impregnating and curing.

Having wound the stator, you then need to consider the impregnation process and therefore tank size and volume of varnish needed. Consider the curing process: will the fit into your oven or do you need to build a temporary oven with heaters and temperature control equipment?

Then you get to the stage of testing the stator to demonstrate to the customer how well the rewind has been done. This requires both the necessary test equipment and a test technician who understands the results of the following tests that the customer expects:

- Micro ohm winding resistance
- Impedance
- Insulation resistance and polarisation index
- HV AC test (2 x Vn + 1000V)
- Tan delta or Tip-up test
- Partial discharge test
- Blackout test

5. Plan the rewind and how it will be managed

Having determined you have the capability to rewind the stator, plan the rewind in detail, using a timeline to facilitate material and resource procurement and planning.

As with all rewinds, once the customer confirms the order, the starting point is to detail the windings and connections. If the connections are too large to retain, ensure there are good photographic records of all connections and leads, including accessories.

To facilitate timely delivery, order the coils as soon as the essential coil data has been obtained.

Next, strip the stator and measure the size of at least four different slots around the core, and in at least three different positions axially along the core. Use a steel block and a feeler gauge to ensure accuracy to the nearest 0.001” (0.025 mm).

Forward the slot dimensions to the coil manufacturer, so they can form the coils to fit the slot accurately, thereby minimising the packing required during coil fitting.

Core testing and inspection

In keeping with EASA’s *Good Practice Guide,* perform a core flux test before burnout oven processing the stator and before winding. Any defects identified need to be addressed before winding. This should include checking the tightness of the core, verifying the integrity of ventilation support fingers, and straightening of any bent or displaced lamination teeth.

Core integrity checking includes looking for signs of:

- Weld cracks in the frame or between the frame and core
- Core waviness
- Core joint lamination displacement or buckling
- Vent finger movement
- Core bolt insulation measurement
- Localised core heating
- Wedge groove damage
- “Greasing” evidence of core movement in the stator frame or of building (support) bars

Any hot spots need to be eliminated by grinding, etching, insulation insertion, or lamination grinding and re-insulation. If core losses in watts/kg or watts/lb are too high, the core should be completely re-insulated or replaced.

When inspecting the stator core before winding, check that the end of core pressure fingers have not moved tangentially to be too close to one side of the coil exiting the slot, or displaced radially to interfere with the rotor. Also, check that the clamp plate has not moved out of concentricity with the bottom of the stator slot.

The last thing you want in an expensive HV rewind is for the HV insulation system to be compromised by a latent defect in the core which you have not identified during rewinding.

Having ordered the coils and prepared the core for winding (clean and paint), ensure that the winding materials have been ordered with delivery planned to meet the project timeline. Do not forget to order the temperature detectors to be fitted in the slots between coils.

Whilst waiting for the coil delivery, connecting rings and bracing rings can be stripped, inspected for defects and reinsulated. All ancillary equipment can also be tested and verified as fit for service. This includes insulated terminals, instrumentation and protection transformers, heat exchangers, heaters, air temperature detectors, pressure switches, and blower units.

Coil fitting

Once you know when the coils will arrive, set up the clean area around the stator with space close by for the coil packing cases to minimise coil movement from shipping case to stator.

After taking a coil from its shipping case, remove the protective materials and visually inspect it for damage.

Correct coil fitting is critical to a successful rewind. Resin-rich diamond coils for 2- and 4-pole stators must be warmed to 50°C (120°F) before fitting, but best practice recommends that coils for machines from 6 to 10 poles should also be warmed to 50°C (120°F) before fitting.

VPI diamond coils should be fitted using an extended temporary slot liner (typically polyester film) to prevent damage to the uncured coil insulation as it enters the slot. The temporary slot liner must be removed after the coil has been fitted in the slot.

Only fit a bottom-of-slot pad if the bottom of the slot surface is uneven. Any bottom-of-slot pad must be of a conducting material and as thin as practicable.

Fitting a formed coil requires two persons–one at each end of the stator. Carefully introduce one end of the bottom coil side into the bottom slot and then gradually ease the rest of the coil side into the slot. Next, ease both ends down to the bottom of the slot, and check the coil projection at each end. Lastly, check the gap at the coil side and if necessary insert conducting side packing.

When inserting the top coil side, both winders should work together to achieve correct alignment with the slot by lifting the knuckle or using coil tongs, if necessary, to align the coil side with the angle of the slot. The coil side is then eased down onto the top of the middle packing strip. The slot pitch is checked as well as coil projection, space between coils, and slot fit.

When easing a resin-rich coil side down into a slot with a mallet, spread the impact with a block [12” (300 mm) x slot width].

With both coil sides in their correct slots, adjust the end winding shape and knuckle angle as necessary, using tongs, bodges and mallets (see Figure 2-154 on Page 2-255 and Figure 2-155 on Page 2-256) to prevent loss of space between coils.

Every time a coil is handled or manipulated to fit into the slots, its shape is distorted from the shape supplied by the coil manufacturer. If this is not corrected after each coil is fitted and lashed to its support ring, there is a high probability that there will be little or no space between coils when the last coils are inserted into the stator slots.

The middle strip must be of conducting material with thickness increasing with line voltage.

TYPICAL THICKNESS OF MIDDLE STRIP

Line voltage (kV)	Thickness–inches (mm)
6.6	0.12 (3 mm)
11.0	0.16 (4 mm)
13.8	0.20 (5 mm)

When fitting middle strips with temperature detectors, ensure that the temperature detector leads within the strip are lying flat with no crossovers. Lead crossovers can short circuit in service, taking the temperature detector out of service or damaging adjacent coil insulation.

Attach temperature detector leads to the end of the stator core and take them radially towards the back of the core, keeping them well away from coils and connections.

When fitting coils, be careful not to damage the coil slot cell by bending it. This can happen if the coil endwinding contacts the bracing ring before the coil side reaches the bottom of the slot; or if the endwinding is too far off of the bracing ring when the coil is at the bottom of the slot and forced down to meet the support ring.

If the coil has been manufactured correctly, the endwinding should be about 1/16” - 1/8” (1.6 - 3.2 mm) away from the bare uninsulated bracing ring. The maximum distance a coil endwinding can be pulled down or forced up to meet an insulated bracing ring is 0.080” - 0.120” (2.0 mm - 3.0 mm). Any gap between the coil and the bracing ring greater than 0.120” (3 mm) must be filled by lashing an epoxy felt-wrapped epoxy glass block to the bracing ring

If the coils hit the bracing ring before the coil side reaches the bottom of the slot, check the coil pitch. If that is correct, adjust the coil shape before fitting the coil into the stator.

If the coil is too far from the bracing ring after the coil side reaches the bottom of the slot, check the coil pitch. If that is correct, and the reduced inside diameter of the endwinding is not going to interfere with rotating parts, it is acceptable to place additional packing between the bracing ring and the coil endwinding. For example, B-stage epoxy felt can be taped or corded in place to prevent it coming adrift in service.

The fit of the coil side into the slot is critical to the long-term performance of the winding. There must be good electrical contact between the coil side and the slot. This coil-to-core resistance should be >100Ω and should not exceed 4000Ω and 80% of the coils should have a contact resistance of less than 2000Ω. This is checked using a multimeter with one lead on the stator tooth and the other lead on a copper strip set on top of the coil side in the slot. The copper strip must not contact the slot walls.

Coils do not want to sit vertical in the slot; they generally sit diagonally across the slot with point contact at the top and bottom of the coil on opposite sides. Conducting material should be fitted between the coil and slot side to obtain good contact and prevent coil movement in service. The maximum gap recommended for 80% of the slot length is 0.005” (0.13 mm), and nowhere should the gap exceed 0.008” (0.20 mm).

