3

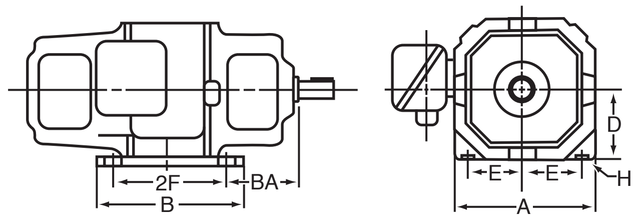
DC Machines

Section Outline Page

Section Outline Page

3.1 DIMENSIONS FOR DC MACHINES—INCHES

NEMA FRAME DIMENSIONS—FOOT-MOUNTED DC MACHINES



DIMENSIONS IN INCHES

FRAME	A MAX	B MAX	D	E	2F	BA	H†
42			2.62	1.75	1.69	2.06	0.28
48			3.00	2.12	2.75	2.50	0.34
56			3.50	2.44	3.00	2.75	0.34
56H			3.50	2.44	5.00	2.75	0.34
142AT	7.00	6.75	3.50	2.75	3.50	2.75	0.34
143AT	7.00	7.25	3.50	2.75	4.00	2.75	0.34
144AT	7.00	7.75	3.50	2.75	4.50	2.75	0.34
145AT	7.00	8.25	3.50	2.75	5.00	2.75	0.34
146AT	7.00	8.75	3.50	2.75	5.50	2.75	0.34
147AT	7.00	9.50	3.50	2.75	6.25	2.75	0.34
148AT	7.00	10.25	3.50	2.75	7.00	2.75	0.34
149AT	7.00	11.25	3.50	2.75	8.00	2.75	0.34
1410AT	7.00	12.25	3.50	2.75	9.00	2.75	0.34
1411AT	7.00	13.25	3.50	2.75	10.00	2.75	0.34
1412AT	7.00	14.25	3.50	2.75	11.00	2.75	0.34
162AT	8.00	6.00	4.00	3.12	4.00	2.50	0.41
163AT	8.00	6.50	4.00	3.12	4.50	2.50	0.41
164AT	8.00	7.00	4.00	3.12	5.00	2.50	0.41
165AT	8.00	7.50	4.00	3.12	5.50	2.50	0.41
166AT	8.00	8.20	4.00	3.12	6.25	2.50	0.41
167AT	8.00	9.00	4.00	3.12	7.00	2.50	0.41
168AT	8.00	10.00	4.00	3.12	8.00	2.50	0.41
169AT	8.00	11.00	4.00	3.12	9.00	2.50	0.41
1610AT	8.00	12.00	4.00	3.12	10.00	2.50	0.41
182AT	9.00	6.50	4.50	3.75	4.50	2.75	0.41
183AT	9.00	7.00	4.50	3.75	5.00	2.75	0.41
184AT	9.00	7.50	4.50	3.75	5.50	2.75	0.41
185AT	9.00	8.25	4.50	3.75	6.25	2.75	0.41
186AT	9.00	9.00	4.50	3.75	7.00	2.75	0.41
187AT	9.00	10.00	4.50	3.75	8.00	2.75	0.41
188AT	9.00	11.00	4.50	3.75	9.00	2.75	0.41
189AT	9.00	12.00	4.50	3.75	10.00	2.75	0.41
1810AT	9.00	13.00	4.50	3.75	11.00	2.75	0.41
213AT	10.50	7.50	5.25	4.25	5.50	3.50	0.41
214AT	10.50	8.25	5.25	4.25	6.25	3.50	0.41
215AT	10.50	9.00	5.25	4.25	7.00	3.50	0.41
216AT	10.50	10.00	5.25	4.25	8.00	3.50	0.41
217AT	10.50	11.00	5.25	4.25	9.00	3.50	0.41
218AT	10.50	12.00	5.25	4.25	10.00	3.50	0.41
219AT	10.50	13.00	5.25	4.25	11.00	3.50	0.41
2110AT	10.50	14.50	5.25	4.25	12.50	3.50	0.41
253AT	12.50	9.50	6.25	5.00	7.00	4.25	0.53
254AT	12.50	10.75	6.25	5.00	8.25	4.25	0.53
255AT	12.50	11.50	6.25	5.00	9.00	4.25	0.53
256AT	12.50	12.50	6.25	5.00	10.00	4.25	0.53
257AT	12.50	13.50	6.25	5.00	11.00	4.25	0.53
258AT	12.50	15.00	6.25	5.00	12.50	4.25	0.53
259AT	12.50	16.50	6.25	5.00	14.00	4.25	0.53

NEMA FRAME DIMENSIONS—FOOT-MOUNTED DC MACHINES—CONTINUED

DIMENSIONS IN INCHES

FRAME	A MAX	B MAX	D	E	2F	BA	H†
283AT	14.00	11.00	7.00	5.50	8.00	4.75	0.53
284AT	14.00	12.50	7.00	5.50	9.50	4.75	0.53
285AT	14.00	13.00	7.00	5.50	10.00	4.75	0.53
286AT	14.00	14.00	7.00	5.50	11.00	4.75	0.53
287AT	14.00	15.50	7.00	5.50	12.50	4.75	0.53
288AT	14.00	17.00	7.00	5.50	14.00	4.75	0.53
289AT	14.00	19.00	7.00	5.50	16.00	4.75	0.53
323AT	16.00	12.50	8.00	6.25	9.00	5.25	0.66
324AT	16.00	14.00	8.00	6.25	10.50	5.25	0.66
325AT	16.00	14.50	8.00	6.25	11.00	5.25	0.66
326AT	16.00	15.50	8.00	6.25	12.00	5.25	0.66
327AT	16.00	17.50	8.00	6.25	14.00	5.25	0.66
328AT	16.00	19.50	8.00	6.25	16.00	5.25	0.66
329AT	16.00	21.50	8.00	6.25	18.00	5.25	0.66
363AT	18.00	14.00	9.00	7.00	10.00	5.88	0.81
364AT	18.00	15.25	9.00	7.00	11.25	5.88	0.81
365AT	18.00	16.25	9.00	7.00	12.25	5.88	0.81
366AT	18.00	18.00	9.00	7.00	14.00	5.88	0.81
367AT	18.00	20.00	9.00	7.00	16.00	5.88	0.81
368AT	18.00	22.00	9.00	7.00	18.00	5.88	0.81
369AT	18.00	24.00	9.00	7.00	20.00	5.88	0.81
403AT	20.00	15.00	10.00	8.00	11.00	6.62	0.94
404AT	20.00	16.25	10.00	8.00	12.25	6.62	0.94
405AT	20.00	17.75	10.00	8.00	13.75	6.62	0.94
406AT	20.00	20.00	10.00	8.00	16.00	6.62	0.94
407AT	20.00	22.00	10.00	8.00	18.00	6.62	0.94
408AT	20.00	24.00	10.00	8.00	20.00	6.62	0.94
409AT	20.00	26.00	10.00	8.00	22.00	6.62	0.94
443AT	22.00	16.50	11.00	9.00	12.50	7.50	1.06
444AT	22.00	18.50	11.00	9.00	15.00	7.50	1.06
445AT	22.00	20.50	11.00	9.00	16.50	7.50	1.06
446AT	22.00	22.00	11.00	9.00	18.00	7.50	1.06
447AT	22.00	24.00	11.00	9.00	20.00	7.50	1.06
448AT	22.00	26.00	11.00	9.00	22.00	7.50	1.06
449AT	22.00	29.00	11.00	9.00	25.00	7.50	1.06
502AT	25.00	17.50	12.50	10.00	12.50	8.50	1.19
503AT	25.00	19.00	12.50	10.00	14.00	8.50	1.19
504AT	25.00	21.00	12.50	10.00	16.00	8.50	1.19
505AT	25.00	23.00	12.50	10.00	18.00	8.50	1.19
506AT	25.00	25.00	12.50	10.00	20.00	8.50	1.19
507AT	25.00	27.00	12.50	10.00	22.00	8.50	1.19
508AT	25.00	30.00	12.50	10.00	25.00	8.50	1.19
509AT	25.00	33.00	12.50	10.00	28.00	8.50	1.19
583A	29.00	21.00	14.50	11.50	16.00	10.00	1.19
584A	29.00	23.00	14.50	11.50	18.00	10.00	1.19
585A	29.00	25.00	14.50	11.50	20.00	10.00	1.19
586A	29.00	27.00	14.50	11.50	22.00	10.00	1.19
587A	29.00	30.00	14.50	11.50	25.00	10.00	1.19
588A	29.00	33.00	14.50	11.50	28.00	10.00	1.19
683A	34.00	25.00	17.00	13.50	20.00	11.50	1.19
684A	34.00	27.00	17.00	13.50	22.00	11.50	1.19
685A	34.00	30.00	17.00	13.50	25.00	11.50	1.19
686A	34.00	33.00	17.00	13.50	28.00	11.50	1.19
687A	34.00	37.00	17.00	13.50	32.00	11.50	1.19
688A	34.00	41.00	17.00	13.50	36.00	11.50	1.19

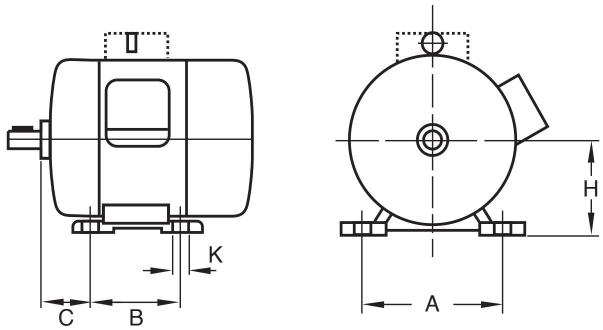
References and tolerances on dimensions: NEMA Stds. MG 1, 4.5.1, 4.5.2 and 4.5.3.

† Frames 42 to 56H, inclusive: the H dimension is Width of Slot.

† Frames 142AT to 688A, inclusive: the H dimension is Diameter of Hole.

IEC MOUNTING DIMENSIONS—FOOT-MOUNTED DC AND AC MACHINES

DIMENSIONS IN INCHES

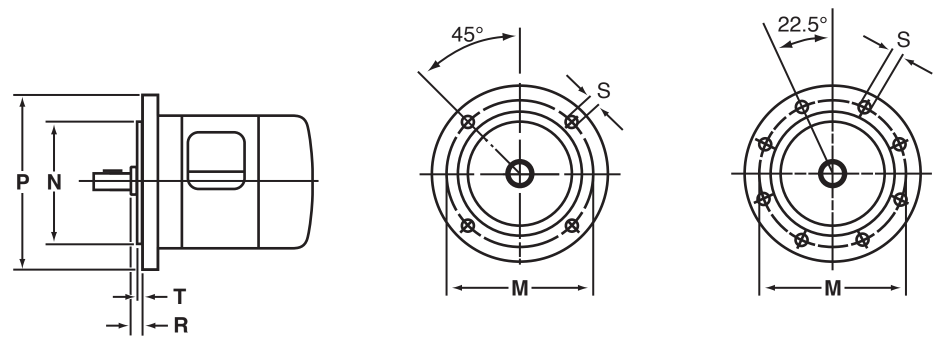


Frame number	H	A	B	C	K	Bolt or screw
56M	2.20	3.55	2.80	1.40	0.23	M5
63M	2.48	3.95	3.15	1.55	0.28	M6
71M	2.79	4.40	3.55	1.75	0.28	M6
80M	3.14	4.90	3.95	1.95	0.40	M8
90S	3.54	5.50	3.95	2.20	0.40	M8
90L	3.54	5.50	4.90	2.20	0.40	M8
100S	3.93	6.30	4.40	2.50	0.48	M10
100L	3.93	6.30	5.50	2.50	0.48	M10
112S	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 DC AND AC 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

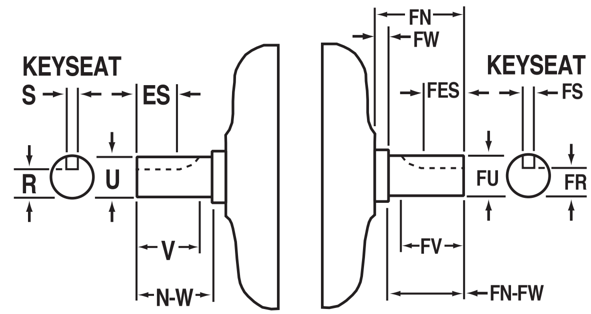
FF flange—Flange with free holes (clearance holes).

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.)

NEMA SHAFT EXTENSION AND KEYSEAT DIMENSIONS—FOOT-MOUNTED DC MACHINES



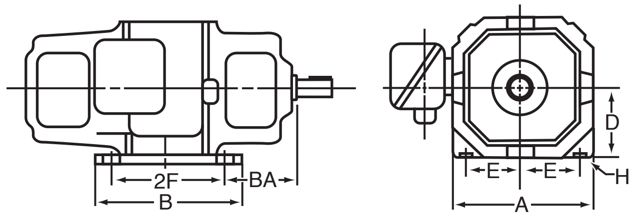
DIMENSIONS IN INCHES

	DRIVE END—BELT DRIVE						DRIVE END—DIRECT-CONNECTED DRIVE						END OPPOSITE DRIVE—STRAIGHT					
	SHAFT EXTENSION			KEYSEAT			SHAFT EXTENSION			KEYSEAT			SHAFT EXTENSION			KEYSEAT		
FRAME DESIGNATIONS	U	N-W	V MIN	R	ES MIN	S	U	N-W	V MIN	R	ES MIN	S	FU	FN-FW	FV MIN	FR	FES MIN	FS
42	0.375	1.12		0.328		Flat	0.375	1.12		0.328		Flat						
48	0.500	1.50		0.453		Flat	0.500	1.50		0.453		Flat						
56	0.625	1.88		0.517	1.41	0.188	0.625	1.88		0.517	1.41	0.188						
56H	0.625	1.88		0.517	1.41	0.188	0.625	1.88		0.517	1.41	0.188						
142AT-1412AT	0.875	2.25	2.00	0.771	0.91	0.188							0.625	1.25	1.00	0.517	0.66	0.188
162AT-1610AT	0.8750	1.75	1.50	0.771	0.91	0.188							0.625	1.25	1.00	0.517	0.66	0.188
182AT-1810AT	1.125	2.25	2.00	0.986	1.41	0.250							0.875	1.75	1.50	0.771	0.91	0.188
213AT-2110AT	1.375	2.75	2.50	1.201	1.78	0.312							1.125	2.25	2.00	0.986	1.41	0.250
253AT-259AT	1.625	3.25	3.00	1.416	2.28	0.375							1.375	2.75	2.50	1.201	1.78	0.312
283AT-289AT	1.875	3.75	3.50	1.591	2.53	0.500							1.625	3.25	3.00	1.416	2.28	0.375
323AT-329AT	2.125	4.25	4.00	1.845	3.03	0.500							1.875	3.75	3.50	1.591	2.53	0.500
363AT-369AT	2.375	4.75	4.50	2.021	3.53	0.625							2.125	4.25	4.00	1.845	3.03	0.500
403AT-409AT	2.625	5.25	5.00	2.275	4.03	0.625							2.375	4.75	4.50	2.210	3.53	0.625
443AT-449AT	2.875	5.75	5.50	2.450	4.53	0.750							2.625	5.25	5.00	2.275	4.03	0.625
502AT-509AT	3.25	6.50	6.25	2.831	5.28	0.750							2.875	5.75	5.50	2.450	4.53	0.750
583A-588A	3.25	9.75	9.50	2.831	8.28	0.750	2.875	5.75	5.50	2.450	4.28		0.750					
683A-688A	3.625	10.88	10.62	3.134	9.53	0.875	3.250	6.50	6.25	2.831	5.03		0.750					

Reference: NEMA Stds. MG 1, 4.5.1, 4.5.2 and 4.5.3.
For tolerances on dimensions, see NEMA Stds. MG 1, 4.9.