Where customer-driven requirements specify a maximum gap of 0.002” (0.05 mm) along 80% of the core, then conducting side ripple springs need to be fitted. When fitting side ripple springs, ensure that the springs are fully compressed (90%) as recommended by the manufacturer, using conducting epoxy glass sheet and ensuring that there are no sharp corners on the ripple spring to bite into the coil side.

It is equally important to prevent the coils from moving vertically within the slot whilst in service. There are several methods of achieving this, including tight-fitting packing, top ripple springs (90% compressed) or contra-wedges. To ensure tight wedging, force the coil sides against the bottom of the slot during wedging using temporary wedges and jacking bolts or jacking bars across the stator.

Coil enwindings must be braced to withstand the electromechanical forces they are subjected to. As a minimum, fit a bracing system equivalent to or better than the manufacturer’s bracing system.

If any of the original bracing rings have been damaged or destroyed during winding removal (e.g., VPI winding in burnout oven), the new bracing rings must be manufactured from epoxy glass laminate, machined Resi-glass rings, or metal hoops with a gap to prevent induced circulating currents.

If during the failure investigation a weakness with the bracing system had been identified, change the bracing to prevent re-occurrence of that failure mode.

When endwinding damage is excessive and the original bracing system cannot be identified, fit the following bracing as a minimum:

- Slot mouth blocks between coil sides if the coil straight length projects more than 2” (50 mm) beyond end of slot.
- Blocks on endwinding straight lengths, typically:

Block length–inches (mm)	Number of block rings
0 - 8 (0 - 200)	1
8 - 12 (200 - 300)	2
12 - 20 (300 - 500)	3

If you are fitting felt blocks between endwinding coil sides using felt which is not taped or lashed to the coil side, these blocks must be of a “dog bone” shape to prevent them from coming adrift in service.

Keep coil-to-coil blocks in symmetrical rings evenly distributed along the endwinding straight length.

When tying blocks to a coil side, ensure there are no sharp corners on solid blocks to bite into the coil insulation; and ensure that the binding materials used will not shrink sufficiently to bite into the coil insulation.

Blocks between coil sides should be tied between the coil sides and then cross banded to ensure they stay in position.

When fitting coil-to-coil blocks, it is important to keep the space between coils as uniform as possible, particularly between the phase end coils of different phases.

TYPICAL REQUIRED GAPS BETWEEN PHASE END COILS

Voltage (kV)	Required gap–inches (mm)
6.6	0.22 (5.5)
11.0	0.32 (8.0)
13.8	0.40 (10.0)

Note: Significantly reducing the space between coils or obstructing airflow through the endwinding (e.g., by introducing felt insulation between the top and bottom coil sides which was not there originally) will change the porosity of the endwinding, causing the machine to run hotter.

In larger machines, particularly 2-pole machines with stator bars, there will often be tapered blocks between the top and bottom coil sides in the endwinding. These blocks require felt pads between the block material and the coil sides. It is critical that these blocks are correctly tied down to the bracing rings or support blocks through the bottom bars before the top bars are tied down to the block.

In some large vertical machines, additional blocks may be fitted to prevent the winding from moving down the slot.

When the number of poles increases and the coil pitch reduces, coil-to-coil blocking can be reduced, depending on the application and physical dimensions of the coil. As a minimum, coils should be tied to a bracing ring. Never use less blocking and bracing than that used by the OEM.

If you are using continuous dry glass roving and VPI epoxy impregnation, it is important to twist and lock the roving between coils and not just rely on the bond between the roving and coil side to maintain coil separation. This bond will fail after several years in service, and the coil will vibrate and damage coil insulation.

Coil testing during winding

The objective of any testing during winding is to identify any defects before the winding has been completed, impregnated and cured. The last thing we want is to have a winding failure during a final HV test.

After coils have been fitted, wedged and tied down to the bracing ring (i.e., in their final operating position), perform an impulse test to detect potential turn-to-turn faults, followed by a HV test to prove no damage has occurred during coil fitting. Normally all coils fitted during each shift should be tested at the end of that shift, reducing any remedial action should a coil fail.

These tests should start with IR, followed by inter-turn surge test, and then by a HV withstand test. The HV withstand test is typically 10% higher than the final test but only held on for 10 seconds. Finally, there is an IR test to verify there has been no damage to coil insulation due to the test.

Only when coils have passed these tests should they be connected and endwinding bracing completed.

Connections

When making connections, replace all transpositions to reduce the parasitic currents caused by voltage differences induced in the different sub-conductors. It is important to get the right transposition at each coil group connection; otherwise the benefit can be lost, causing the winding to run hotter.

Before connecting ensure that the sub-conductors are aligned to minimise mechanical stress on the connection. Where possible, use a suitable ferrule to add some mechanical strength to the connection.

Although copper is malleable, it will work harden easily. When shaping the conductors at a connection, ensure there are no sharp bends or knife marks on the conductor surface. When making a connection, ensure an overlap of at least the copper width. Take into account any space required for inter-turn insulation you may need to add after connecting.

Before brazing, cut back and protect coil lead insulation from excessive heat (burn back), typically using damp ceramic fibre or equivalent. Squeeze out any excess water before applying the ceramic fibre; excessive moisture increases the drying-out time before impregnation.

Use brazing material with a minimum of 15% silver, applying heat to bring the joint to flow temperature [705°C -815°C (1300°F - 1500°F)] quickly. Use just sufficient heat to ensure good braze flow to provide a good electrical connection, and then wipe and remove any sharp points or edges to reduce electrical stress and eliminate points of mechanical stress. If necessary, before insulating sub-conductor connections file and clean conductors to remove any sharp points or edges.

When coil-to-coil transpositions are used, it is important to replace them in the same sequence as in the original winding, or as specified by the machine designer. Also, ensure that insulation of sub-conductor layers being transposed is maintained throughout each parallel path of the phase.

After the sub-conductors have been insulated, apply any conductor (turn) insulation as required. Some coil designs will have all the turn insulation on each sub-conductor. Other coil designs will have minimal insulation on each sub-conductor with the conductor (turn) insulation applied to groups of sub-conductors.

On some connections the layer-to-layer insulation may be strips of mica-splitting, with voids filled with two-part epoxy putty and not taped.

Before applying any lead or ground insulation, minimise any voids between layers of sub-conductors to reduce discharge activity. One material which is very useful for this purpose is 2-pack epoxy putty, which after mixing can be pressed into the voids and shaped to make the coil and lead insulation easier.

The lead insulation will need to be applied over the connections. Generally this will be the same as the endwinding insulation as specified by the coil manufacturer.

When applying new insulation to connect with existing insulation, always use a scarf (taper) joint. Never use a simple butt joint where two insulations are joined.

The object of an insulation scarf joint is to ensure there is a much longer tracking path through the insulation than just the radial thickness of the insulation of a butt joint.

TYPICAL SCARF JOINT LENGTHS

Voltage (kV)	Scarf length–inches (mm)
6.6	1.2 (30)
11.0	1.6 (40)
13.8	2.0 (50)

The existing insulation must reduce in thickness gradually over a length of conductor; the length is dependant on the voltage. The new insulation starts with the first layers on the conductor, with subsequent layers gradually overlapping the scarfed (tapered) old insulation until the final layers seal over the old scarfed insulation.

Obviously any insulating tape must be applied in clean conditions, with care to minimise wrinkles and with sufficient uniform tension to reduce voids and ensure the insulation layers amalgamate when cured.

B-stage insulation tapes stored in a controlled temperature [e.g., 7°C (45°F)] must be allowed to normalise to room temperature before being applied to prevent formation of condensation.