3.2 DIMENSIONS FOR DC MACHINES—MILLIMETERS

NEMA FRAME DIMENSIONS—FOOT-MOUNTED DC MACHINES



DIMENSIONS IN MILLIMETERS

FRAME	A MAX	B MAX	D	E	2F	BA	H†
42			66	44.5	43	52	8
48			76	54.0	70	64	9
56			88	62.0	76	70	9
56H			88	62.0	127	70	9
142AT	177	171	88.5	70.0	90	70	9
143AT	177	184	88.5	70.0	102	70	9
144AT	177	196	88.5	70.0	114	70	9
145AT	177	209	88.5	70.0	127	70	9
146AT	177	222	88.5	70.0	140	70	9
147AT	177	241	88.5	70.0	159	70	9
148AT	177	260	88.5	70.0	178	70	9
149AT	177	285	88.5	70.0	203	70	9
1410AT	177	311	88.5	70.0	222	70	9
1411AT	177	336	88.5	70.0	254	70	9
1412AT	177	361	88.5	70.0	279	70	9
162AT	203	152	101.5	79.0	102	64	11
163AT	203	165	101.5	79.0	114	64	11
164AT	203	177	101.5	79.0	127	64	11
165AT	203	190	101.5	79.0	140	64	11
166AT	203	208	101.5	79.0	159	64	11
167AT	203	228	101.5	79.0	178	64	11
168AT	203	254	101.5	79.0	203	64	11
169AT	203	279	101.5	79.0	229	64	11
1610AT	203	304	101.5	79.0	254	64	11
182AT	228	165	114.0	95.5	114	70	11
183AT	228	177	114.0	95.5	127	70	11
184AT	228	190	114.0	95.5	140	70	11
185AT	228	209	114.0	95.5	159	70	11
186AT	228	228	114.0	95.5	178	70	11
187AT	228	254	114.0	95.5	203	70	11
188AT	228	279	114.0	95.5	229	70	11
189AT	228	304	114.0	95.5	254	70	11
1810AT	228	330	114.0	95.5	279	70	11
213AT	266	190	133.0	108.0	140	89	11
214AT	266	209	133.0	108.0	159	89	11
215AT	266	228	133.0	108.0	178	89	11
216AT	266	254	133.0	108.0	203	89	11
217AT	266	279	133.0	108.0	229	89	11
218AT	266	304	133.0	108.0	254	89	11
219AT	266	330	133.0	108.0	279	89	11
2110AT	266	368	133.0	108.0	318	89	11
253AT	317	241	158.5	127.0	178	108	14
254AT	317	273	158.5	127.0	210	108	14
255AT	317	292	158.5	127.0	229	108	14
256AT	317	317	158.5	127.0	254	108	14
257AT	317	342	158.5	127.0	279	108	14
258AT	317	381	158.5	127.0	318	108	14
259AT	317	419	158.5	127.0	356	108	14

NEMA FRAME DIMENSIONS—FOOT-MOUNTED DC MACHINES—CONTINUED

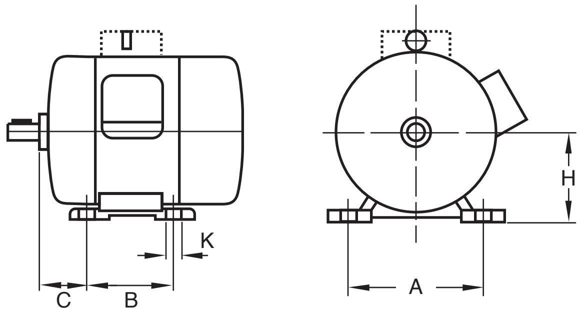
DIMENSIONS IN MILLIMETERS

FRAME	A MAX	B MAX	D	E	2F	BA	H†
283AT	355	279	177.5	139.5	203	121	14
284AT	355	317	177.5	139.5	241	121	14
285AT	355	330	177.5	139.5	254	121	14
286AT	355	355	177.5	139.5	279	121	14
287AT	355	393	177.5	139.5	318	121	14
288AT	355	431	177.5	139.5	356	121	14
289AT	355	482	177.5	139.5	406	121	14
323AT	406	317	203.0	159.0	229	133	17
324AT	406	355	203.0	159.0	267	133	17
325AT	406	368	203.0	159.0	279	133	17
326AT	406	393	203.0	159.0	305	133	17
327AT	406	444	203.0	159.0	356	133	17
328AT	406	495	203.0	159.0	406	133	17
329AT	406	546	203.0	159.0	457	133	17
363AT	457	355	228	178.0	254	149	21
364AT	457	387	228	178.0	286	149	21
365AT	457	412	228	178.0	311	149	21
366AT	457	457	228	178.0	356	149	21
367AT	457	508	228	178.0	406	149	21
368AT	457	558	228	178.0	457	149	21
369AT	457	609	228	178.0	508	149	21
403AT	508	381	254	203.0	279	168	24
404AT	508	412	254	203.0	311	168	24
405AT	508	450	254	203.0	349	168	24
406AT	508	508	254	203.0	406	168	24
407AT	508	558	254	203.0	457	168	24
408AT	508	609	254	203.0	508	168	24
409AT	508	660	254	203.0	559	168	24
443AT	558	419	279	228.5	318	191	27
444AT	558	469	279	228.5	381	191	27
445AT	558	520	279	228.5	419	191	27
446AT	558	558	279	228.5	457	191	27
447AT	558	609	279	228.5	508	191	27
448AT	558	660	279	228.5	559	191	27
449AT	558	736	279	228.5	635	191	27
502AT	635	444	317	254.0	318	216	31
503AT	635	482	317	254.0	356	216	31
504AT	635	533	317	254.0	406	216	31
505AT	635	584	317	254.0	457	216	31
506AT	635	635	317	254.0	508	216	31
507AT	635	685	317	254.0	559	216	31
508AT	635	762	317	254.0	635	216	31
509AT	635	838	317	254.0	711	216	31
583A	736	533	368	292.0	406	254	31
584A	736	584	368	292.0	457	254	31
585A	736	635	368	292.0	508	254	31
586A	736	685	368	292.0	559	254	31
587A	736	762	368	292.0	635	254	31
588A	736	838	368	292.0	711	254	31
683A	863	635	431	343.0	508	292	31
684A	863	685	431	343.0	559	292	31
685A	863	762	431	343.0	635	292	31
686A	863	838	431	343.0	711	292	31
687A	863	939	431	343.0	813	292	31
688A	863	1041	431	343.0	914	292	31

† Frames 42 to 56H, inclusive; the H dimension is Width of Slot.
† Frames 142AT to 688A, inclusive; the H dimension is Diameter of Hole.
References and tolerances on dimensions: NEMA MG 1, 4.5.1, 4.5.2 and 4.5.3.
(Note: Data in NEMA tables is shown in inches.) All dimensions are rounded off.

IEC MOUNTING DIMENSIONS—FOOT-MOUNTED DC AND AC MACHINES

DIMENSIONS IN MILLIMETERS

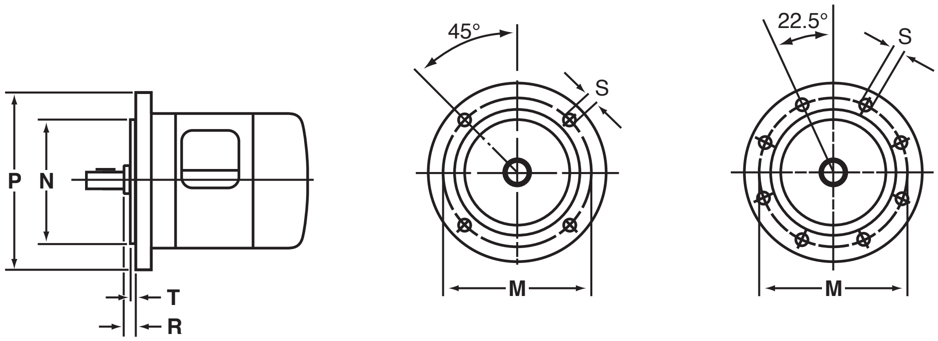


Frame number	H	A	B	C	K	Bolt or screw
56M	56	90	71	36	5.8	M5
63M	63	100	80	40	7	M6
71M	71	112	90	45	7	M6
80M	80	125	100	50	10	M8
90S	90	140	100	56	10	M8
90L	90	140	125	56	10	M8
100S	100	160	112	63	12	M10
100L	100	160	140	63	12	M10
112S	112	190	114	70	12	M10
112M	112	190	140	70	12	M10
132S	132	216	140	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 DC AND AC 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

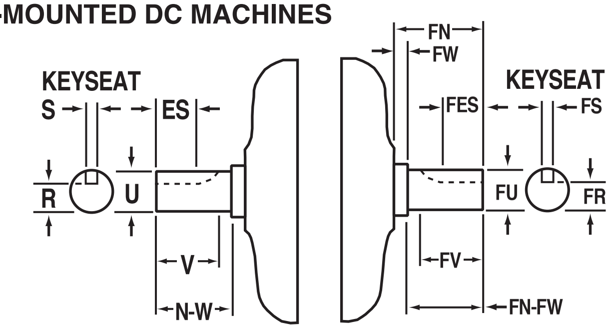
FF flange—Flange with free holes (clearance holes).

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.

NEMA SHAFT EXTENSION AND KEYSEAT DIMENSIONS—FOOT-MOUNTED DC MACHINES



DIMENSIONS IN MILLIMETERS

FRAME DESIGNATIONS	DRIVE END—BELT DRIVE						DRIVE END—DIRECT-CONNECTED DRIVE						END OPPOSITE DRIVE—STRAIGHT					
	SHAFT EXTENSION			KEYSEAT			SHAFT EXTENSION			KEYSEAT			SHAFT EXTENSION			KEYSEAT		
	U	N-W	V MIN	R	ES MIN	S	U	N-W	V MIN	R	ES MIN	S	FU	FN-FW	FV MIN	FR	FES MIN	FS
42	9.52	28		8.3		Flat	9.52	28		8.3		Flat						
48	12.70	38		11.5		Flat	12.70	38		11.5		Flat						
56	15.87	48		13.1	36	4.80	15.87	48		13.1	36	4.80						
56H	15.87	48		13.1	36	4.80	15.87	48		13.1	36	4.80						
142AT-1412AT	22.22	57	51	19.5	24	4.80							15.87	32	26	13.1	17	4.80
162AT-1610AT	22.22	44	39	19.5	24	4.80							15.87	32	26	13.1	17	4.80
182AT-1810AT	28.57	57	51	25.0	36	6.35							22.22	44	39	19.5	24	4.80
213AT-2110AT	34.92	70	64	30.5	46	7.95							28.57	57	51	25.0	36	6.35
253AT-259AT	41.27	83	77	35.9	58	9.55							34.92	70	64	30.5	46	7.95
283AT-289AT	47.62	95	89	40.4	65	12.70							41.27	83	77	35.9	58	9.55
323AT-329AT	53.97	108	102	46.8	77	12.70							47.62	95	89	40.4	65	12.70
363AT-369AT	60.32	121	115	51.3	90	15.90							53.97	108	102	46.8	77	12.70
403AT-409AT	66.67	133	127	57.7	103	15.90							60.32	121	115	51.3	90	15.90
443AT-449AT	73.02	146	140	62.2	116	19.05							66.67	133	127	57.7	103	15.90
502AT-509AT	82.55	165	159	71.9	135	19.05							73.02	146	140	62.2	116	19.05
583A-588A	82.55	248	242	71.9	211	19.05	73.02	146	140	62.2	109	19.05	0.750					
683A-688A	92.07	276	270	79.6	243	22.25	82.55	165	159	71.9	128	19.05	0.750					

Reference: NEMA Stds. MG 1,, 4.5.1, 4.5.2 and 4.5.3.
All dimensions are rounded off.
For tolerances on dimensions, see NEMA Stds. MG 1,, 4.9.
(Note: Data in NEMA tables is shown in inches.)

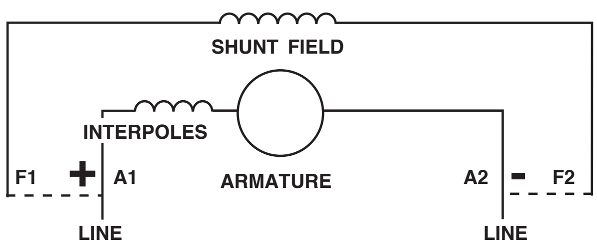
3.3 STANDARD TERMINAL MARKINGS AND CONNECTIONS

STANDARD TERMINAL MARKINGS AND CONNECTIONS (NEMA NOMENCLATURE)

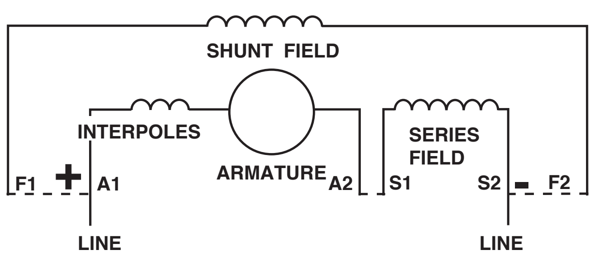
Note: Never energize the armature unless the field is energized.

DC MOTORS

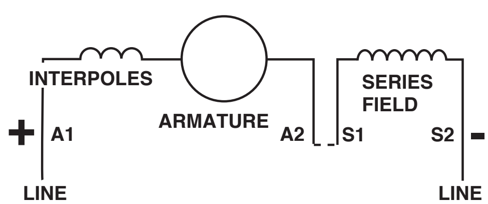
SHUNT MOTOR



COMPOUND MOTOR



SERIES MOTOR



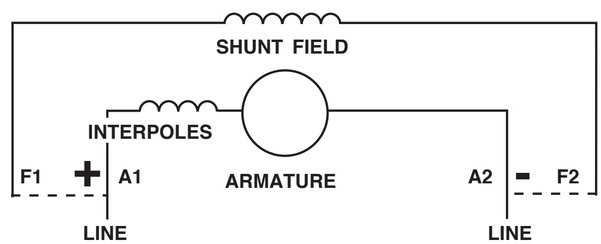
All connections are for counterclockwise rotation facing the end opposite the drive. For clockwise rotation, interchange A1 and A2.

Some manufacturers connect the interpole winding on the A2 side of the armature.

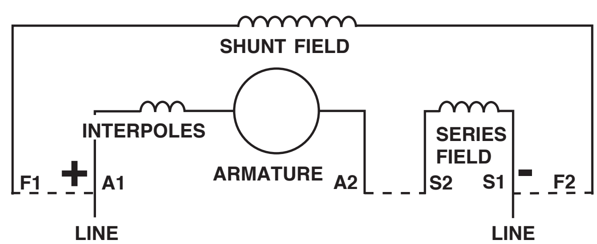
When the shunt field is separately excited, the same polarities must be observed for a given rotation.

DC GENERATORS

SHUNT GENERATOR



COMPOUND GENERATOR



All connections are for counterclockwise rotation facing the end opposite the drive. For clockwise rotation, interchange A1 and A2.

Some manufacturers connect the interpole winding on the A2 side of the armature.

For the above generators, the shunt field may be either self-excited or separately excited. When it is self-excited, connections should be made as shown by the dotted lines. When the shunt field is separately excited, it is usually isolated from the other windings of the machine, but the polarity or the voltage applied to the shunt field should be as shown for the particular rotation and armature polarity.

Reference: NEMA MG 1, 2.13 and 2.14.

STANDARD TERMINAL MARKINGS AND CONNECTIONS (IEC NOMENCLATURE)

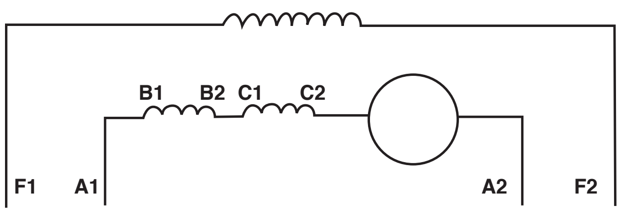
Note: Never energize the armature unless the field is energized.

DC COMMUTATOR MACHINES

A Armature winding
B Commutating winding
C Compensating winding
D Series excitation winding
E Shunt excitation winding
F Separately excited winding
H Direct-axis auxiliary winding
J Quadrature-axis auxiliary winding

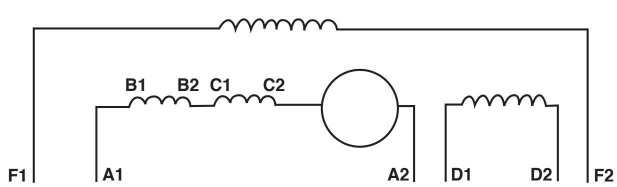
Reference: IEC Std. 60034-8, 4.2.

SHUNT MOTOR OR GENERATOR (4 TERMINALS)



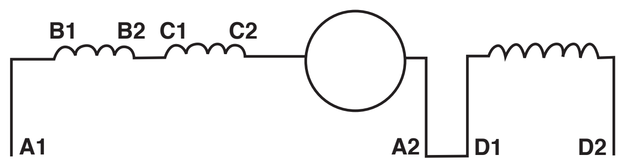
ROTATION	L+	L-
Clockwise	F1, A1	F2, A2
Counterclockwise	F1, A2	F2, A1

SHUNT MOTOR OR COMPOUND GENERATOR WITH CUMULATIVE SERIES AND COMMUTATING WINDINGS (6 TERMINALS)



ROTATION	L+	L-
Clockwise	F1, A1, D1	F2, A2, D2
Counterclockwise	F1, A2, D2	F2, A1, D1

SERIES-WOUND MOTOR (2 TERMINALS)



ROTATION	L+	L-
Clockwise	A1	A2, D2
Counterclockwise	A1	A2, D1

Reference: IEC Std. 60034-8, A.4.

3.4 FULL-LOAD CURRENT OF DC MOTORS

FULL-LOAD CURRENT OF DC MOTORS
(RUNNING AT BASE SPEED)

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

HP	RATED ARMATURE VOLTAGE					
	90V	120V	180V	240V	500V	550V
0.25	4.0	3.1	2.0	1.6	—	—
0.33	5.2	4.1	2.6	2.0	—	—
0.5	6.8	5.4	3.4	2.7	—	—
0.75	9.6	7.6	4.8	3.8	—	—
1	12.2	9.5	6.1	4.7	—	—
1.5	—	13.2	8.3	6.6	—	—
2	—	17	10.8	8.5	—	—
3	—	25	16	12.2	—	—
5	—	40	27	20	—	—
7.5	—	58	—	29	13.6	12.2
10	—	76	—	38	18	16
15	—	—	—	55	27	24
20	—	—	—	72	34	31
25	—	—	—	89	43	38
30	—	—	—	106	51	46
40	—	—	—	140	67	61
50	—	—	—	173	83	75
60	—	—	—	206	99	90
75	—	—	—	255	123	111
100	—	—	—	341	164	148
125	—	—	—	425	205	185
150	—	—	—	506	246	222
200	—	—	—	675	330	294

OVER 200 HP

Approx. Amps/hp	—	—	—	3.4	1.7	1.5

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

Rated armature current varies inversely as rated voltage.

Example: 40 hp motor, 300 volt armature

$$\text{Armature current} = 140 \times \frac{240}{300} = 112 \text{ Amps}$$

The above table is based on Table 430.247 of the *National Electrical Code*®.
National Electrical Code® and NEC® are registered trade marks of the National Fire Protection Association, Inc. Quincy, MA 02269.

3.5 DC MACHINE THEORY AND DESIGN

DC theory and design 101

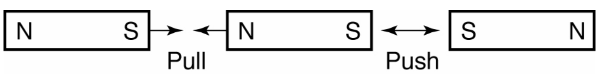
By Chuck Yung, EASA Senior Technical Support Specialist

DC MOTOR THEORY

Understanding how DC machines work is as simple as understanding magnets. If you've ever played with magnets, you've already observed two of the basic laws of magnets:

- Opposite poles attract, and like poles repel (Figure 3-1).
- Magnetic force is inversely proportional to the square of the distance.

FIGURE 3-1



Attraction, repulsion of magnets: This simple illustration of bar magnets shows how opposite poles attract one another, while like poles repel each other.

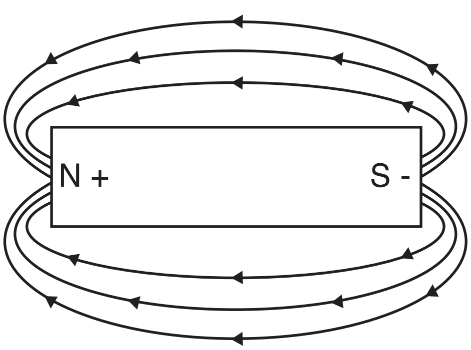
Why is it important to understand magnets? A DC motor is a collection of strategically placed magnets, and its operation is based on the two basic laws above.

Principles of magnets

Every magnet has 2 poles, one "north" and one "south." Magnetic force attracts the "north" pole of one magnet to the "south" pole of the other, while poles of the same polarity (e.g., north – north) are pushed apart.

Magnets attract ferrous metals (such as iron or steel) and other magnets. As Figure 3-2 shows, lines of magnetic force (flux) flow from negative (south pole) to positive (north pole). The lines of flux come closest together when they pass through ferrous material. Concentrating the flux by use of a ferrous material makes the flux more effective. This is why motors have steel cores.

FIGURE 3-2



Magnetic force (flux): The flux is concentrated at the poles and weakens farther from the magnet.

PROPERTIES OF MAGNETIC FIELDS

It is important to understand some of the basic properties of magnetic fields.

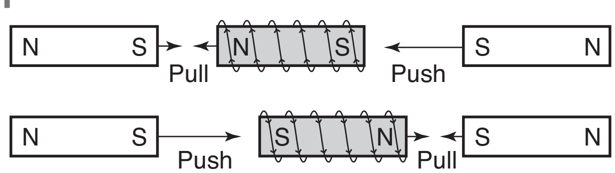
- Magnetic fields are bipolar with a north pole and a south pole. (The polarities can be detected with a compass.)
- Like poles repel while opposite poles attract.
- The lines of force (flux) of each magnetic field form a closed loop connecting each pair of poles.
- Magnetic fields penetrate most materials.
- The magnetic field is depicted by lines of force (flux) indicating the directions of the field.
- The strength of a magnetic field is measured by its flux density (number of flux lines per unit area).

Magnetic fields can also be created by electromagnets. A weak electromagnet can be made by passing DC current through a coil of wire. However, wrapping the coil of wire around a piece a ferrous material will enhance the flux, creating a much stronger electromagnet.

The direction of the current passing through an electromagnetic coil determines its polarity. Reversing the current in the coil reverses the polarity of the electromagnet.

By replacing one of the magnets in Figure 3-1 with an electromagnet, we can control whether the magnets are pulled toward or pushed away from one another–simply by reversing the current in the electromagnet (Figure 3-3).

FIGURE 3-3



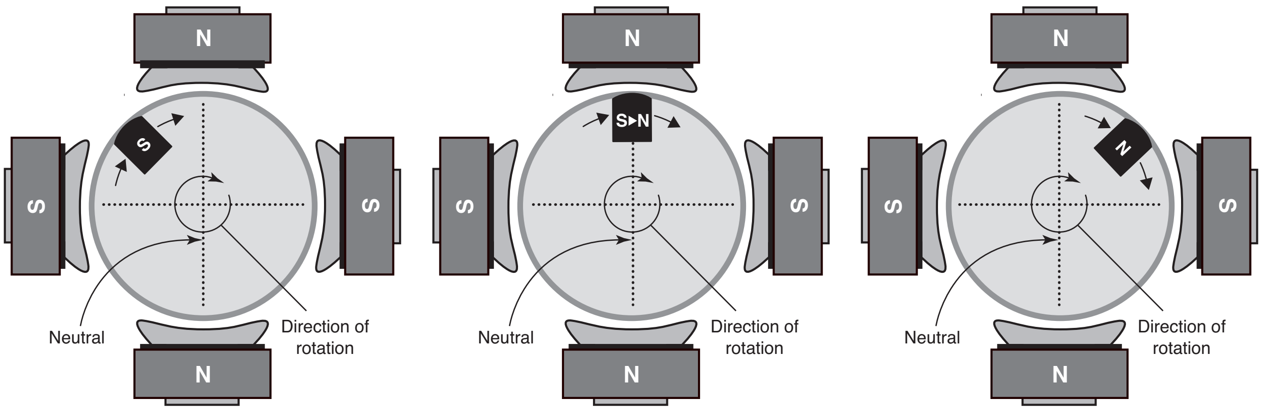
The polarity of an electromagnet can be controlled by reversing the direction of current passed through the coil.

To create a DC motor, an electromagnet (armature) is mounted to pivot around a shaft, with additional pairs of magnets (field poles) forming a circle around it. Rotational motion is created by the attraction and repulsion of these magnets. The field poles must be arranged in alternating polarities for the rotational motion to be continuous. The rotating speed of the armature and shaft can be varied by how quickly the polarity of the armature coil is changed.

If the armature had only one "magnet," and if its polarity didn't change, the armature magnet would be attracted to

FIGURE 3-4

If the DC machine had only one magnet in the armature and its polarity never changed, the polarity of the armature magnet would draw it toward the nearest pole of opposite polarity, where it would stop.



The armature magnet with south polarity is pulled toward the closest north pole while being pushed away from the closest south pole.

When the armature magnet reaches the brush neutral position, its polarity is changed from south to north. If the polarity did not change, the armature would stop rotating.

The armature magnet, now with north polarity, is pushed away from the closest north pole and pulled toward the next south pole.

Changing armature coil polarity to create rotational motion.

the nearest field pole of opposite polarity and stop. Because the polarity of the stationary fields can't be switched easily, the armature polarity must be changed each time the armature "magnet" gets to point where it would otherwise stop (Figure 3-4). This ongoing process of reversing the polarity of the armature coils is called commutation, so the collection of bars connected to the armature leads is called the commutator.

To energize the rotating electromagnets, each armature coil is connected to a pair of copper bars. The commutator is machined concentric to the shaft. DC power is supplied to the coils through carbon brushes that ride on the copper bars of the commutator.

Two factors affect where and when the armature polarity should be reversed.

First, consider the magnets. Depending upon their polarity at a certain moment, the coils will be pulled toward or pushed away from the field poles. These forces act to turn the armature. The closer together the magnets, the stronger the force acting on them. If the polarity were reversed before the coil gets to its closest point, magnetic "push" force would tend to slow down the armature.

The second factor is electrical. When electrons flow through a circuit, the resistance to that flow is current. If the coil leads are shorted together while there is current, one result is arcing. That arcing can damage the brushes or the commutator bars. To avoid damage from arcing, the brushes short the coil leads together when the current flowing through that coil is at its minimum. That point, where the polarity of the coil reverses, is called the **brush neutral position** (see Figure 3-7 on Page 3-20).

Magnetic force

The closer together magnets are, the stronger the force acting to attract or repel them becomes.

Magnetic force is inversely proportional to the square of the distance from the magnet. The physical distance between the magnet(s)–or magnet and iron–is called the air gap. Reducing the air gap by half will increase the force four times. Reduce the air gap to one-fourth the distance, and the force will increase 16 times.

The force turning the shaft increases as the armature coil approaches each stationary field, and weakens as it moves further away. To control this, several coils are evenly spaced around the armature.

In a good design, there are enough armature coils so that some coils are always in the region with the maximum attraction/repulsion force. With an appropriate number of coils, the torque can be kept steady by changing their polarities at just the right time (brush neutral).

DC MACHINE BASICS

Here are some basic rules governing construction of DC machines:

- A DC machine may have 2, 4, 6 or more poles, as long as the poles are in multiples of 2.
- The polarity of adjacent fields must alternate (north and south).
- Symmetry is critical. Poles must be spaced evenly around the circumference of the frame. This uniformity applies to all electrical components of a DC machine (e.g., interpoles, armature slots, commutator bars, brushholders and brushes).

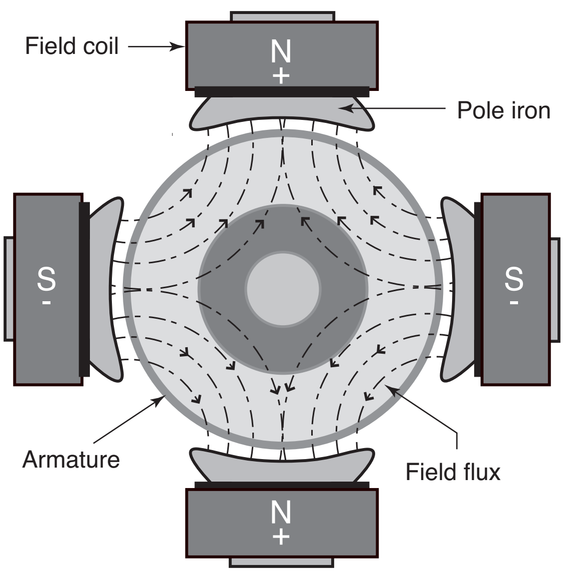
As an armature coil draws closer to a field pole of opposite polarity, the attracting force increases. By reversing the polarity of each coil as it reaches the position where it would otherwise stop, the repelling force pushes the coil further along its path, and rotational motion is maintained.

Since the field frame has at least one pair of stationary magnetic poles, it would not be very effective to have only one magnet on the armature. The more "magnets" created on the armature, the more effectively the armature can develop torque to keep it rotating smoothly. With several coils equally spaced around the armature, the polarity of each coil can be changed as it reaches that critical point.

Magnetic field strength (flux)

The magnetic force (flux) established by the magnetic fields is shown in Figure 3-5. Note that the field flux is symmetrical about the center of the pole iron and forms loops connecting each pair of poles.

FIGURE 3-5



Field flux paths in a 4-pole machine are symmetrical through the armature.

The strength of an electromagnet is described in ampere-turns (AT). Ampere-turns are equal to coil current (I) multiplied by the number of turns in each coil (T).

Ampere-turns (AT) = I x T

Where: I = current

T = turns per coil

To strengthen an electromagnetic field, the ampere-turns can be increased by:

- Increasing the current with the same turn count.
- Increasing the number of turns at the same current.
- A combination of both.

Electromagnetic fields can be weakened by doing the opposite of any of the above, but field weakening is the usual method of speed control for a DC machine. Weakening the fields increases the armature speed. Since DC follows Ohm's Law [Current (I) = Volts (V)/Resistance (R)], the current is decreased by reducing the applied voltage (resistance is constant).

The field flux is necessary for the armature to produce torque. It provides an obstacle for the armature flux to push against. An analogy is a swimmer: water provides a dense medium for the swimmer to pull through. Try swimming through air! The following formula illustrates the interrelationship of field strength, armature current and torque:

$T = k\Phi I$

Where: T = torque

k = (poles x conductors)/(2 x pi x circuits)

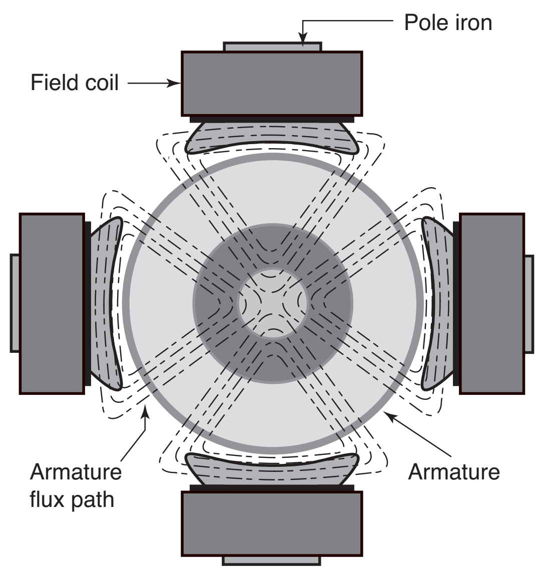
Φ = lines of flux

I = armature current

If the fields are weakened, more armature current is needed to produce the same torque. The importance of this formula, for the technician, is that a reduction in field strength also reduces torque if armature current is held constant.

When the armature is energized, the armature flux is also symmetrical (Figure 3-6).

FIGURE 3-6



In a 4-pole machine with the armature energized but the motor not rotating, the flux paths are symmetrical through the field poles.

The same field strength can be accomplished two ways:

- Few turns at a high current (series).
- Many turns at a low current (shunt).

When a field coil has few turns but carries a high current, it is called a series field. A series field is connected in series with the armature circuit and does not require a separate power supply. Because it has a high current rating, the wire has to be large enough to safely carry the current.

When a field coil has many turns at a low current, it is called a shunt field. The shunt field coil uses smaller wire than a series coil because it carries less current. The shunt fields are usually energized by a power supply separate from that of the armature.

There are other variations for modifying the strength of a magnetic field:

- Some manufacturers key the pole iron into position, rather than bolting it in place. This means the air gap between the pole iron and armature cannot be changed. However, shims can be added or removed from the air gap between the pole iron and frame.
- Change the number of circuits.
- Change the relative position of the magnetic and nonmagnetic shims. Any magnetic shims between the pole iron and a nonmagnetic shim add to the pole iron mass and thus strengthen the electromagnet.
- On rare occasions, one finds field poles that have been milled to remove material. This was sometimes done to increase the speed by roughly 15%. *This is NOT a recommended modification because it reduces the contact area between the coil and pole. It may accomplish the desired speed change, while increasing field temperature.*

The rpm of a DC machine is independent of the number of poles, unlike an AC machine, where speed is a function of winding poles and line frequency. For example, a 4-pole DC machine could be designed to operate at 99 rpm or at 3500 rpm. Unlike an AC motor, the speed of a DC machine is governed by the magnetic flux densities of the armature. The air gap density of any given armature is directly proportional to the armature voltage and the number of armature circuits (i.e., the plex).

Compound fields

While a shunt field offers good speed control, and a series field offers high torque throughout the speed range, a compound motor combines the advantages of both. The shunt field allows speed control, and the relatively few turns of the series field provide the increased torque needed. The application needs dictate the percent compounding–the amount of field strength provided by the shunt and series, respectively.

From the service center perspective (reverse engineering), field compounding is determined by the relative strengths of the shunt field and series field wound onto each pole. The percent compounding is the percentage of total field strength supplied by the series field.

The strength of a DC field is reported in ampere-turns (i.e., amperage times the number of turns). Shunt field amperage is relatively constant, while series field amperage depends on the load. Series fields are connected in series with the armature circuit, so they draw more current as the load increases.