When making group and phase connections, ensure that there is adequate space between connections of different phases to minimise discharge activity. The bracing must also be sufficient to prevent movement in normal operation and fault conditions. This includes the transit of the phase leads from the winding connections to the terminals.

Where possible, always maintain typical clearance distances to earth (ground).

TYPICAL CLEARANCE TO EARTH (GROUND)

Voltage (kV)	Inches (mm)
6.6	1.5 (38)
11.0	2.0 (50)
13.8	2.25 (57)

After the connections have been made, perform a final impulse test followed by another HV test, once again at 110% volts for 10 seconds.

Impregnation

Preferably the stator and winding should be dried and then totally immersed under a suitable insulating varnish until all bubbles have stopped rising. Allow the stator to drain, wipe the bore, and cure the stator in accordance with the varnish manufacturer's instructions.

In many instances, however, the stator will be too large to fit into your varnish tank, or too large to remove to your service facility, so you need to make alternative arrangements.

Pumping varnish over a winding using a hose with ≥1" (25 mm) ID is an alternative to immersion. Another alternative is to spray the endwindings with a suitable 2-part epoxy paint.

When using the alternative impregnation methods, it is equally important to dry the winding at 90°C (195°F) before impregnation and fully cure it at 165°C (330°F) before final testing. The PI should not be <2.0.

When making alternative arrangements for drying and curing, minimise the volume being heated by blocking the stator bore. Ensure that the temporary enclosure is well insulated and has an exhaust vent and a fail-safe temperature control system to prevent overheating. It is not unknown for operatives on duty to control temperature to fall asleep and allow the new winding to overheat.

Stator testing

Having wound the stator you now have to produce test data as evidence of the quality of the rewind.

The starting point is measurement of the insulation resistance (IR), which will be carried out at 1000V DC for machines with terminal voltage from 5 -10 kV AC, at 5000V DC for higher voltages, or as specified in IEC 60034-27-4 or IEEE 43.

During the measurement of insulation resistance, a measurement of the polarisation index (PI) will taken by measuring the IR after 1 min and after 10 minutes. A PI in excess of 2 is expected.

This is followed by the voltage withstand test, which preferably will be carried out as an AC test rather than a DC test.

The AC voltage withstand test evaluates the insulation system as it operates in service, with voltage distribution through the insulation dependant upon the capacitance of the component parts. As a result, the AC test stress tests any voids within the insulation system.

On the other hand, with a DC voltage withstand test the voltage is distributed though the insulation dependant upon the resistance of the component parts. As a result the DC test does not stress test any voids within the insulation system.

However, for site testing DC withstand is sometimes a simpler test due to the difficulty of transporting a suitable transformer and regulator to the site for an AC withstand. The DC withstand test will be at 1.7 times the specified AC withstand test voltage.

When further tests like a tan delta (tip-up) test are required, you need an AC transformer and regulator capable of energising the winding to line voltage as a minimum.

When carrying out tan delta testing, you are looking to achieve a small gradual increase in tan delta as voltage applied increases; with the tan delta measurement at 0.2Vn being as low as can be achieved but definitely less than 0.03.

More customers are looking for measurement of off line partial discharge as a benchmark for ongoing discharge measurement. It is almost impossible to calculate an anticipated discharge level, since with manufacturing tolerances no two machines are identical. And even taking a measurement on a new winding does not necessarily give a true benchmark for the winding in service.

Initial discharge measurement may in some instances be higher than discharge measured after some time in service. Until the winding has gone through a number of thermal cycles, has reached its fully cured insulation condition, and has normalised its position in the stator, the true base PD will not be known.

IEEE 1799 details blackout testing of stator windings to identify visible PD activity in the end-winding at line voltage With UV instruments the test can be conducted in daylight, eliminating the risks associated with personnel observing PD activity under blackout conditions.

On-line partial discharge monitoring is the way forward to monitor winding condition during service. However, it is still only one tool out of many others which are used to verify winding condition during service life.

Conclusion

By careful preparation, planning and attention to detail during the process, it is possible to minimise the risks during the rewind of a stator operating at a line voltage in excess of 5 kV. The key areas to be addressed are:

- Detail the original stator winding
- Investigate the cause of failure
- Apply failure mode prevention strategy
- Communicate with the coil manufacturer
- Pre-heat coils before fitting
- Maintain electro-mechanical performance
- Ensure good electrical coil-slot contact
- Ensure coils are wedged tight in slot
- Provide good endwinding bracing
- Replace transpositions
- Ensure good electrical and mechanical connections
- Minimise voids in connection, jumpers, etc.
- Dry, impregnate and test

Remember, the object of the exercise is to produce a stator rewind which is fit for service, delivered to the customer when he was told he was going to get it at the start of the process, with a winding life that matches or exceeds his expectations, and within the project budget, so that you at least make your budgeted margin.

Definition of terms

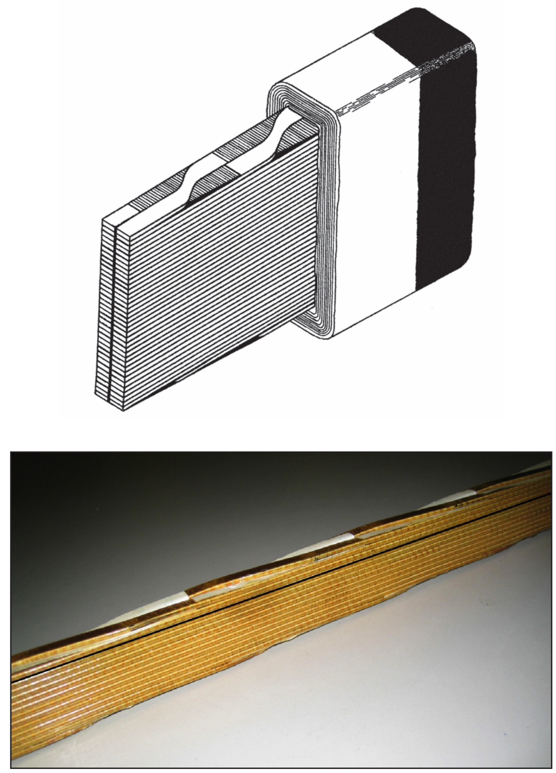
Mal-synchronisation. When a generator circuit breaker is closed onto the grid (mains supply or local network), the voltages and phase relationship of the generator and grid should be the same. If the generator breaker is closed when the phase relationship is not aligned with the grid, there will be a current surge as the generator is pulled into synchronism with the grid. This current surge can cause significant damage to the stator winding and is known as mal-synchronisation.

Roebel transposition. A method of manufacturing stator bars (half coils) where each sub-conductor spends an equal time in each location down and across the slot to minimise parasitic I^2R circulating current losses caused by induced voltages from flux leaking across the slot (see Figure 2-143 and Figure 2-144).

Kuyser transposition. This is a method of manufacturing stator bars (half coils) where each bundle of 4 or 5 sub-conductor spends a period of time in a different location down the slot to reduce parasitic I^2R circulating current losses caused by induced voltages from flux leaking across the slot (see Figure 2-145). Because the conductor cross-section area is reduced by at least 50% at the crossovers, there is a small increase in resistance and a localised hot spot.

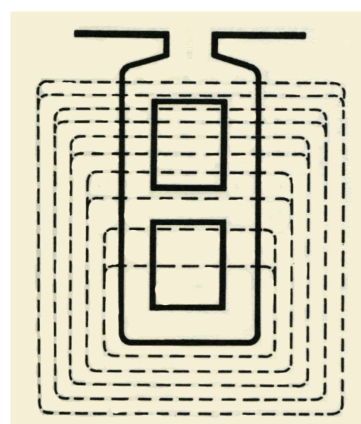
GE or Summers transposition. A method of manufacturing coils with a twisted turn or turns within the coil endwinding to reduce some of the parasitic I^2R circulating current losses caused by induced voltages from flux leaking across the slot (see Figure 2-146).