Depending on relative polarity of the shunt and series coil on each pole, the net effect can be additive (cumulative) or subtractive (differential). The following example illustrates the difference.

Data: Each shunt field has 1000 turns, rated 2 amps
1000 x 2 = 2000 ampere-turns
Each series field has 4 turns, rated 200 amps
4 x 200 = 800 ampere-turns

CUMULATIVE			
	Polarity	**Turns x amps**	**Strength**
Shunt	N	1000 x 2	2000 ampere-turns
Series	N	4 x 200	800 ampere-turns
Same polarity, total strength = 2800 ampere-turns			

DIFFERENTIAL			
	Polarity	**Turns x amps**	**Strength**
Shunt	N	1000 x 2	2000 ampere-turns
Series	S	4 x 200	800 ampere-turns
Opposite polarity, total strength = 1200 ampere-turns			

The percent compounding is 800/(800+2000) = 0.29 or 29% compounding.

With a differential connection, the effect is similar to field-weakening as the load increases. The total field strength will decrease, so the speed will increase. The higher the percent compounding, the more dramatic the change at full load. With 50% compounding, the effect would be the same as losing the fields, and the motor would accelerate wildly. If the motor is connected differential rather than cumulative and the percent compounding is high enough (i.e., above 50%), the motor could reverse suddenly when the load reaches a certain level.

Brush neutral

To apply voltage and current to the rotating armature, the leads of each armature coil are connected to bars of a commutator.

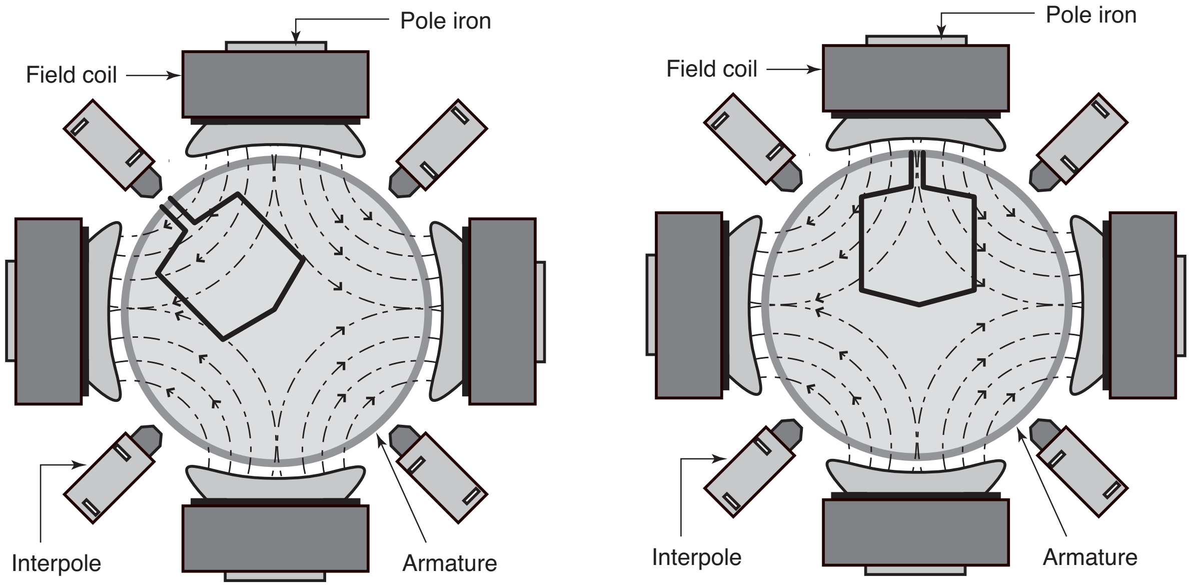
As the coil approaches neutral, the internal voltage decreases. At the point that the coil polarity reverses, the voltage is at its lowest value (Figure 3-7 on Page 3-20). Because the armature coil spans the symmetrical field flux, no current flows in the coil.

Interpoles

When the machine is operating, the armature flux tends to distort the field flux, pulling a portion of it in the opposite direction. The amount of field flux distortion depends on the strength of the armature flux, which varies in proportion to the load. Figure 3-8 on Page 3-20 illustrates how armature flux disturbs the symmetry of the field flux about the field poles. (As the load increases, armature current increases. Increased current results in increased ampere-turns.)

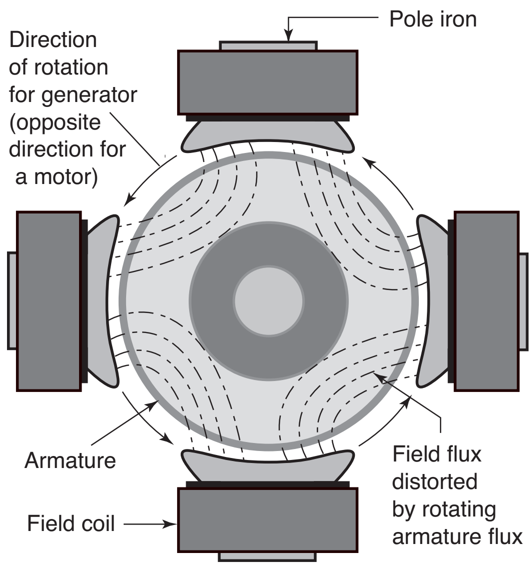
This distortion is undesirable because the neutral position moves with the field flux. If the brush shorts the armature coils while they have induced voltage, arcing occurs. The further the field flux is distorted, the greater the voltage in the armature coil when the brushes short the leads and the more pronounced the arcing. The problem with changing the brush-holder position to remedy field distortion is that the amount of field distortion changes whenever the armature current (load current) changes. A better solution is to add another set

FIGURE 3-7



Brush neutral: As the coil passes through the field flux (left), current is induced. When at the neutral position (right), no current is flowing in the coil.

FIGURE 3-8



Distorted flux path in a 4-pole machine: With the armature energized and rotating, armature flux passing through the fixed field flux deflects the field flux.

of electromagnets, called interpoles between the field poles to establish flux to the armature flux.

Upon examining the effect of armature flux on an opposing field flux, it is easy to understand the role of the interpoles in preventing excessive arcing at the brushes. Interpole polarity, relative to the armature, is equally important. If interpole polarity is correct, the cross-flux counteracts the armature flux. If the interpole polarity is reversed, the cross-flux acts in concert with the armature flux, actually increasing the distortion of the field flux. That is exactly what happens when the brushholder leads are inadvertently switched. When interpoles are rewound/replaced, when interpole leads are replaced, when an armature is rewound, or even when the brushholder end bracket is removed, there is the possibility that the interpole polarity relative to that of the armature could accidentally be changed (Figure 3-9 on Page 3-21).

The strength of the armature flux varies with the load, so the interpole strength must also vary with the load. To accomplish this, the interpoles are connected in series with the armature. Any change in load has a proportional effect on the armature and interpole strength.

As the armature flux strengthens and its effect on the field flux increases, there is a corresponding increase in interpole cross-flux. If the interpoles are properly designed, the net effect is the field flux remains unchanged (Figure 3-10 on Page 3-21).

Interpole or field strength, as with any electromagnet, depends on several factors:

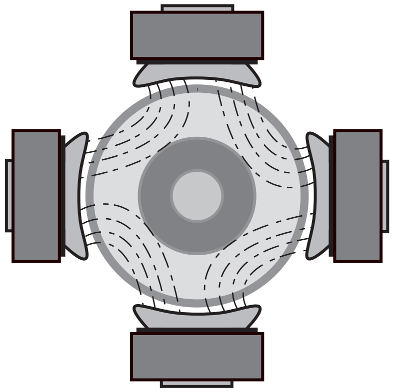
- Mass (or volume) of the pole iron inside the coil.
- Number of turns in the coil.
- Current through the coil.
- Air gap between the pole iron and armature.
- Air gap between the pole iron and frame.

These factors can be changed singly or in combination, to change the strength of an electromagnet.

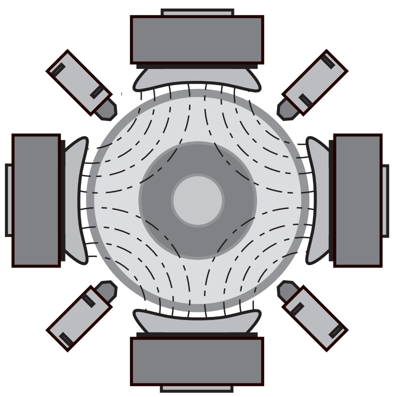
To strengthen the interpole:

- Add steel to the pole iron.
- Add turns to the coil (leave the current unchanged).

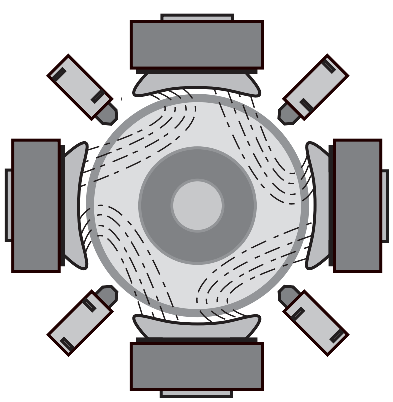
FIGURE 3-9



No interpoles
Without interpoles, the armature flux distorts the field flux.



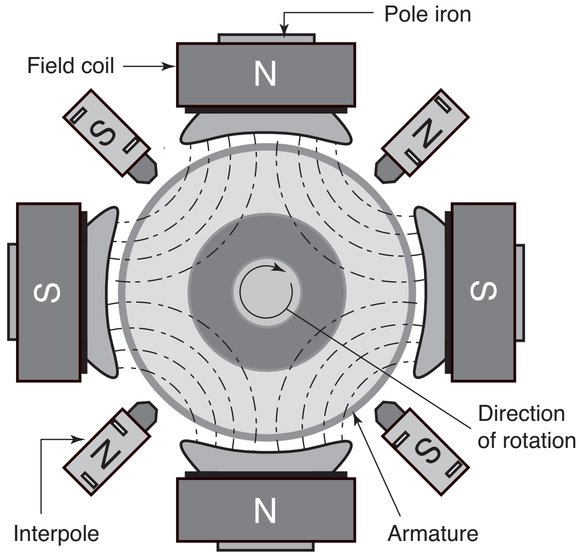
With interpoles, correct polarity
With interpoles added, the interpole flux oppose the armature flux, preserving the field flux.



With interpoles, reversed polarity
With the interpole polarity reversed, the interpol flux combines with the armature flux, further exaggerating the field flux distortion as the load increases.

Polarity of interpoles with respect to polarity of main poles in DC motors and generators.

FIGURE 3-10



Interpoles added to stabilize field flux. With the armature energized and rotating, interpoles have the same effect as the armature flux, but in the opposite direction.

- Increase current (leave the turns unchanged).
- Decrease the air gap between the pole iron and armature.
- Decrease the nonmagnetic shim thickness between the pole iron and frame.

To weaken the interpole, do the opposite of the above steps.

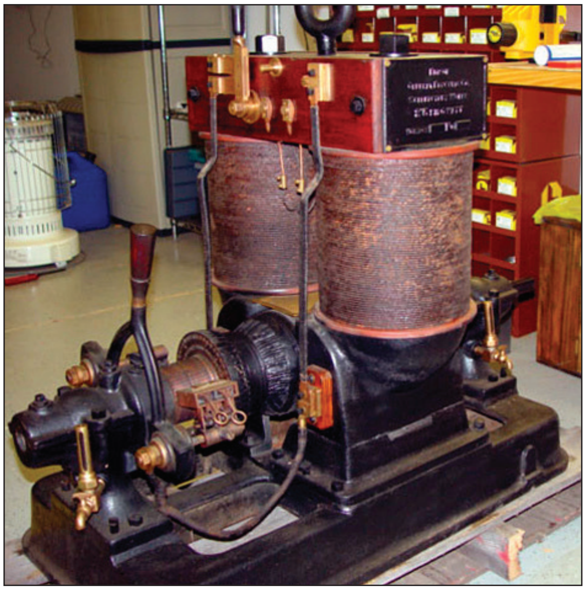
Interpole air gap is a combination of the distance between the armature and interpole, plus any gap in conductive material (shims) between the frame and interpole. A change in nonmagnetic shim thickness has roughly twice the effect as an equivalent change in air gap between the interpole and armature. Manufacturers often use an assortment of magnetic and nonmagnetic shims between the interpole and frame to obtain the desired interpole strength. Since the amount of iron in the interpole affects its strength, the position of the nonmagnetic shim will also affect interpole strength.

When a nonmagnetic shim is used beneath an interpole, the interpole bolts are normally nonmagnetic as well. They may be brass or nonmagnetic stainless steel, depending on the manufacturer.

The early DC motors (Figure 3-11 on Page 3-22) did not have interpoles, requiring an operator to shift the brush-rigging position each time the load changed. We know that interpoles were added to eliminate this inconvenience. The interpoles provide an equal-but-opposite force to counterbalance the armature flux. If you have ever seen a motor with the brushholder leads reversed, you recognize that even though the brushes may arc when a load is applied, the motor might exhibit no symptoms when running unloaded. With low armature current (no load), the interpoles really are not necessary.

If you suspect an interpole problem, bypass the interpoles. Use leads connected to brushholders of each polarity and test run the motor unloaded. If the performance problem disap-

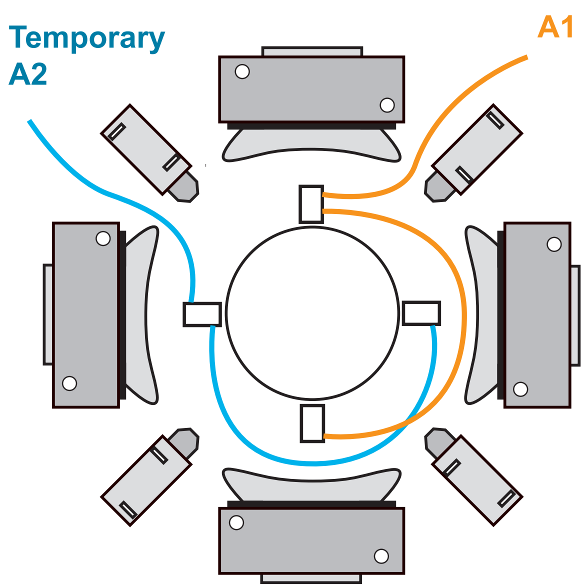
FIGURE 3-11



An early bi-polar DC motor without interpoles.

pears, you know the problem is in the interpoles. There may be a shorted interpole or a polarity/connection problem. But now you can focus on the interpoles as the problem (Figure 3-12). This method certainly beats dismantling the motor to verify whether or not the polarities are correct.

FIGURE 3-12



Bypassing interpoles: Route a temporary A-lead from the brushholder so the interpoles are not energized.

Compound wound machines can be connected cumulatively or differentially (see the "Assembly and Test" section of EASA's *Fundamentals of DC Operation and Repair Tips* manual). Virtually all compound wound DC motors are connected cumulatively, meaning that the shunt and series fields on each pole have the same polarity. When our polarity testing indicates otherwise, there is a tendency to assume that the customer is connecting the motor differentially for a reason. The truth is that the polarity test just revealed that the leads are marked incorrectly. Either the customer is connecting the leads incorrectly or he is about to do so – unless we make sure they understand that we found and corrected a lead marking problem.

The interpoles provide a magnetic flux equal to, but opposing, the armature flux (Figure 3-10 on Page 3-21). This minimizes distortion of the field flux, so the brush neutral position remains fixed. Before interpoles were developed, the brushholder position had to be manually shifted each time the load changed. A DC motor with interpoles should not arc within the normal range of load and speed.

Because the interpole and armature circuits are connected in series, the current—which varies with the load—is the same in the interpoles and the armature. The magnetic strength of a DC coil can be calculated in ampere-turns per pole. An interpole with 25 turns, carrying 100 amps, has a field strength of 2,500 ampere-turns. Using 50 turns at 50 amps would result in the same 2,500 ampere-turn field strength (25 x 100 = 2500 = 50 x 50).

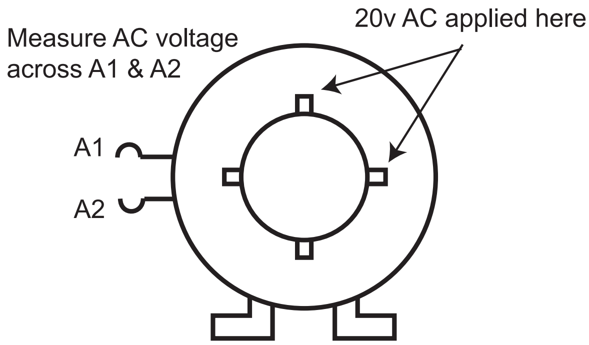
How did the designer determine the number of turns to use for each interpole? There is a "square of the inverse" relationship between distance and magnetic strength. Because the interpole iron is farther than the armature from the field iron, the interpoles normally require more ampere-turns/ pole than the armature. That gives us a rule-of-thumb that the ampere-turns of the interpole should be approximately 1.2 times the ampere-turns per pole of the armature. And that leads to our first good test to determine the interpole connection: By applying AC voltage to the armature-interpole circuit, we can determine the turn ratio between the armature and interpoles. The greater the armature current, the larger the conductor required for the interpoles. At some point, the wire becomes too large to manage. The designer increases the interpole circuits and turns so as to use a smaller conductor.