FIGURE 2-143



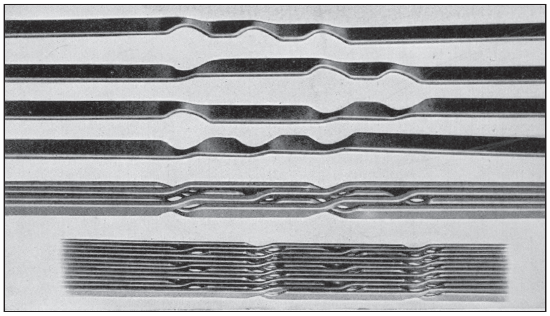
Roebel transposition connections.

FIGURE 2-144



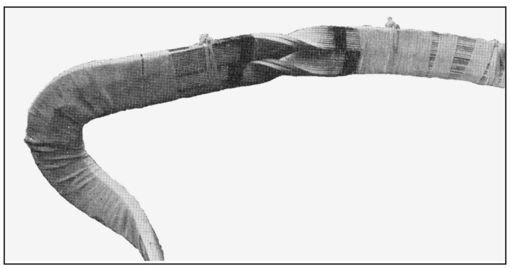
Flux leakage across the slot.

FIGURE 2-145



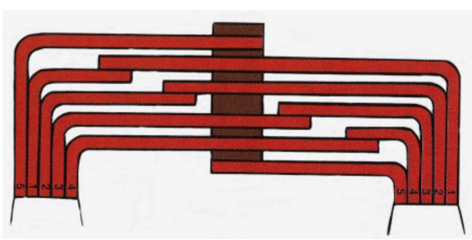
Kuyser transposition.

FIGURE 2-146



GE or Summers transposition.

FIGURE 2-147



Westinghouse or coil lead transposition.

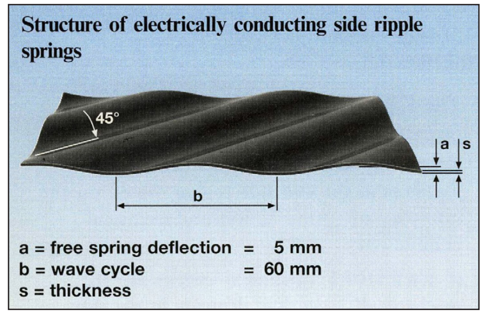
Westinghouse or coil lead transposition. A method of connecting coils with sub-conductor rotation at each coil-to-coil connection and group-to-group connection to reduce some of the parasitic I^2R circulating current losses caused by induced voltages from flux leaking across the slot (see Figure 2-147). The integrity of strand insulation has to be maintained throughout the phase or each parallel path within the phase.

Conducting side ripple springs. See Figure 2-148.

Slot content. The content of the slot includes the wedge, top packing, ground wall insulation, sub-conductors, the middle strip, side ripple springs, side packing, and the bottom pad/strip (see Figure 2-149).

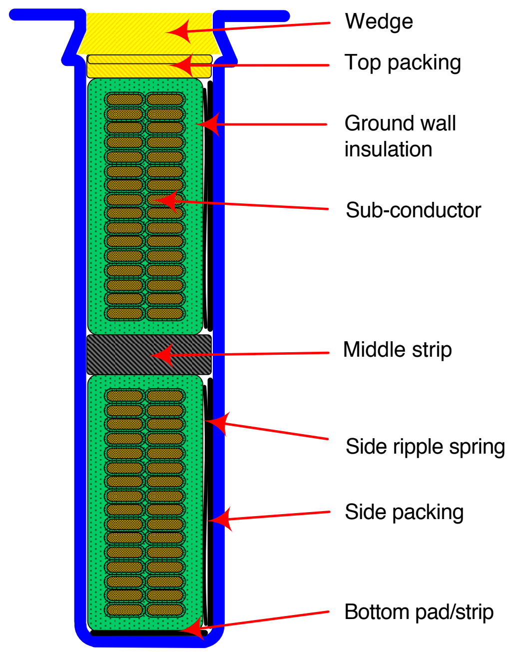
Slot mouth blocks. Tapered blocks at end of straight lengths of coil sides, to reduce risk of cracks where the coil enters the slot (see Figure 2-150).

FIGURE 2-148



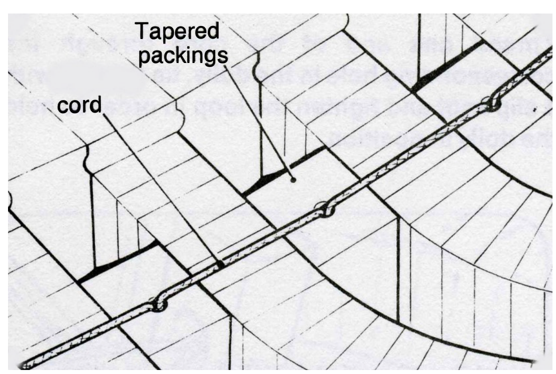
Structure of electrically conducting side ripple springs.

FIGURE 2-149



Slot content.

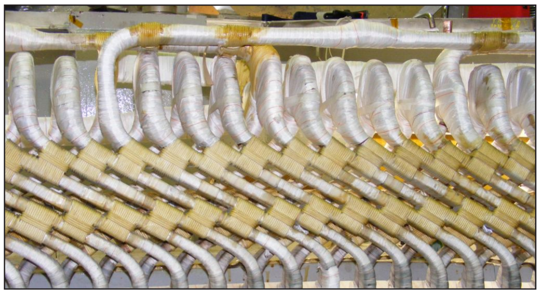
FIGURE 2-150



Slot mouth blocks.

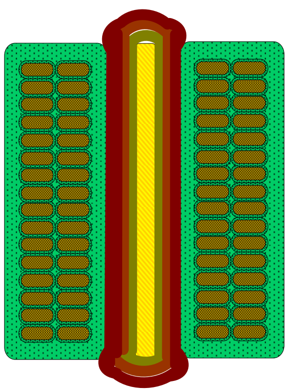
Endwinding blocks. Tapered blocks fitted in the straight length of the endwinding to provide mechanical support for coil sides during normal operation and current surges, and to provide ventilation paths between coil sides (see Figure 2-151).

FIGURE 2-151



Endwinding blocks.

FIGURE 2-152



Dog bone blocks.

Dog bone blocks. Epoxy glass block (depth of coil), wrapped with polyester felt, with sufficient layers to permit compression of felt between coil sides and bulge over the tops of the coils sides to retain block in position in service (see Figure 2-152).

Roving. Longitudinal glass fibre strands enclosed within a polyester or glass braided sleeve (see Figure 2-153).

Winders tongs. A winder's tool (see Figure 2-154).

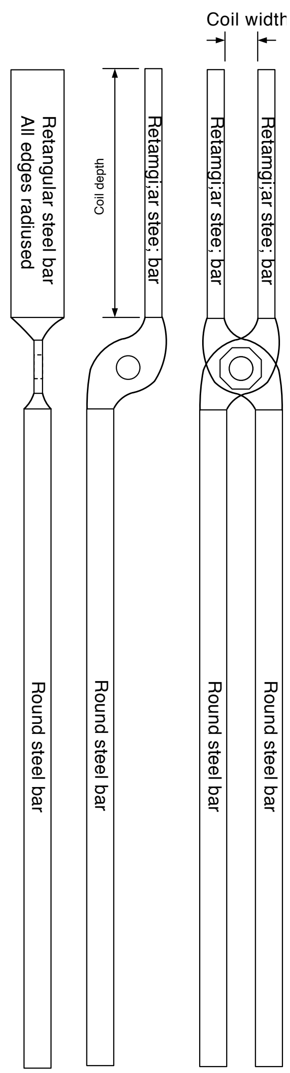
Winder's bodge. A winder's tool, used with a mallet, to re-shape coils after a coil has been inserted into its correct slots (see Figure 2-155). The bodge can be made from a steel bar or a woven epoxy glass block. The tapered end must have well rounded corners to prevent damaging the coil ground wall insulation. The tapered head of steel bodges are sometimes covered with a layer of adhesive glass tape.

Insulation scarf joint. A tapered overlapping connection between existing original insulation and the new insulation that the winder applies after making up the connections (see Figure 2-156). The new insulation is built up in half-lap layers, starting from the conductor and gradually building up over the original insulation scarf length. When the tapered length of

FIGURE 2-153

Roving.

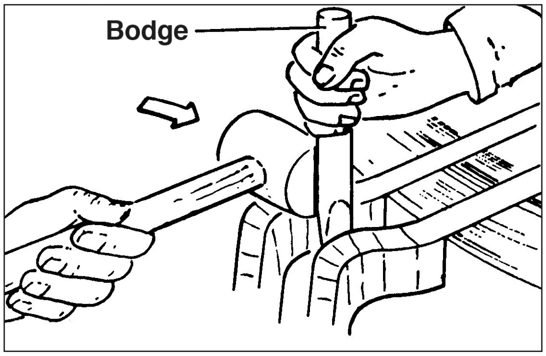
FIGURE 2-154



Winder's tongs.

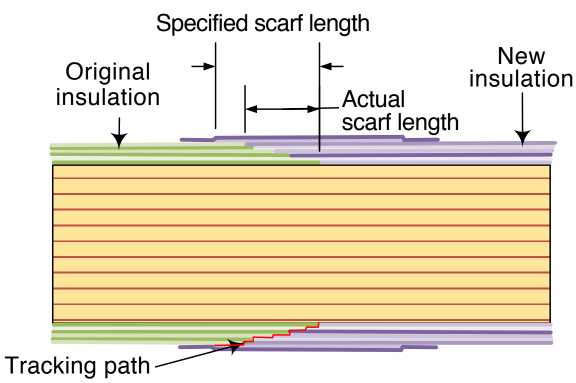
the original insulation is shorter than the desired scarf length, the new insulation is extended over the original insulation, beyond the original insulation scarf, until the specified scarf length has been achieved.

FIGURE 2-155



Winder's bodge.

FIGURE 2-156



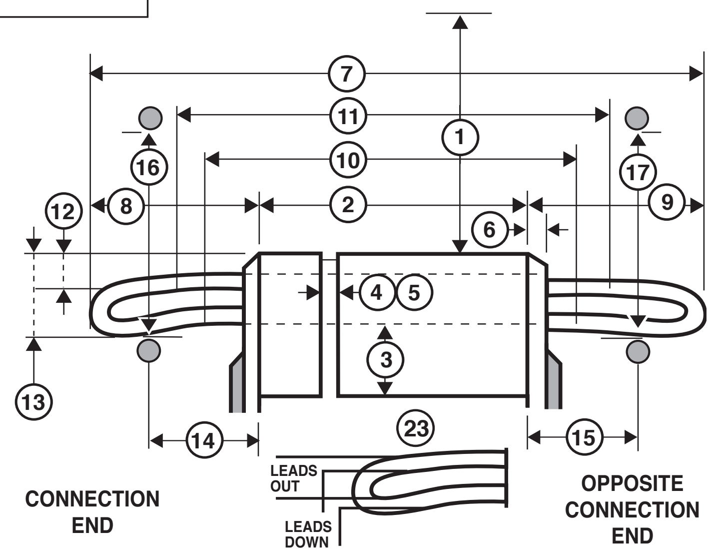
Insulation scarf joint.

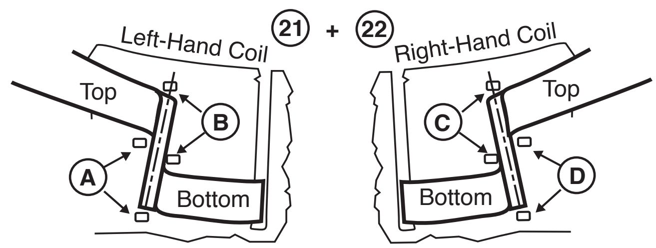
2.14 AC WINDING DATA FORMS

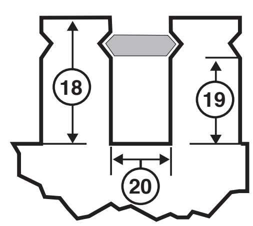
AC STATOR FORM COIL DATA

COMPANY		CONTACT		DATE	JOB #
ADDRESS		CITY		STATE/PROVINCE	ZIP
P. O. BOX	PHONE	FAX		EMAIL	
MFR.	HP/KVA/KW	POLES	RPM	FRAME	
MODEL	VOLTS	AMPS	HERTZ	PHASES	
SERIAL #	TYPE				

1	CORE BORE DIAMETER	
2	TOTAL CORE LENGTH	
3	BACK IRON	
4	NO. OF VENTS	
5	WIDTH OF VENT(S)	
6	FINGER PLATE WIDTH	
7	OVERALL COIL LENGTH	
8	CONNECTION END EXTENSION	
9	OPPOSITE CONN. END EXTENSION	
10	STRAIGHT LENGTH, BOTTOM SIDE	
11	STRAIGHT LENGTH, TOP SIDE	
12	SMALL KNUCKLE DROP CE ______ OCE ______	
13	LARGE KNUCKLE DROP CE ______ OCE ______	
14	CONN. SUPPORT RING FROM CORE	
15	OPP. CONN. SUPP. RING FROM CORE	
16	CONNECTION SUPPORT RING I.D.	
17	OPP. CONN. SUPPORT RING I.D.	
18	TOTAL SLOT DEPTH	
19	SLOT DEPTH UNDER WEDGE	
20	SLOT WIDTH	
21	LEAD LOCATION ❑ A ❑ B ❑ C ❑ D	
22	COIL TYPE ❑ LEFT-HAND ❑ RIGHT-HAND	
23	COIL LEADS LONG # _______ LG ______ SHORT # _______ LG ______ ❑ OUT ❑ DOWN	
24	JUMPER (1 - 4 OR 1 - 7)	1 -
25	CONNECTION (WYE OR DELTA)	
26	NO. OF CIRCUITS	
27	NO. OF SLOTS	
28	COIL THROW	1 -
29	TURNS PER COIL	
30	TOTAL WIRES IN PARALLEL	
31	BARE WIRE SIZES (______) X _______ (______) X _______	
32	STRAND INSULATION ❑ FILM ❑ GLASS ❑ MICA ❑ BARE ❑ OTHER	
33	COIL WEIGHT	LBS.
34	__________ GROUPS OF _________ COILS __________ GROUPS OF _________ COILS	
35	IRON SKEWED ❑ RIGHT ❑ LEFT _______ IN.	







SPECIAL FEATURES	YES	NO
DATA CHANGE		
COIL SUPPORT RING STEEL		
TERRACE WOUND		
CORONA PROTECTION		
RTDs OHMS QTY		
HERMETIC		
SLOT PAPER USED		
INSULATION CLASS ❑ B ❑ F ❑ H		
❑ VPI ❑ DIP & BAKE ❑ SEALED		
❑ LEADS TAPED ❑ LEADS SLEEVED		

COMMENTS

Please mail or fax a copy to EASA Headquarters, 1331 Baur Blvd., St. Louis, MO 63132; fax (314) 993-2998.