Verify the relative polarity

One important step after assembling every DC machine is to verify the relative polarity of the interpoles and armature. The simplest method for doing so is to apply 20-30v AC to adjacent brushholders, and measure the output voltage between leads A1 and A2 (Figure 3-13). The measured voltage should be lower than the input voltage. If the voltage across A1-A2 is higher than the input voltage, we should exchange the leads at the brushholders to obtain the correct relative polarity.

The simple test just described uses the armature-interpole circuit as an autotransformer. Because the polarity of the interpoles must oppose that of the armature, our autotransformer should "step down" the voltage. If the output voltage "steps up" instead, the armature and interpole polarities are the same, so we swap the position of the brushholder leads to reverse the relative polarity.

FIGURE 3-13



Verifying interpole polarity.

Here is where knowledge of that 1.2 ampere-turn ratio is useful: When the polarity relationship between the armature and interpoles is correct, and 20v AC is applied to adjacent brush posts, we should measure approximately 12 - 16 volts AC across A1 and A2.

If the interpole circuits are incorrect, there will be a corresponding change in the ratio of input-to-output voltage. For example, if the interpoles should be connected series-parallel, but instead are connected in series, the output voltage will be approximately one-quarter to one-half of the expected value, or approximately 3-6 volts. That is a strong indication that the interpole circuits are incorrect. See Table 3-1.

The exception

As mentioned earlier the relationship between distance and magnetic pull. That explains an important exception to the input-output ratio. When a machine has compensating windings ("pole-face bars"), the output voltage will be unusually low. That is because the compensating winding, an extension of the interpoles, is embedded directly in the face of the field poles. For the same reason, the European design which looks similar to an AC core (stacked laminations, with slots instead of individual poles) also results in very low output voltage.

What happens if the circuits change?

The parallel DC circuit is a current divider. Figure 3-14A on Page 3-24 illustrates the series circuit of 4 interpoles, and Figure 3-14B shows the series-parallel connection. For a machine rated 100 amps, and each interpole having 15 turns, a series connection results in 1500 ampere-turns per interpole. The series-parallel circuit results in 750 (50 x 15) ampere-turns, while a 4-parallel circuit yields only 375 (25 x 15) ampere-turns per interpole. With the wrong interpole circuit connection, the interpoles will either be much too strong or much too weak, and the brushes will arc as the load changes.

It works the other way, too

If we know the armature and interpole winding data, we can calculate the ampere-turn ratio as follows:

$$\frac{\text{Armature total turns} \times \text{Armature current}}{\text{Number of poles} \times \text{Plex}} = \text{Ampere-turns per pole}$$

Interpole ampere-turns per pole =

$$\text{Turns of 1 interpole} \times \frac{\text{Armature current}}{\text{Parallel circuits}}$$

The armature plex is easily overlooked in this comparison. If the armature data is unknown, use a digital low-resistance ohmmeter (DLRO) to determine the commutator pitch. Measure the resistance between bars 1-2, 1-3, 1-4 for a lap winding. The pair with the lowest resistance is the commutator pitch, or lead throw. The most common armature connection (commutator pitch of 1-2) is a lap simplex (1 circuit per pole), while a lap duplex (1-3 commutator pitch) connection has 2 circuits/pole.

For a wave winding, use the following formula to determine the probable commutator pitch:

(Bars +/- plex)/pole pairs

Example: An armature has 41 slots, 123 bars, wave simplex 4-pole:

- (123+/-1) / 4 = 61; the commutator pitch must be either 1-62 (retrogressive) or 1-63 (progressive)
- 122 / 2 pole pairs = 61; commutator pitch of 1-62 or 124 / 2 pole pairs = 62; commutator pitch of 1-63

Measure the resistance between bars 1-60, 1-61, 1-62, 1-63, 1-64. The lowest resistance pair of bars identifies the lead throw (commutator pitch). The plex is the number of circuits, which we can use for the purpose of determining the ampere-turns of the armature. For a simplex (whether the armature winding is lap or wave wound) connection, the ampere-turns

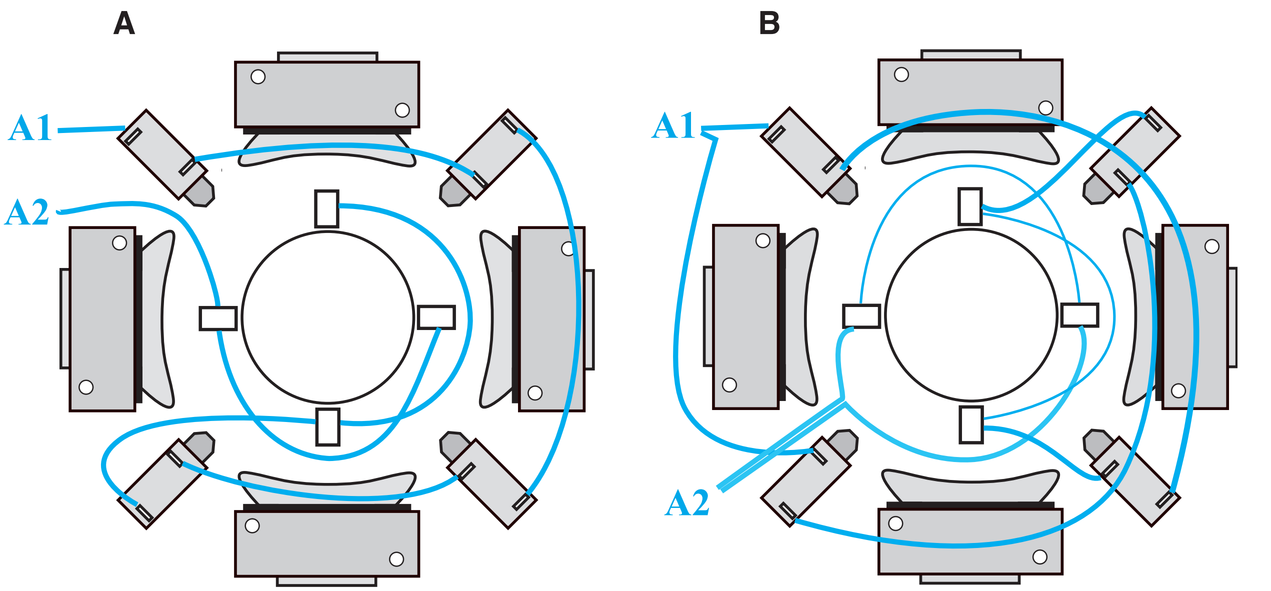
TABLE 3-1: INTERPOLE CIRCUIT TROUBLESHOOTING GUIDE

Voltage out	Circuits	Interpole polarity	Corrective action	Example
12-16v	Correct	Correct	None	—
24-28v	Correct	Reversed	Exchange leads at brush-holder	Swap + and - polarity brushholder leads
3-6	Incorrect*	—	Double the interpole circuits	Change series to series-parallel
= Input voltage, = +/-5%	Incorrect	—	Reconnect interpoles with 1/2 the number of circuits	Change 4-parallel to series-parallel or series parallel to series

Apply 20v AC to positive and negative brush posts (INPUT). Measure voltage across A1 and A2 (OUTPUT) at the terminal box.

*See paragraph title "The exception."

FIGURE 3-14



Series circuit of 4 interpoles.

Series-parallel connection

Interpole circuits.

per pole equals the total number of armature turns divided by the number of poles. For a duplex connection, divide that number by two, by 3 for a triplex, etc.

A less reliable method for determining the interpole connection varies with the age of the machine. Designs built prior to approximately 1980 typically had 600 to 1000 circular mils/amp (CMA) for the interpoles. Later designs are sometimes as low as 300 CMA; hence, the uncertainty in the results when using this method.

Turn-ratio most reliable

If both methods indicate the interpole circuits are incorrect, that makes a very strong case. Of the two methods described, the turn-ratio is the most reliable. There are cases where a typographical error on the OEM paperwork resulted in incorrect identification of the interpole circuits.

A significant advantage of the turn-ratio method is that it can be incorporated in the routine interpole polarity verification that should be done as part of every DC machine repair. Just standardize the voltage at which the test is done, and have the technician document the measured voltage.

This test is a simple expansion of a test you should already perform on every DC machine repaired. The results will not only confirm when the interpole circuit is correct; when incorrect, the results will help you determine the correct number of circuits.

A word of caution: There is no correlation between the plex of an armature and the number of interpole circuits. For example, a duplex armature (2 circuits) might use interpoles connected in series (1 circuit), series-parallel (2 circuits), or 4-parallel (4 circuits.) In other words, the interpole circuits and armature circuits are arrived at independent of one another, during the design process. The armature plex is influenced by the armature voltage and speed rating, while the interpole circuit decision is influenced by wire size, ease of manufacture, and the armature current rating. So this test can reveal incorrect number of circuits in the interpoles or the armature. If the armature is where the error is, the rpm will be off by a large factor.

Interpole shims

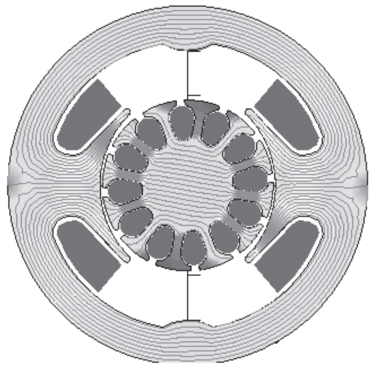
DC machines require interpoles to provide a magnetic flux equal, but opposite, to the armature flux. This controls distortion of the field flux through the load range, thus preventing arcing at the brushes. (See Figure 3-9 on Page 3-21.)

As stated earlier, interpole strength is approximately 1.2 x the ampere-turns per pole of the armature. However, that rough setting requires fine-tuning. Most manufacturers accomplish this by adjusting the air gap (the physical distance, or gap) between the interpole and armature. Because there is an inverse square relationship between magnetic force and distance, the effect of an incremental change in air gap diminishes quickly as the air gap is increased. Simply put, a 0.010” (0.25 mm) change in air gap has far greater impact for an air gap of 0.040” (1 mm) than a 0.120” (3 mm) air gap; each subsequent increase in air gap has a diminishing effect. It becomes impractical to make large changes in the air gap between the interpole and armature.

Use non-magnetic material

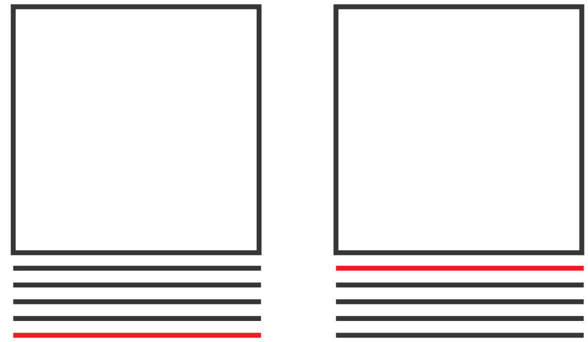
The solution is to work from the interface between the interpole and the frame. After all, the flux path passes through the armature, air gap, interpole and frame to the next interpole and back through the armature (see Page 3-25 for the field flux path). To accomplish this, a nonmagnetic shim material

FIGURE 3-15



The field flux path also travels through the frame.

FIGURE 3-16



Position of shims: The position of the non-magnetic shim (in red above) on the left permits the ferrous shims to contribute to the interpole core

is used. The material most often used is brass or non-magnetic stainless steel. Substitutes such as insulation deteriorate and should never be used.

The total air gap affecting an interpole is the sum of the physical air gap between the interpole and armature, plus the total thickness of non-magnetic shim(s) beneath that interpole. Given the square relationship described above, a non-magnetic shim of a given thickness has a far greater impact on the interpole strength than the same increase in air gap between the armature and interpole. [For example, increasing from an air gap of zero to 0.010" (0.25 mm) is a larger incremental change than an increase from 0.040 to 0.050" (1 mm to 1.25 mm).]

We know that an iron core yields a much stronger field than an air core, so it should be no surprise that the interpole strength is affected by the amount of iron within the interpole coil. Adding ferrous shims beneath an interpole does two things, both of which strengthen the interpole: It reduces the physical distance between the interpole and armature, and it adds ferrous material to the interpole iron.

If one of the shims is non-magnetic, the position of the non-magnetic shim relative to the other shims affects the interpole strength. Place the nonmagnetic shim against the frame, and all the ferrous shims add functional mass to the interpole. Move the nonmagnetic shim closer to the interpole, and the ferrous shims bypassed by doing so no longer act as part of the interpole core.

Position of shims

The position of the interpole shims is critically important to the performance of the machine. If shims are left out, or replaced in no particular sequence, the interpole strength changes (Page 3-25). The result is arcing at the brush associated with that interpole. When a machine has selective arcing at only certain brush posts, that is often is caused by irregular brush spacing around the commutator. If the spacing is correct, incorrect interpole strength caused by improper interpole shimming may be the problem.

Before a DC machine leaves the factory, a black band test is performed to confirm interpole strength. This test requires a separate power supply to alternately "buck" and "boost" the interpole strength. Interpole shims are added or removed to fine-tune the interpole strength. On larger machines, a final adjustment is sometimes made by shifting the brush neutral position.

In those cases, clearly visible marks on the brush rigging and end bracket identify the required position. It is not unheard of to adjust neutral using the preferred AC method, only to have a motor arc when fully loaded.

Rate of brush wear

When a DC machine arcs under load, one additional clue may be the rate of brush wear. If the negative brushes wear faster, weak spring tension is suspected. If the positive brushes wear faster, suspect weak interpoles. Remove the brushes and inspect the surface that rides against the commutator for telltale evidence of arcing.

The arcing caused by distortion of the field flux depends on two factors: Direction of rotation and whether the interpoles are too strong or too weak (see Figure 3-9 on Page 3-21). If the interpoles are too weak, the field flux distorts in the direction opposite the armature rotation. If they are too strong, it distorts with the rotation. If arcing occurs on the leading edge of the brush, the interpoles are too weak; if on the trailing edge, the interpoles are too strong. To strengthen the interpoles, add a ferrous shim or move the non-magnetic shim closer to the frame.

Perform black band test

When a manufacturer load-tests a DC machine, it is standard to do so at 25% increments from 25% load through 150% load. Assuming the neutral position is adjusted for the expected full-load condition, it is still possible for arcing to occur when a customer loads the machine beyond that percent load.

It may be necessary to perform a black band test at the increased load rating to eliminate arcing caused by field flux distortion.

You can see how much extra work is created by careless placement of interpole shims. When a repair requires interpole removal, keep the shims in the correct sequence. Bolt or tie them to the correct frame position, in the order in which they were removed.

Equally important: If there are nonmagnetic shims, the bolts may also be non-magnetic. Expect the fasteners to be either non-magnetic stainless steel or brass. If the interpole bolts are carbon steel, someone has replaced them with the wrong material.

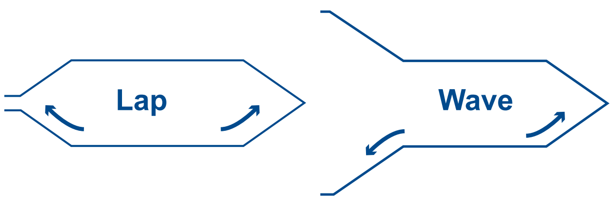
ARMATURE DESIGN

The armature coil pitch can be determined by dividing the number of armature slots by the number of poles.

Lap or wave?

Before even taking data, count the number of armature slots and commutator bars. Most lap wound armatures have an even number of armature slots, while most wave windings have an odd number of slots. Look at the coil top side as it exits the slot on both ends of the armature. If both ends of the top turn in the same direction, the armature is lap wound. If they turn away from each other, it is a wave winding (see Figure 3-17).

FIGURE 3-17



Visual difference between lap- and wave-wound armatures.

Divide the number of commutator bars by armature slots; the result should be an integer (i.e., a whole number). If not, the armature either has a dead coil or conjoined bars. The combination of unequal (odd) turns with a dead coil might explain an abrupt change in the bar-to-bar test results. It's better to know that when evaluating the armature rather than to discover it when recording data on what was a good (i.e., not defective until you stripped it) armature.

Coil pitch

The coil pitch of an armature should always be as close as possible to full pitch (see Figure 3-18). The full pitch design places the coil sides at the same position of adjacent poles at exactly the same time. Full pitch can be defined as follows:

For a full pitch coil, the number of teeth spanned = slots divided by poles.

For example, with 40 slots and 4 poles: 40/4 = 10; a full pitch coil would span 10 teeth, for a pitch of 1-11.

With only 1 more slot, a 41-slot, 4-pole armature requires a coil pitch of 1-11:

41 / 4 = 10.25; full pitch of 1-11.25 is impossible; coil pitch must be rounded to 1-11.

With 43 slots: 43 / 4 = 10.75; full pitch of 1-11.75 is impossible, so a 1-12 pitch should be used.

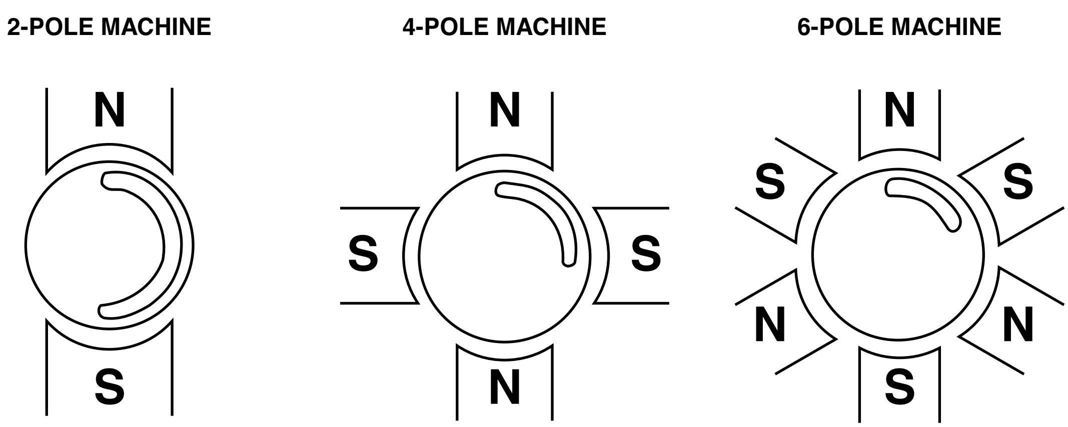
But what about a 4-pole armature with 42 slots? 42 / 4 = 10.5; full pitch would be 1-11.5; so a 1-11 or 1-12 would be equally close to full pitch.

That moves us into an area where designer experience often seems lacking. Ideally, the armature slots divided by poles should not result in any "integer point 5" (e.g., 11.5). Consider our example with 42 armature slots and 4 poles. Although the 1-11 or 1-12 pitch would be equally close to full pitch, neither is ideal. **When the slots/poles results in a fraction of exactly ½, the neutral position becomes less defined, because the coil sides are not exactly a pole-pitch apart** (see Figure 3-12 on Page 3-22). Difficulty in setting brush neutral is one consequence of this; arcing at the brushes is another. To address the arcing, the designer returns to the drawing board and adds equalizers (more on those in a moment). A more experienced design engineer would have realized the need for a split-pitch coil (more on these later, too).

Circuits

Winders understand that (except in a few special cases) the number of poles must be a multiple of the number of circuits. We know that a 4-pole AC 3-phase winding can have 1, 2 or 4

FIGURE 3-18



Armature coil span in 2-, 4- and 6-pole machines.

circuits. Likewise, a 6-pole can only have 1, 2, 3 or 6 circuits. The reverse ratio holds for lap wound DC armatures. The number of circuits is determined by multiplying the poles times the plex. As Table 3-2 indicates, a 4-pole lap wound armature can have 4 (simplex), 8 (duplex) or 12 (triplex) circuits. **For a given hp / size, lower armature voltage requires more circuits.** That means a 24V marine-duty motor operating on a boat requires more circuits (plex) than the same armature designed to operate at 500V.

TABLE 3-2: ARMATURE LAP WINDINGS – NUMBER OF WINDING CIRCUITS

Number of poles	Simplex	Duplex	Triplex
2	2	4	6
4	4	8	12
6	6	12	18
8	8	16	24
10	10	20	30
12	12	24	36

For wave windings, the lead throw must equal the number of commutator bars divided by the pole-pairs. It should be intuitive, but that makes it impossible for a 2-pole DC machine to have a wave-wound armature. The number of commutator bars offers a clue to the plex of the armature. That is because the lead throw (commutator pitch) of a wave winding must follow this formula:

Lead throw = Bars +/- plex / pole pairs

Example: a 4-pole machine has 123 commutator bars and 41 slots.

41 slots / 4 poles = 10.25; coil pitch = 1-11

123+1 = 124; 124 / 2 = 62; lead throw = 1-63

123-1 = 122; 122 / 2 = 61; lead throw = 1-62

Note that either a 1-62 or 1-63 lead throw will work for this armature; one is progressive, the other retrogressive. For more depth on this, read the Armature section of EASA's *Fundamentals of DC Operation and Repair Tips* manual.

Since most of the armatures we rewind are for industrial use, 240V or higher, most of them are simplex. We are accustomed to simplex connections, so it is easy to overlook a duplex, triplex, etc. I helped a member several years ago who had an armature with a 100-plex winding. I was certain they had made an error in tracing the leads, but the application turned out to be unique. That DC motor drove a telescope, and was synchronized to the earth's rotation.

Equalizers

Because of all those circuits and slight inequities in the physical air gap between different poles and the armature, there is often a current unbalance between the parallel paths. Current tries to flow to balance the paths, resulting in circulating currents that cause heating and arcing. To minimize the effect, a lap wound armature has equalizers directly connecting points of equal voltage potential. (Equalizers are unnecessary in wave wound armatures because the two coils are connected in series and therefore carry the same current.)

Visually, each equalizer must connect two coils exactly 2 pole-pitches apart. That gives us this formula:

Equalizer pitch = Bars / pole pitches

Example #1

A 4-pole armature with 84 commutator bars:

84 bars / (4 poles/2) = 42; equalizer pitch must be 1-43.

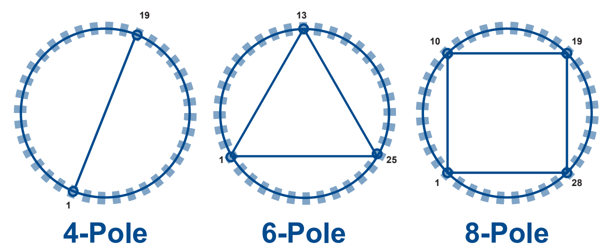
Example #2

A 6-pole armature with 324 bars:

324 / (6 poles/3) = 108; equalizer pitch must be 1-109. Note that for a 6-pole armature, each equalizer should be comprised of a triangle: 1-109-217.

The same concept holds true for armatures with 8 or more poles (see Figure 3-19). Using the wrong equalizer pitch connects two points that are not at equal voltage potential, and will cause arcing and overheating for the brief time until the armature fails.

FIGURE 3-19



End view of 4-pole, 6-pole and 8-pole equalizers.

An armature with 40 slots and 120 bars has 3 coil sections per slot. With 20 equalizers, a coil section in every slot is equalized. That is normally sufficient to yield good performance. But in a case where the slots divided by poles = X.5, the designer usually must increase the number of equalizers. When taking data, finding 1 equalizer end per commutator bar should alert us that the manufacturer had to increase the normal complement of equalizers to manage circulating currents within the armature.

When evaluating an armature design, there are clues that, if recognized in time, indicate that the design can be improved. First, divide the armature slots by the poles to determine if the result is an integer or fraction. If the result is "X.5," flag it for further review. Next, if the armature is lap wound, consider the number of equalizers. ***Most armature designs are satisfactory if the number of equalizers equals half the number of armature slots.***

Relationship of main and interpole polarities in DC machines

FIGURE 3-20

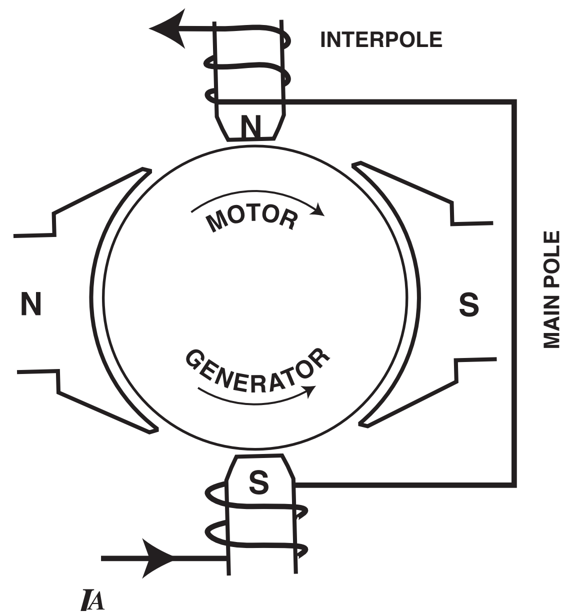


Figure 3-20 shows the polarity of interpoles with respect to the polarity of the main poles.

For a **motor**, the polarity of the interpole is the same as that of the main pole **preceding** it in the direction of rotation.

For a **generator**, the polarity of the interpole is the same as that of the main pole **following** it in the direction of rotation.

See also the article "The function of interpoles in DC machines" on Page 3-29.

The function of interpoles in DC machines

By Preben Christensen, EASA Staff Engineer (retired)

The performance of DC machines was significantly improved with the introduction of interpoles about the turn of the century. Interpoles, however, are probably the most intricate feature of the DC machine, and often the least understood.

In order to appreciate the importance of the interpole, it is necessary to briefly review the process of commutation, since the two go hand in hand.

The basic principles of commutation are quite simple and are tied in with the various fluxes originating from the armature. Let us, therefore, consider those fluxes in the armature that are most important to commutation.

During operation under load, the armature coils cutting the main pole flux carry a constant current proportional to the load current. The current flowing in these coils sets up a flux called the armature cross flux (so called because it is at right angles to the main pole flux). Most of the armature cross flux will be directed toward the main poles, but a small amount of flux is also directed between the main poles toward the frame (see Figure 3-21).

However, the current flowing through the coils being commutated is not constant. The current in these coils diminishes to zero and then builds up again to full value, but in the opposite direction. This process takes place in a fraction of a second as the commutator bars to which the coils are connected pass under the brushes, thereby short-circuiting the coils (see Figure 3-21).

As the current reverses in the coils, the magnetic field surrounding them decreases to zero before building up in the opposite direction. This change in the magnetic field induces a **reactance voltage** in the coils.

The nature of the reactance voltage is to act against the change of the current that produces it, consequently delaying its reversal. A high reactance voltage that is not neutralized will cause sparking at the brushes.

The reactance voltage can be neutralized in the coils undergoing commutation by inducing an equal, but opposing, voltage. This is accomplished by having these coils cut a flux of proper magnitude and direction. This flux is provided by the interpoles.

The interpoles (or commutating poles) are electro magnets centered between the main poles of the DC motor or generator. Although their pole piece is much narrower than the main pole, it is usually the same length. The interpole coils are made of relatively few turns of heavy wire connected in series with the armature.

Most DC machines are built with a full complement of interpoles (an equal number of interpoles and main poles). For economic reasons, however, many small DC machines are designed with only half as many interpoles as main poles.

Remember that the presence of the interpole greatly intensifies the armature cross flux field in the interpole air gap. Unless neutralized, the immensely increased strength of this magnetic field would induce a high voltage in the coils being commutated and be detrimental to commutation (see Figure 3-22).

The flux required in the interpole air gap to cancel both the reactance voltage and the armature cross flux is provided by the interpole ampere turns. The total ampere turns needed on the interpoles is the sum of the ampere turns for the armature cross flux field and those required to counteract the reactance voltage. When we know the armature winding data, we can readily calculate the ampere turns (AT_{arm}) required for establishing the armature cross flux per pole:

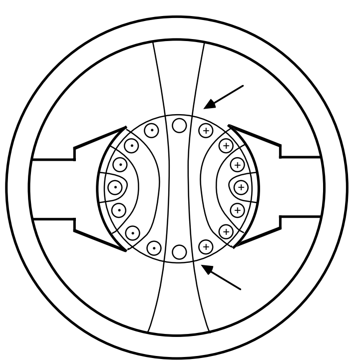
$$AT_{arm} = \frac{I}{CIR} \times \frac{B \times T}{P}$$

I = Load current

B = Number of commutator bars

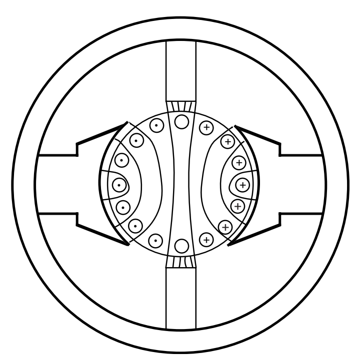
T = Armature turns per coil

FIGURE 3-21



Distribution of armature cross flux in a non-interpole DC machine. Arrows indicate coils being commutated.

FIGURE 3-22



Distribution of armature cross flux in a DC machine equipped with interpoles. Note the concentration of flux in the interpole air gaps.

CIR = Number of armature circuits

P = Number of main poles

Calculating the exact number of ampere turns required to neutralize the reactance voltage, however, is an elaborate process. The design engineer usually approximates the number of ampere turns. Final correction is then made on the test floor by adjusting the interpole air gaps and shimming for optimum commutation.

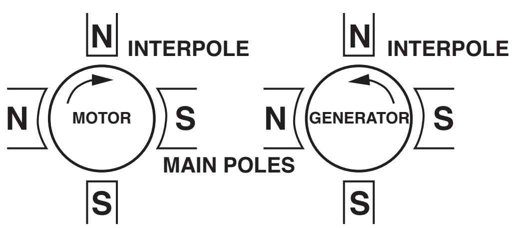
When the machine has a full complement of interpoles, the ampere turns on the interpoles are normally about 20 percent higher than the ampere turns on the armature itself. Since the same load current flows in both the armature and interpoles, the turns per coil of the interpole (T_{ip}) may be written:

$$T_{ip} = 12 \times \frac{B \times T}{CIR \times P} \text{ (approximately)}$$

Three factors determine the polarity of the interpoles as well as the direction of the flow of the armature cross flux: the direction of armature rotation; the polarity of the main poles; and whether the machine is operating as a motor or a generator. The interpole flux, however, always opposes the armature cross flux.

An easy way to remember the correct polarity of the interpoles with respect to the main poles is as follows: in a motor a Main pole precedes an interpole of the same polarity in the direction of rotation; in a generator, the reverse is true (see Figure 3-23).

FIGURE 3-23



Polarity of interpoles with respect to polarity of main poles in DC motors and generators.

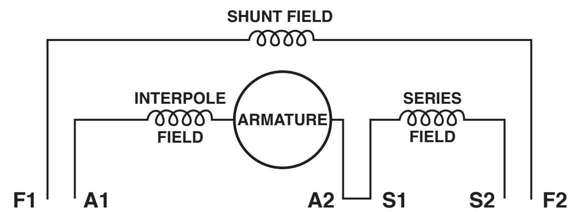
The windings of the interpoles and the armature are always connected in series, because they must both carry the same current. This assures a perfect balance of flux from both the armature and the interpoles. The polarity of the interpoles in a motor or generator **must** alternate from pole to pole, N-S, etc. (The one exception is a four-pole machine having only two interpoles. In this case, the interpoles, located 180° apart, have the same polarity.)

Although it is preferable to connect the interpole coils in series, sometimes you may find a machine in which the coils are connected in parallel. In parallel connections there is always the possibility that the current might not be equal in all circuits. This possibility does not exist when the coils are connected in series.

When it is necessary to reverse the flow of the load current, it must be reversed in **both** the armature and the interpole. Interchanging the brushholder connections would only reverse the load current in the armature.

In order to change the direction of current flow in **both** the armature and interpole winding, the connections A1 and A2 must be interchanged (see Figure 3-24).

FIGURE 3-24



Connection diagram for a compound motor.

In repairing interpoles extreme care should be exercised to maintain original factory specifications for air gap length, shimming, wire size and number of turns.

If it is not possible to rewind the interpoles with the factory specified wire size or its equivalent, it is permissible to increase the circular mils of the wire, provided that the new coils do not unduly restrict the air flow through the machine. The number of turns in the interpole coil, however, **must** be the same as specified by the manufacturer.

The shims should be kept with each pole piece, making certain that magnetic and nonmagnetic shims are not interchanged. Maintaining the original interpole air gap length is critical because a difference as little as 1/64" (.4 mm) may cause bad commutation.

The introduction of interpoles was a great step forward in the development of the DC machine. Commutation was improved so greatly that, except for very small size machines, it is rare to find a motor or generator today without interpoles.

Note: This article was first published as *EASA Tech Note 2* (October 1983). It was reviewed and updated as necessary in October 2020.