INSTRUCTIONS

GENERAL

- All dimensions should be taken to the nearest 1/16” (1 mm) except 18, 19, 20 and 31, which should be to the nearest .001” (0.03 mm) and 23, which should be to the nearest 1/4” (6 mm).
- All items must be completed unless otherwise explained.
- To make the data easier to read when the form is transmitted via facsimile machine, use only a blue or black felt or nylon tip pen. Please press heavily and record the data in the answer column provided.

1 **Core Bore Diameter**–Inside diameter of the stator iron. This is measured from tooth to tooth through the center line of the machine.

2 **Total Core Length**–Length of the stator iron including vents but excluding finger plates. Please make several measurements and give the average.

3 **Back Iron**–The distance from the outer edge of the stator iron near the frame to the bottom of the slot.

4 **No. of Vents**–The number of vents in the stator iron.

5 **Width of a Vent**

6 **Finger Plate Width**–When present, give the width of the plate that applies pressure to the stator laminations.

7 **Overall Coil Length**–The overall insulated coil length measured from the outer edge of one coil knuckle to the outer edge of the other knuckle.

8 **Connection End Extension**–The coil extension measured from the outer edge of the coil knuckle to the stator iron on the lead end.

9 **Opposite Connection End Extension**–The coil extension measured from the outer edge of the coil knuckle to the stator iron opposite the lead end.

10 **Straight Length, Bottom Side**–The length of the straight portion of the coil in the bottom of the slot. This is measured along the inside edge of the coil from point to point where the diamonds just begin to form.

11 **Straight Length, Top Side**–The length of the straight portion of the coil in the top of the slot. See Item 10 for details.

12 **Small Knuckle Drop**–When extending a straight edge across the stator iron and out over the coil extension, the distance from the bottom of the straight edge to the area of the coil where the knuckle starts to form. Measure on both ends.

13 **Large Knuckle Drop**–When extending a straight edge across the stator iron and out over the coil extension, the distance from the bottom of straight edge to the lowest point of the coil knuckle where it touches the support ring. Measure on both ends.

14 **Connection End Support Ring from Core**–The distance from the inside edge of the insulated front support ring to the stator iron on the lead end. If there is more than one ring on each end, note the number of rings and the distance between rings. Allow for ring insulation if it is not present when the measurements are made.

15 **Opposite Connection End Support Ring from Core**–The distance from the inside edge of the insulated support ring to the stator iron on the opposite lead end. See Item 14 for details.

16 **Connection End Support Ring Inside Diameter**–The inside diameter of the insulated support ring on the lead end. Scribe an arc from the inner edge of the ring to the opposite inner edge and take the largest measurement.

17 **Opposite Connection End Support Ring Inside Diameter**–The inside diameter of the insulated support ring on the opposite lead end. See Item 16 for details.

18 **Total Slot Depth**–The total slot depth of the stator slot measured from the top of the tooth to the bottom of the slot.

19 **Slot Depth Under Wedge**–The distance from the bottom of the slot to the bottom of the wedge groove.

20 **Slot Width**–The stator slot width measured at the bottom of the slot.

21 **Lead Location**–Choose one letter (A, B, C or D) to indicate which lead arrangement is applicable.

22 **Coil Type**–Indicate the type of coil desired, either left-hand or right-hand. Looking from the connection end of the coil, is the right-hand slot section of the coil in the top or bottom of the slot?

23 **Coil Lead Length and Number**–Both long and short leads. Indicate if leads are down (i.e., perpendicular to the length of the coil) or straight out.

24 **Jumper**–The internal connection of the coil group.

25 **Connection**–The connection of the stator windings: Wye or Delta.

26 **No. of Circuits**–Number of parallel circuits.

27 **No. of Slots**–The number of stator slots. This is also the number of coils unless otherwise advised.

28 **Coil Throw**–The span of the stator coil. The slot that holds the bottom coil side is Slot #1.

29 **Turns per Coil**–The number of turns that the coil conductor(s) is (are) looped. Count turns on the opposite connection end.

30 **Total Wires in Parallel**–The number of wires in parallel. This is easily indicated by the number of wires that make up one of the coil leads.

31 **Wire Sizes**–This measurement is taken on the bare copper. If more than one wire size is used, please indicate these sizes as well.

32 **Strand Insulation**–Wire insulation type. Examples are: glass, film, mica, glass over film, and bare.

33 **Coil Weight**–The weight of the one coil, preferably with the insulation removed.

34 **Groups of Coils**–Number of coil groups and the number of coils in each group.

35 **Iron Skewed?**–If the stator slots are skewed, measure the offset in inches.

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POLYPHASE AC WINDING

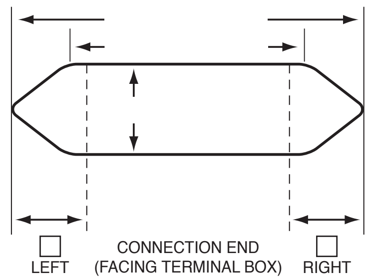
DATE ________________

HP/KW RPM POLES MANUFACTURER

SLOTS		TYPE				VOLTS	
COILS		MODEL				AMPS	
GROUPING	______ OF ______	SERIAL #				PHASE	
	______ OF ______	LEAD MARKINGS				HERTZ	
TURNS/COIL		LEAD LENGTH		°C RISE		FRAME	
WIRE SIZE		LEAD SIZE		DUTY		°C AMB.	
WIRES IN MULT.		# OF LEADS		EFF.		INS. CLS.	
PITCH: 1 TO		☐ DP ☐ TEFC		☐ XPRF ☐ TENV		S. F.	

CONNECTION		
JUMPER		
CORE LENGTH		
CORE I.D.		
BACK IRON		
SLOT DEPTH*		
SLOT/TOOTH WIDTH		
TOTAL WIRE WEIGHT		
VENTS	#	SIZE
ROTOR BARS		

COIL



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CUSTOMER		JOB #	

* Under wedge.

Version 1215

SINGLE PHASE

{ SPLIT PHASE ❒
CAPACITOR: ❒ START ❒ START & RUN ❒ PERM. SPLIT

HP RPM MANUFACTURER

	RUN	START						
			TYPE			VOLTS		
NO. SLOTS			MODEL			AMPS		
NO. POLES			STYLE			HERTZ		
COILS/POLE			FORM			FRAME		
DWG. NO.								
WIRE SIZE			°C RISE		HRS.		CAP. MFD.	
WIRES IN PAR.			SERIAL					
NO. CIRCUITS			DUTY: APPL. - FAN - UTIL. - STD.				BB SB	
COIL EXT.			OPEN - D.P. - XPRF - TENV - TEFC					
STATOR BORE			STA. LENGTH		STA. B.I.			