Proper placement of interpole shims prevents arcing

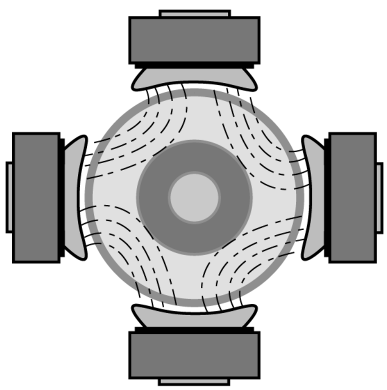
By Chuck Yung, EASA Senior Technical Support Specialist

Have you ever wondered about the purpose of the shims found under the interpoles in most DC machines? Those shims are used by the manufacturer to adjust the interpole strength. If they are lost, left out or mixed up, the result will be a DC motor or generator that arcs–especially when loaded.

WHAT INTERPOLES DO

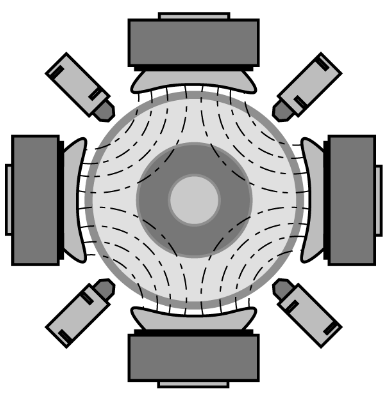
DC machines require interpoles to provide a magnetic flux equal to, but opposite, the armature flux. This controls distortion of the field flux through the load range, thus preventing arcing at the brushes (see Figure 3-25 and Figure 3-26).

FIGURE 3-25



Without interpoles, the armature flux distorts the field flux.

FIGURE 3-26



With interpoles added, the interpole flux opposes the armature flux, preserving the field flux.

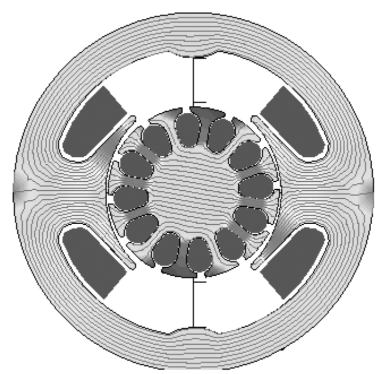
Interpole strength is approximately 1.2 x the ampere-turns per pole of the armature. However, that rough estimate requires fine-tuning. Most manufacturers accomplish this by adjusting the air gap (the physical distance, or gap) between the interpole and armature.

Because there is an inverse square relationship between magnetic force and distance, the effect of an incremental change in air gap diminishes quickly as the air gap is increased. Simply put, a 0.010" (0.25 mm) change in air gap has far greater impact for an air gap of 0.040" (1 mm) than a 0.120" (3 mm) air gap; each subsequent increase in air gap has a diminishing effect. It becomes impractical to make large changes in the air gap between the interpole and armature.

USE NONMAGNETIC MATERIAL

The solution is to work from the interface between the interpole and the frame. After all, the flux path passes through the armature, air gap, interpole and frame to the next interpole and back through the armature. (See Figure 3-27 for the field flux path.) To accomplish this, a nonmagnetic shim material is used. The material most often used is brass or nonmagnetic stainless steel. Substitutes such as insulation deteriorate and should never be used.

FIGURE 3-27



The field flux path also travels through the frame.

The total air gap affecting an interpole is the sum of the physical air gap between the interpole and armature, plus the total thickness of nonmagnetic shim(s) beneath that interpole. Given the inverse square relationship described above, a nonmagnetic shim of a given thickness has a far greater impact on the interpole strength than the same increase in air gap between the armature and interpole. For example, increasing from an air gap of zero to 0.010" (0.25 mm) is a larger incremental change than an increase from 0.040 to 0.050" (1 mm to 1.25 mm).

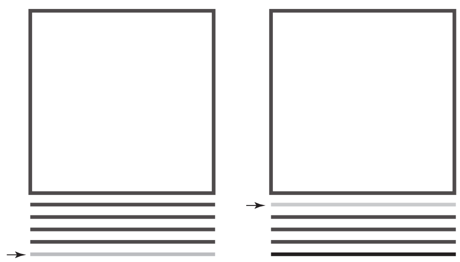
An iron core yields a much stronger field than an air core, so it should be no surprise that the interpole strength is affected by the amount of iron within the interpole coil. Adding ferrous shims beneath an interpole does two things, both of which strengthen the interpole: It reduces the physical distance between the interpole and armature, and it adds ferrous material to the interpole iron.

If one of the shims is nonmagnetic, the position of the nonmagnetic shim relative to the other shims affects the interpole strength. Place the nonmagnetic shim against the frame, and all the ferrous shims add functional mass to the interpole. Move the nonmagnetic shim closer to the interpole, and the ferrous shims bypassed by doing so no longer act as part of the interpole core.

POSITION OF SHIMS

The position of the interpole shims is critically important to the performance of the machine. If shims are left out, or replaced in no particular sequence, the interpole strength changes (see Figure 3-28). The result is arcing at the brush associated with that interpole. When a machine has selective arcing at only certain brush posts, that is often is caused by irregular brush spacing around the commutator. If the spacing is correct, incorrect interpole strength caused by improper interpole shimming may be the problem.

FIGURE 3-28



The position of the nonmagnetic shims (light grey line) on the left permits the ferrous shims to contribute to the interpole core.

Before a DC machine leaves the factory, a black band test is performed to confirm interpole strength. This test requires a separate power supply to alternately "buck" and "boost" the interpole strength. Interpole shims are added or removed to fine-tune the interpole strength.

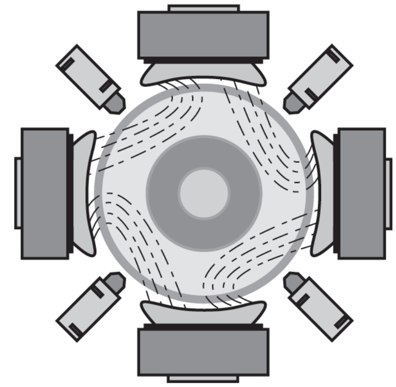
On larger machines, a final adjustment is sometimes made by shifting the brush neutral position. In those cases, clearly visible marks on the brush rigging and end bracket identify the required position. It is not unheard of to adjust neutral using the preferred AC method, only to have a motor arc when fully loaded.

RATE OF BRUSH WEAR

When a DC machine arcs under load, one additional clue may be the rate of brush wear. If the negative brushes wear faster, spring tension may be weak. If the positive brushes wear faster, suspect weak interpoles. Remove the brushes and inspect the surface that rides against the commutator for telltale evidence of arcing.

The arcing caused by distortion of the field flux depends on two factors: Direction of rotation and whether the interpoles are too strong or too weak (see Figure 3-29). If the interpoles are too weak, the field flux distorts in the direction opposite the armature rotation. If they are too strong, it distorts with the rotation. If arcing occurs on the leading edge of the brush, the interpoles are too weak; if on the trailing edge, the interpoles

FIGURE 3-29



The effects of interpole strength.

are too strong. To strengthen the interpoles, add a ferrous shim or move the nonmagnetic shim closer to the frame.

PERFORM BLACK BAND TEST

When a manufacturer load-tests a DC machine, it is standard to do so at 25% increments, from 25% load through 150% load. Assuming the neutral position is adjusted for the expected full-load condition, it is still possible for arcing to occur when a customer loads the machine beyond that percent load.

It may be necessary to perform a black band test at the increased load rating to eliminate arcing caused by field flux distortion.

Careless placement of interpole shims creates lots of extra work. When a repair requires interpole removal, keep the shims in the correct sequence. Bolt or tie them to the correct frame position, in the order in which they were removed.

Equally important: If there are nonmagnetic shims, the bolts may also be nonmagnetic. Expect the fasteners to be either nonmagnetic stainless steel or brass.

Note: This article was originally published in *EASA Currents* (November 2006). It was reviewed and updated as necessary in October 2020.

3.6 BRUSHHOLDERS AND CARBON BRUSHES

Brushholders and the performance of carbon brushes

By Jeff D. Koenitzer, P.E.
Helwig Carbon Products, Inc.
Milwaukee, WI

INTRODUCTION

A carbon brush is an electrical contact which makes a connection with a moving surface. Optimal performance on motors, generators and other types of moving contact applications will be attained only when the carbon brush, the brushholder, and the contact surface are properly designed and maintained. All three components are critical factors in a complex electromechanical system.

The brushholder, as the name suggests, holds the brush so that the brush can perform properly. Holders provide stable support in the proper position in relation to the contact surface and often provide the means for application of the contact force on the brush.

For many decades brushholders received little attention. New rotating equipment was supplied with copies of the same old brushholder designs. Typically, when performance problems occurred, the focus was on the brush because this was the part exhibiting rapid wear. More recently, however, consideration has also been given to brushholders, and particularly to spring pressure, as a common cause of many brush problems. Recent holder developments and the coordination of the designs of constant-pressure holders with insulated top-padded brushes also have resulted in significant advancements in performance and life.

The purpose of this paper is to review the critical areas of consideration for brushholders in relation to the proper functioning of brushes. The most important factors are: 1) maximum stability of the carbon in the holder, 2) proper positioning of the brush on the contact surface, and 3) minimum resistance through the brush and holder portion of the electrical circuit.

HOLDER SIZE DIMENSIONS

The fit of the carbon portion of the brush in the holder is critical for stable electrical contact. If there is inadequate space between the holder walls and the thickness and width of the brush, there is potential for binding of the brush in the holder, particularly with increased temperature and contamination. On the other hand, excess space between the holder and the carbon will result in an unstable electrical contact because the brush face can move tangentially or axially within the holder.

The holder and brush tolerances on the **thickness** and **width** therefore must be well coordinated. Brushes are machined undersize per NEMA tolerances or per drawing specifications while brushholders are made oversize. As a general guideline for brushholders, industrial sizes typically should be held oversize to a tolerance of +0.002/+0.008" (+0.051 mm/+0.203 mm). Smaller frame units with a brush thickness less than 0.500" (13 mm) and greater than 0.125" (3 mm) should have holders with a tolerance of +0.001/+0.005" (+0.025 mm/+0.127 mm). Micro size units with brushes of thickness 0.125" (3 mm) or less should have holders held to a tolerance of +0.001/+0.003" (+0.025 mm/+0.076 mm). For more information on brushholder fit, see ANSI/EASA Std. AR100, *Recommended Practice for the Repair of Rotating Electrical Apparatus*, and NEMA Std. CB 1-2000, *Brushes for Electrical Machines*.

Over a long period of usage the thickness dimension on a holder can become worn from brush movement or distorted from heat. Therefore it is important to periodically measure the thickness and width dimensions on the top and bottom of the holders to ensure that they are within tolerance and that the brush will have adequate support for a stable electrical contact.

When motor and generator brushholders are subjected to high temperatures, it may be necessary to provide extra compensation for thermal expansion, depending on the temperature rise and the degree of heat dissipation. To prevent the brush from sticking in the holder in these cases, it is easier to reduce the brush thickness and width dimensions slightly than to adjust holder dimensions. Metal graphite brushes with over 50% metal content by weight are manufactured with an increased undersize tolerance per NEMA standards since they usually carry higher current, generate more heat, and have a higher coefficient of thermal expansion than nonmetal grades.

Brush and holder **length** can also have a significant effect on the stability and performance of the brush (Figure 3-30). Most often the length is limited due to the space available within the frame. There are also practical length limitations due to the excess resistance of a long piece of carbon. As the carbon length is increased, the resistance of the current path from the shunt to the contact surface is increased. At the same time, the amount of contact area between the carbon and the longer holder is increased, and the corresponding contact resistance is decreased. This then creates the potential for distorted current flow directly between the holder and the carbon rather than through the shunting.

On the other hand, short brush and holder designs are

FIGURE 3-30

Holder length contributes to the stability of the brush contact.

more susceptible to instability at the contact surface. There is potential for a higher degree of brush tilt in the holder since the length of support is less in relation to the brush thickness.

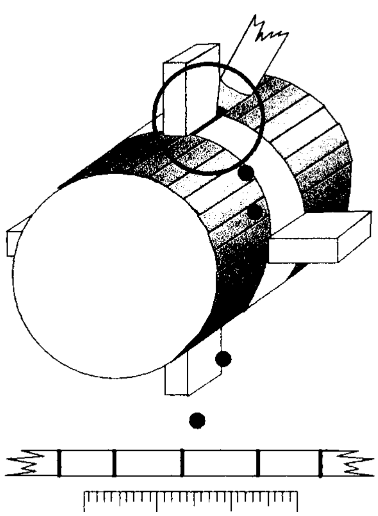
In addition to dimensional concerns the insides of the holder must be smooth and free of all obstructions including burrs. If a used brush has any straight scratches down the sides of the carbon, there are protrusions inside the brush box that will restrict the brush from making proper electrical contact. Rough handling of brushholders can distort the metal and affect the critical inside dimensions of the brush cavity. Holders made from metal stampings are particularly susceptible to irregularities on the inside dimensions and on squareness. Broaching is generally accepted as the best manufacturing method to assure consistent inside dimensions and a smooth finish.

HOLDER POSITION

The holder position will determine the location of the brush on the moving contact surface. For slip-ring applications, the holders are usually located around the top portion of the ring for ease of access. In this position the weight of the brush contributes to the contact force. If holders are mounted on the underside of a contact surface, additional spring force may be necessary to compensate for the weight of the brush.

On DC machines with commutators, proper positioning of the holders in relation to the field poles is critical. The brushes should be equally spaced around the commutator. This spacing can be checked by wrapping a paper tape around the commutator, marking the location of the same edge of each brush, and then measuring the distance between marks on the paper. Spacing should be as nearly equal as possible (Figure 3-31), within 3/64" (1 mm).

FIGURE 3-31



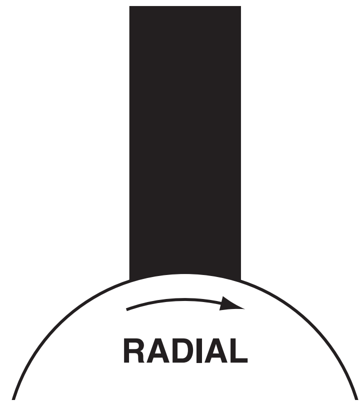
Spacing should be as equal as possible and within 3/64" (1 mm).

The brushes must also contact the commutator within the neutral zone where voltage levels are near zero. When the holder position allows the brush to make contact outside the neutral zone, there will be higher bar-to-bar voltages under the brush, circulating currents, bar edge burning, and damage from arcing.

HOLDER ANGLE

The most common angle for holder mounting is 0 degrees–i.e., perpendicular to the contact surface (Figure 3-32). Most slip rings and reversing commutator applications make use of this so-called radial mount. The advantages are ease of holder installation, maximum spring force transferred to the contact surface, and fair stability of brush contact upon reversal of direction.

FIGURE 3-32



The most common mounting angle is 0 degrees–i.e., perpendicular to the contact surface.

Any brush face movement within the holder will result in a change in the contact surface. The most stable surface contact will occur when the top and bottom of the brush are always held to the same side of the holder regardless of the direction of rotation. Angle holder mountings were developed to increase this stability and the effective area of the brush contact.

FIGURE 3-33

Angle mountings can increase the stability of the surface contact if the correct angles are used in relation to the direction of rotation.

However, stability will occur only when the correct angles are used in relation to the direction of rotation (Figure 3-33).

When the entering edge is the short side of the brush or a trailing position, the face angle should be 20 degrees or less. At greater angles the action of the rotation and the spring force wedges the brush into the bottom corner of the holder and causes high friction and an unstable contact. Normally, trailing brushes also have a shallow top bevel.

When the entering edge is the long side of the brush or a leading position, the face angle should be 25 degrees or more. At angles of 20 degrees and less the action of the rotation pulls the bottom of the brush to the opposite side of the holder from the top of the brush. Leading brushes should have a top bevel of 20 to 30 degrees.

FIGURE 3-34

Brush face angles between 20 and 25 degrees can maintain stable contact in either or both directions of rotation.

A stable contact can be maintained in either or both directions of rotation with brush face angles between 20 and 25 degrees (Figure 3-34).

The potential disadvantage of holder angles is the loss of effective downward force of the spring. A portion of the spring force is dissipated in holding the brush stable to one side of the holder. The amounts of downward contact force lost at various angles are as follows:

Angle Degrees	Loss in Downward Force
5	0.4%
10	1.5%
15	3.4%
20	6.0%
25	9.4%
30	13.4%
35	18.1%
40	23.4%
45	29.3%

The spring force should be increased to compensate for the loss of effective downward force from the action of the brush angle in holding the brush to the side of the holder. If a brush has bevels of 20 degrees on the top and 30 degrees on the bottom, the spring force should be increased 6.0% + 13.4% (or about 20%) to maintain the proper level of effective downward contact force at the brush face.