RUNNING																		
SLOT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
STARTING																		

CUSTOMER

(Please return a copy to EASA Headquarters, 1331 Baur Blvd., St. Louis, MO 63132)

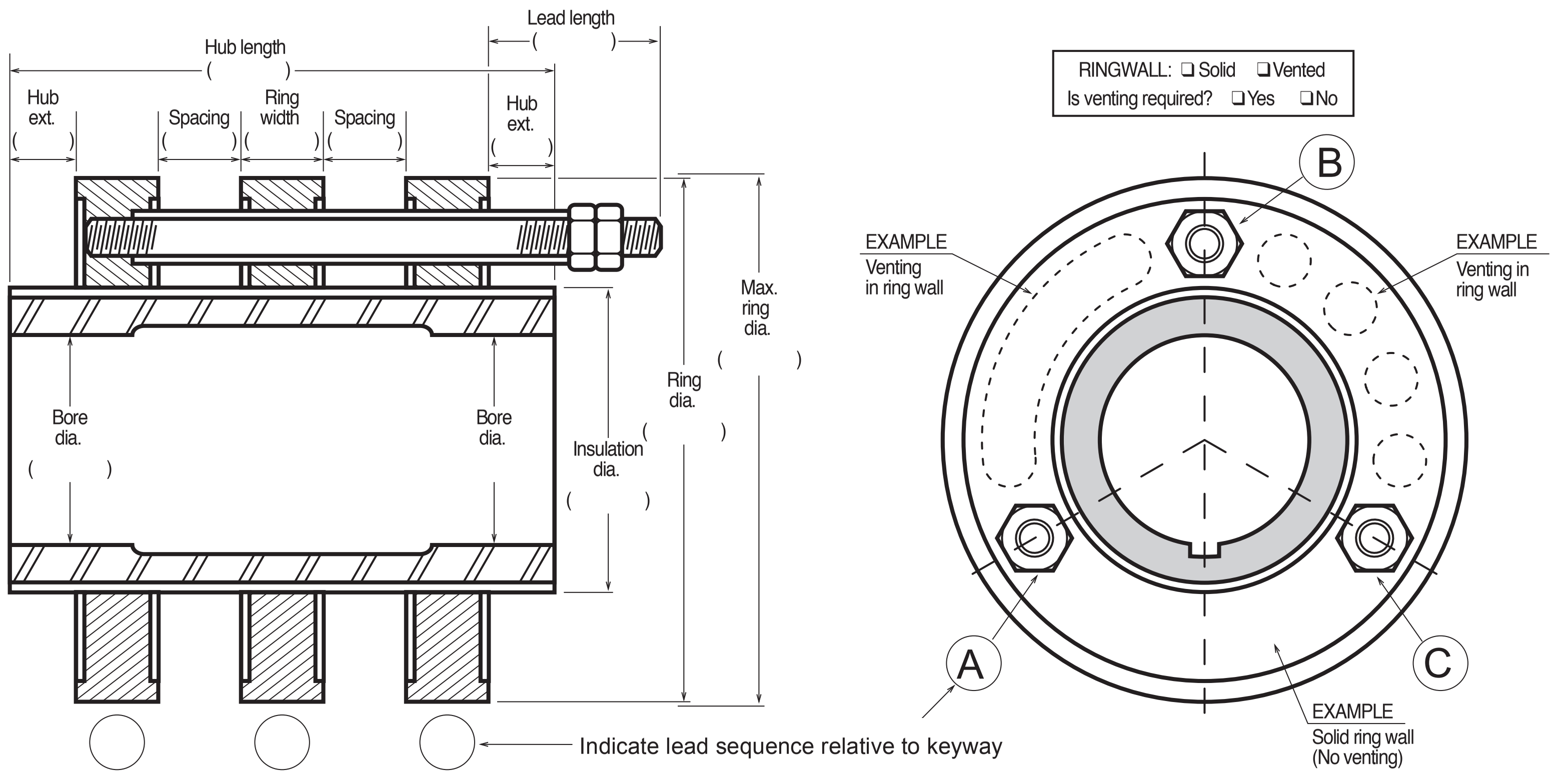
Note: PDF copies of EASA's Polyphase AC Winding form and Single Phase Winding form may be downloaded from the Resources section of the EASA website (www.easa.com).

2.15 SLIP RING DATA

Electrical Apparatus Service Association

EASA The Electro•Mechanical Authority

SLIP RING DATA



Original Mfr. ______ Frame No. ______ Type ______ Model No. ______

HP ______ KW ______ RPM ______ Secondary volts ______ Secondary amps ______

No. of rings ______ Ring material: ❑ Bronze ❑ Steel ❑ Copper ❑ Other ______ Ring-to-Ring Space is: ❑ Insulated ❑ Air gap

Type of leads: ❑ Strap ❑ Rod ❑ Other ______ Size of leads ______ Leads per ring ______

Hub material: ❑ Steel ❑ Molded *If Molded – Micrometer measurement of shaft diameter corresponding to the hub bore diameter is required.*

Shaft diameter ______ Keyway size ______

Job No. ______ Notes: ______

2.16 NAMEPLATES FOR AC MACHINES

SAMPLE NAMEPLATES

EASA® The Electro•Mechanical Authority

AC SQUIRREL CAGE MACHINE

☐ MOTOR ☐ GENERATOR JOB #______________

MFR.	ENCL.		DUTY	TYPE/CATALOG NO.		
FR.	INS.	HZ	°C AMB	MODEL/STYLE/SPEC.		
SER. NO./ID	DES.	PH.	SF	VOLTS		
☐ HP ☐ KW	RPM		FLA		CODE	
DE BRG.			ODE BRG.			

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AC WOUND ROTOR MACHINE

☐ MOTOR ☐ GENERATOR JOB #______________

MFR.	ENCL.		DUTY	TYPE/CATALOG NO.		
FR.	INS.	HZ	°C AMB	MODEL/STYLE/SPEC.		
SER. NO./ID		PH.	SF			
☐ HP ☐ KW	RPM	STATOR VOLTS	STATOR AMPS	ROTOR VOLTS	ROTOR AMPS	
DE BRG.			ODE BRG.			

2.17 AC THREE-PHASE MOTOR SERVICE ORDER

AC 3-PHASE MOTOR SERVICE ORDER Company ____________ JOB # ________

SOLD TO	SHIP TO	CUSTOMER P.O.#
		TEL#
		FAX#
CONTACT	MARKS	QUOTED ☐ YES ☐ NO
DATE RECEIVED	DATE REQUIRED	AUTHORIZED BY

NAMEPLATE DATA

MFR.	HZ CODE OR L.R. AMPS	ENCLOSURE
FRAME	EFF DESIGN	INSULATION CLASS
HP/KW	MODEL / STYLE / SPEC	TEMPERATURE RISE °C
RPM	TYPE / CATALOG NO.	AMBIENT °C
VOLTS	SERIAL NO. / I.D.	DUTY
AMPS	DATE CODE	SERVICE FACTOR
ROTOR: ☐ SQUIRREL CAGE ☐ WOUND	SECONDARY VOLTS	SEC. AMPS

REASON FOR SERVICE
CAUSE OF FAILURE

ACTIVITY CHECK LIST - STATUS INDICATOR

STATOR

ACTIVITY	DATE COMPLETE	SIGNATURE	ACTIVITY	DATE COMPLETE	SIGNATURE
INCOMING TESTS			RESTORE WORN FITS		
MECHANICAL INSPECTION			WIND STATOR		
RECORD WINDING DATA			CONNECT LEADS		
STATOR CORE TEST #1			TEST WINDING		
STRIP WINDING			DIP / VPI / BAKE		
STATOR CORE TEST #2			FINAL TESTS		
CLEAN MECHANICAL PARTS			PAINT		

ROTOR

ACTIVITY	DATE COMPLETE	SIGNATURE	ACTIVITY	DATE COMPLETE	SIGNATURE
INCOMING TESTS			CONNECT LEADS		
MECHANICAL INSPECTION			TEST WINDING		
RECORD WINDING DATA			DIP / VPI / BAKE		
STRIP WINDING			BALANCE ROTOR		
CLEAN MECHANICAL PARTS			INSTALL BEARINGS		
RESTORE WORN FITS			FINAL TESTS		
WIND ROTOR					

(Sample)

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AC THREE-PHASE MOTOR SERVICE ORDER—Continued

AC 3-PHASE MOTOR SERVICE ORDER Company ____________ JOB # ________

INCOMING INSPECTION AND TESTS

INSPECTION

ITEM	OK	D	M	ITEM	OK	D	M
FRAME				NAMEPLATE			
ENDBRACKET DRIVE END				HEATERS			
ENDBRACKET OPPOSITE DRIVE END				STATOR CORE			
CONNECTION BOX				ROTOR			
CONNECTION BOX COVER				SLIP RINGS			
COUPLING / PULLEY / GEAR				BRUSH RIGGING			
SHAFT				BRUSH HOLDERS			
FAN / BLOWER				BRUSHES			
FAN COVER / HOOD				OTHER (SPECIFY)			
COVERS							
LEADS							
EYEBOLTS							

LEGEND: OK - GOOD CONDITION ; D - DAMAGED; M - MISSING (INDICATE QUANTITY IF MORE THAN ONE)

WINDING TESTS

TYPE OF TEST	STATOR					WOUND ROTOR				
	AMBIENT ☐ °F ☐ °C			OK	NOT OK	AMBIENT ☐ °F ☐ °C			OK	NOT OK
WINDING RESIS. Ω	ϕ1-2	ϕ2-3	ϕ1-3			ϕ1-2	ϕ2-3	ϕ1-3		
INSUL. RESISTANCE	MΩ at VDC					MΩ at VDC				
SURGE TEST	VAC					VAC				
HIGH-POT TEST	VOLTS ☐ VAC ☐ VDC MINUTE(S) µA					VOLTS ☐ VAC ☐ VDC MINUTE(S) µA				

ROTOR — SINGLE-PHASE TEST

VOLTS	AMPS	REPAIR REQUIRED ☐ YES ☐ NO

NO-LOAD RUN TEST

APPLICABLE ☐ YES ☐ NO		HORIZONTAL	VERTICAL	AXIAL	BALANCE REQUIRED	WINDING REQUIRED
VIBRATION READINGS	DRIVE END				YES ☐ NO ☐	STATOR YES ☐ NO ☐
	OPP. DRIVE END					ROTOR YES ☐ NO ☐
VOLTS	AMPS	ϕ1	ϕ2	ϕ3	SHAFT END PLAY	
NOTES						
SIGNED				DATE		

(Sample)

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AC THREE-PHASE MOTOR SERVICE ORDER—Continued

AC 3-PHASE MOTOR SERVICE ORDER Company ____________ JOB # ________

MECHANICAL INSPECTION BEFORE REPAIR

ITEM	DRIVE END	OPP. DRIVE END	ITEM	DRIVE END	OPP. DRIVE END
BEARING MANUFACTURER			SLEEVE BRG. DIAMETRAL CLRNC.		
BEARING TYPE			SHAFT EXTENSION T.I.R.		
BEARING NUMBER			SHAFT EXTENSION DIAMETER		
BRG. JOURNAL DIAMETER			SHAFT KEYSEAT WIDTH		
BRG. HOUSING BORE DIAMETER			COUPLING BORE DIAMETER		
BRG. CONDITION AS FOUND			COUPLING KEYSEAT WIDTH		
OTHER					

ARRANGEMENT SKETCH DRIVE END	ARRANGEMENT SKETCH OPPOSITE DRIVE END
INSPECTED BY	DATE

STATOR CORE TEST

EVALUATED BY	DATE	☐ ACCEPTED	☐ REJECTED

WORK REQUIRED

MECHANICAL	ELECTRICAL

MECHANICAL INSPECTION AFTER REPAIR

ITEM	DRIVE END	OPP. DRIVE END	ITEM	DRIVE END	OPP. DRIVE END
ROTOR T.I.R.			SLEEVE BRG. DIAMETRAL CLRNC.		
ROTOR BALANCED TO			SHAFT EXTENSION T.I.R.		
BRG. JOURNAL DIAMETER			SHAFT EXTENSION DIAMETER		
BRG. HOUSING BORE DIAMETER			SHAFT KEYSEAT WIDTH		
OTHER			COUPLING BORE DIAMETER		
			COUPLING KEYSEAT WIDTH		

INSPECTED BY	DATE

(Sample)

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AC THREE-PHASE MOTOR SERVICE ORDER—Continued

AC 3-PHASE MOTOR SERVICE ORDER Company ____________ JOB # ________

WINDING TESTS AFTER REWIND BUT PRIOR TO TREATMENT

TYPE OF TEST	STATOR			WOUND ROTOR		
INSUL. RESISTANCE	MΩ at VDC			MΩ at VDC		
WINDING RESIS. Ω	φ1-2	φ2-3	φ1-3	φ1-2	φ2-3	φ1-3
POLARITY TEST (OPEN STATOR/BALL TEST)	☐ OK ☐ NOT OK			☐ OK ☐ NOT OK		
SURGE TEST	VAC ☐ OK ☐ NOT OK			VAC ☐ OK ☐ NOT OK		
HIGH-POT TEST	VOLTS ☐ VAC ☐ VDC MINUTE(S) µA			VOLTS ☐ VAC ☐ VDC MINUTE(S) µA		
TESTED BY				DATE		

WINDING TESTS PRIOR TO ASSEMBLY

TYPE OF TEST	STATOR					WOUND ROTOR				
	AMBIENT ☐ °F ☐ °C			OK	NOT OK	AMBIENT ☐ °F ☐ °C			OK	NOT OK
INSUL. RESISTANCE	MΩ at VDC					MΩ at VDC				
WINDING RESIS. Ω	φ1-2	φ2-3	φ1-3			φ1-2	φ2-3	φ1-3		
SURGE TEST	VAC					VAC				
POLARIZATION INDEX	AT VOLTS DC					AT VOLTS DC				
HIGH-POT TEST	VOLTS ☐ VAC ☐ VDC MINUTE(S) µA					VOLTS ☐ VAC ☐ VDC MINUTE(S) µA				
TESTED BY						DATE				

NO-LOAD RUN TEST

APPLICABLE ☐ YES ☐ NO		HORIZONTAL	VERTICAL	AXIAL	BEARING TEMPERATURE
VIBRATION READINGS	DRIVE END				
	OPP. DRIVE END				
VOLTS	AMPS	φ1	φ2	φ3	INPUT WATTS
RPM	TEST RUN TIME			SHAFT END PLAY	
MEASURED SECONDARY VOLTAGE	φ1-2		φ2-3		φ1-3
TESTED BY			DATE		

SHIPPING DETAILS

DATE SHIPPED	CARRIER	
SHAFT BLOCKED ☐ YES ☐ NO	SKID MOUNTED ☐ YES ☐ NO	WEATHER PROTECTED ☐ YES ☐ NO
SIGNED	DATE	

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(Sample)

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2.18 REFERENCED STANDARDS

The following standards are referenced in this section of the *EASA Technical Manual*. In cases where there is a later edition than is cited in the text, both editions are listed below.

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IEC 61972:2002: *Method for determining losses and efficiency of three-phase cage induction motors*, ed. 1.0. International Electrotechnical Commission. Geneva, Switzerland, 2002.

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IEEE Std. 112-2017: *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2017.

IEEE Std. 117-2015: *Standard Test Procedure for Thermal Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery* (revision of IEEE Std. 117-1974 and ANSI C50.32-1976). Institute of Electrical and Electronics Engineers, Inc. New York NY, 2016

IEEE Std. 275-1992: *IEEE Recommended Practice for Thermal Evaluation of Insulation Systems for Alternating-Current Electric Machinery Employing Form-Wound Preinsulated Stator Coils for Machines Rated 6900 V and Below*. Institute of Electrical and Electronics Engineers, Inc. New York NY, 1992.

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