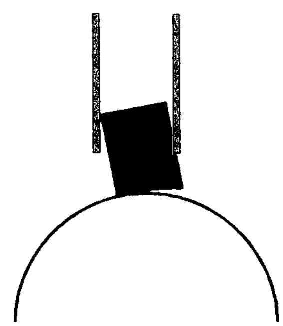
In the special case of post-mounted double holders commonly used on slip rings, the best design would allow both brushes to make contact at zero degrees or perpendicular to the ring. Any angle will result in one brush in the pair operating with less contact stability.

HOLDER MOUNTING HEIGHT

The vertical position of the holders above the contact surface is very important in assuring proper brush support throughout the wearable length of the brush and for proper positioning on the contact surface.

When a brushholder is mounted too high above the contact surface or when the surface has been turned down to a significantly smaller diameter, there will not be adequate support for the carbon as the brush wears to a short length. This will contribute to increased electrical wear due to the instability of the contact (Figure 3-35).

FIGURE 3-35

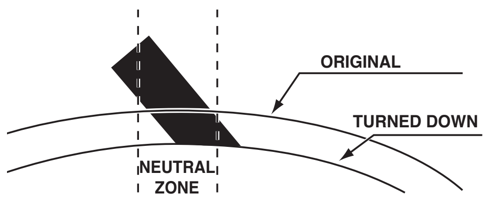


If the brushholder is too far from the contact surface, it will not provide adequate support as the carbon brush wears down.

The holder mounting height should be proportional to the size of the unit. On the large frame sizes the holders should be mounted a maximum of 0.125” (3 mm) above the contact surface. In a few cases units operate with intentional runout of the contact surface that must be taken into consideration. The small micro frame sizes should have a holder mounting height of approximately 0.032” (.8 mm). Manufacturer’s specification, when available, should be followed. During holder mounting a flexible mounting pad of the appropriate thickness can be placed on the contact surface to ensure consistent height and spacing. This pad also helps protect the commutator from damage during mounting.

There are several common problems related to excess height of the holder. When a commutator has been turned down several times, angled brushes will make contact in a different position. With steep bottom bevels and significant

FIGURE 3-36

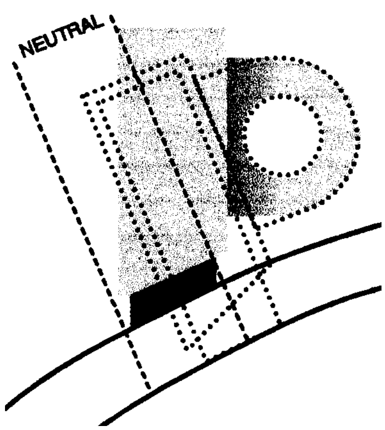


When a commutator has been turned down several times, angled brushes will make contact in a different position and could even move outside the neutral zone

decreases in diameter the location of the brush contact could even move outside the neutral zone (Figure 3-36). There will be a significant increase in wear unless the holder is moved closer to the commutator or the neutral is adjusted.

Although single post-mounted holders can be rotated to move the holder closer to the commutator, the position of brush contact will change (Figure 3-37). As mentioned above, it is very likely that adjustment of the neutral position will be required to avoid edge arcing. The brush rigging should be positioned so that the brushes are set for brush neutral and clearly marked. (See ANSI/EASA Std. AR100: *Recommended Practice for the Repair of Rotating Electrical Apparatus*.)

FIGURE 3-37



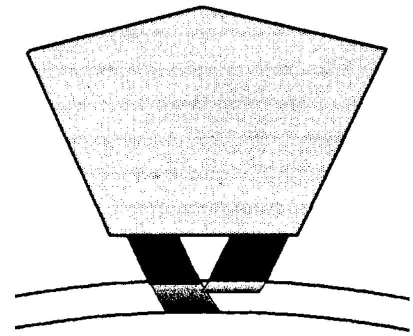
Rotating single post-mounted holders to move them closer to the commutator will change the brush contact position and likely require adjustment of the neutral position.

On V-shaped toe-to-toe holders that are mounted too high above the commutator the brushes can interfere at the toes. This will result in one or both brushes not making contact with the commutator (Figure 3-38). It is especially important to mount these old-style holders sufficiently close to the commutator to avoid this problem.

SPRING FORCE

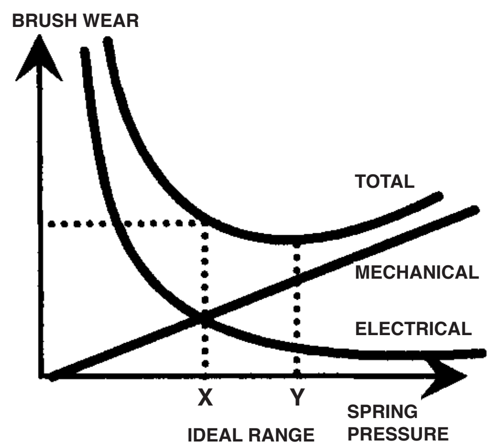
Many inventive methods have been used for the application of the contact force on brushes. These included clock type springs, torsion bars, lever springs, helical coil springs, and constant-force negator springs. As noted in the graph above (at right), the brush wear rate will change as the spring pressure changes (Figure 3-39). This is one of the most important concepts in understanding brush performance.

FIGURE 3-38



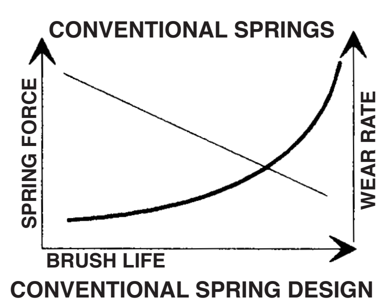
Mounting a V-shaped holder too far from the commutator can keep one of the brushes from making contact.

FIGURE 3-39



The brush wear rate will change as the spring pressure changes.

FIGURE 3-40



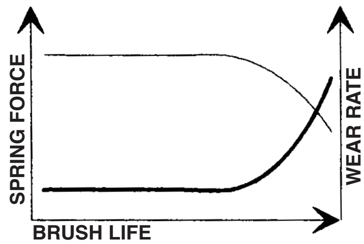
Consistent brush performance is attained by keeping the spring force virtually constant at the correct level.

There has always been a problem with an accelerating rate of wear as the brush gets shorter due to the declining spring force and the dramatic increase in electrical wear. The most consistent brush performance will be attained when the spring force is virtually constant at the correct level throughout the wear length of the brush (Figure 3-40).

The use of the proper **constant-force springs** can be a significant advantage in obtaining consistent minimal wear rate of the brushes, reduced wear of the contact surface, less carbon dust, and much lower overall maintenance costs on the unit (Figure 3-41).

FIGURE 3-41

CONSTANT-FORCE SPRING



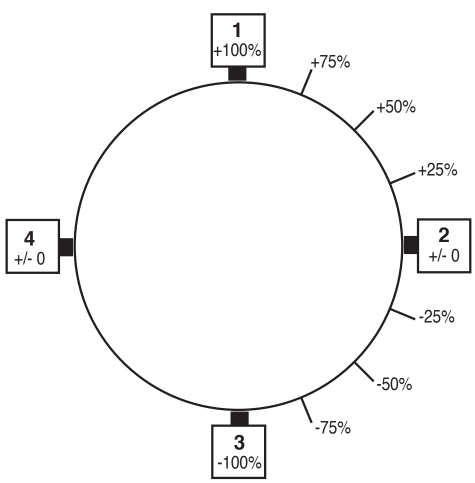
CONSTANT-FORCE SPRING DESIGN

Use of the correct constant-force springs can help in obtaining consistent minimal brush and contact surface wear rates, while reducing carbon dust and overall maintenance costs.

Testing and application experience have resulted in the following recommended ranges of spring tension. For larger machines, Figure 3-42 explains the importance of allowing for brush weight when determining brush pressure.

FIGURE 3-42

ESTIMATED ADJUSTMENT FACTORS FOR SPRING TENSION BASED ON BRUSH WEIGHT AND POSITION



For larger machines, be sure to include the brush weight in calculations. Add brush weight to spring tension for position 1. Subtract brush weight from spring tension for position 3. The brush weight has no effect in position 2 or 4.

BRUSH PRESSURE RECOMMENDATION

Application	Brush Pressure
General industrial	4.0 - 6.0 psi (0.281 - 0.422 kg/cm^2)
Fractional hp	4.0 - 7.0 psi (0.281 - 0.492 kg/cm^2)
Traction	5.0 - 8.0 psi (0.352 - 0.562 kg/cm^2)
Induction & synchronous	3.5 - 4.5 psi (0.246 - 0.316 kg/cm^2)
High-speed slip rings	2.25 - 2.75 psi (0.158 - 0.193 kg/cm^2)
Elevator generators	3.5 - 4.0 psi (0.246 - 0.281 kg/cm^2)

When operating conditions vary from the standard, some adjustment in spring force can improve performance. If the current density is very low, the humidity is very low, or the speed is extremely high, a slightly lower spring force than shown above can be an advantage. However, if the current loads are high, the speed low, there is contamination causing "over-filming," or where external vibration and roughness of the contact surface are affecting the brush, then a spring force near the high end of each range is recommended.

The unique set of conditions on each application will result in its own specific graph and numbers for the ideal spring force to obtain minimum wear of the brushes and the contact surface. Often a change in spring force will have a far more dramatic effect than a change in brush grade. Several original equipment manufacturers test for the ideal spring force prior to testing different brush materials.

The springs on all holders should be checked every two or three brush changes to ensure that the pressure is still within the recommended tolerance. The force of the spring must first be measured with an accurate scale. This value is then used to calculate brush pressure as shown below.

BRUSH PRESSURE CALCULATION

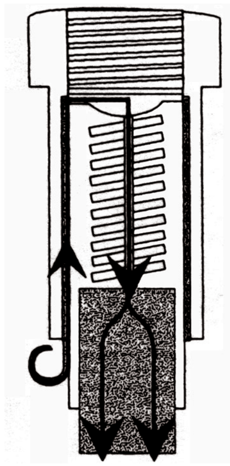
$$\text{Brush pressure (psi)} = \frac{\text{Measured spring force (pounds)}}{\text{Brush thickness (inch)} \times \text{Brush width (inch)}}$$

If the brush pressure value is below the recommended range, the springs should be replaced to avoid accelerated wear of the brush and the contact surface.

ELECTRICAL CONNECTIONS

The primary function of the brush involves conducting current. In many cases the brushholder is also a part of this electrical circuit. It therefore is necessary that all electrical connections are of minimal resistance to provide the best path for current flow from the main lead connection to the contact surface. Corrosion, contamination, or electrolytic action over a period of time can cause dramatic increases in resistance, making it necessary to clean the electrical connections. Careless installation of the brushes or the holders can lead to loose connections. Any high resistance in the brush circuit will result in excess heat or an undesirable path of current flow and unequal loading of the brushes.

FIGURE 3-43



On cartridge brushholders with captive coil spring brushes, the current should flow from the clip connector up the brass insert to the cap on the end of the brush and then down through the shunt to the carbon.

On fractional horsepower cartridge-style brushholders with captive coil spring brushes, the current should flow from the clip connector at the bottom of the holder up the brass insert to the cap on the end of the brush and then down through the shunt to the carbon (Figure 3-43). The brushes fail very quickly if the round or eared cap on the end of the brush does not make proper contact with the brass holder insert. When this condition exists, current will flow directly from the brass insert to the spring or to the carbon. In either case there will be extreme heat, loss of brush contact, commutator wear, and eventually motor failure.

Another problem with larger frame sizes can occur when the holder mounting is part of the electric circuit. If the holder mounting surface becomes dirty, corroded, or even painted over, current will again need to follow another path and thereby cause problems.

SUMMARY

The general knowledge and experience in the field on rotating equipment has been slowly declining for many years. In addition, brushholders have seldom received proper attention during troubleshooting or as part of a maintenance program. Therefore it is hoped that the above information will be helpful in creating awareness of the potential problems with brushholders as a very critical component in the satisfactory performance of carbon brushes on motors, generators, and other types of sliding contacts. The important factors to check for proper functioning of the holder and brush are:

1. Inside holder dimensions
2. Holder spacing
3. Holder angle
4. Holder height
5. Spring force
6. Electrical connections

When there is an opportunity to install new holders, the use of the principles mentioned above in combination with the latest constant-pressure holder and top-padded brush designs will yield a significant improvement in brush life and overall performance of the equipment.

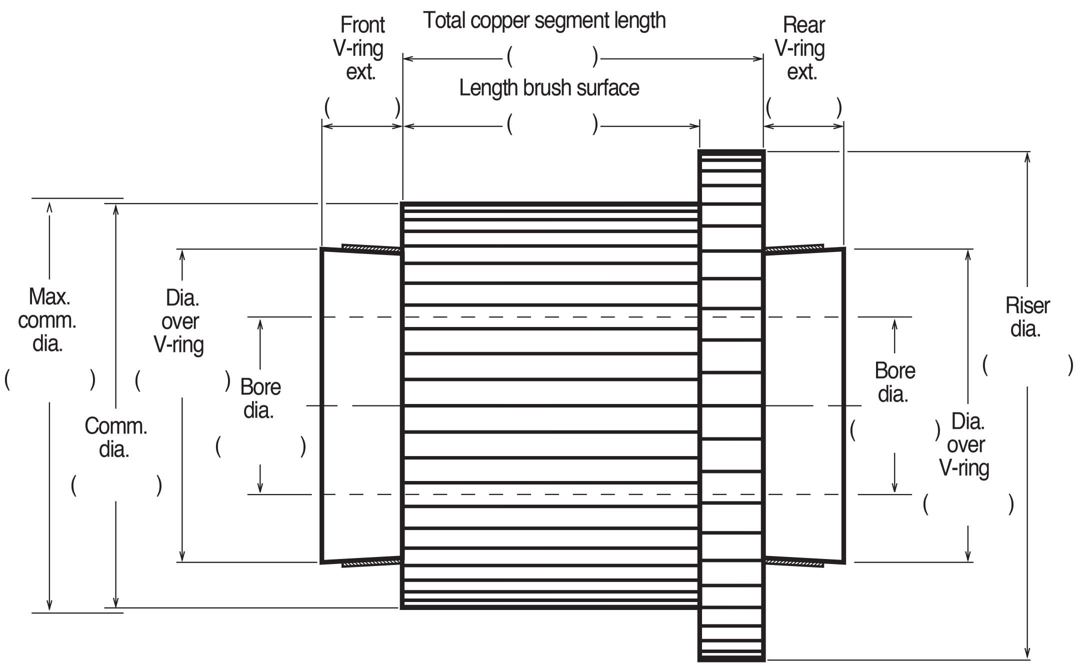
Note: This paper was presented on June 28, 1994, at EASA's Convention in San Antonio, Texas. It was published as *EASA Tech Note 22* (September 1995) with the permission of Helwig Carbon Products, Inc. It was reviewed and updated as necessary in October 2020.

3.7 COMMUTATORS

EASA® The Electro•Mechanical Authority

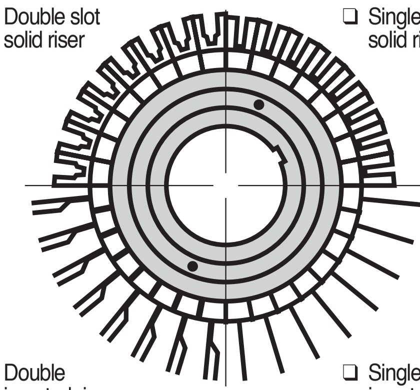
Electrical Apparatus Service Association

COMMUTATOR DATA



INDICATE RISER TYPE

❑ Double slot solid riser ❑ Single slot solid riser



❑ Double inserted riser ❑ Single inserted riser

Inserted riser thickness: ______________

Original mfr. ______ Frame No. ______ Type ______ Model No. ______

HP ______ KW ______ RPM ______ Volts ______ Amps ______

Number of copper segments ______ Mica segment thickness ______ Wire size ______ Wires per riser slot ______

Equalizer size ______ Equalizers per riser slot ______ Equalizer sequence on commutator ______

Commutator type: ❑ Nut V-ring ❑ Bolt V-ring ❑ Glassband ❑ External shrink ring
❑ Riveted* ______ ❑ Molded* ______ ❑ Other* ______

**If molded, riveted or other, micrometer measurement of shaft diameter corresponding to the commutator bore diameter is required.*

Shaft diameter

Keyway alignment with center line of: ❑ Mica ❑ Copper segment **Keyway size** ______

Job No. ______ Notes ______

COMMUTATOR MACHINING: TURNING AND UNDERCUTTING

PREPARING THE ARMATURE

1. Check tightness of commutator bolts (tightening nut) while commutator is hot. Tighten to manufacturer's specifications.	3. Make sure bearing seats run true before machining the commutator.
2. Repair commutator and armature winding as needed.	4. Wrap armature winding to keep chips out while machining the commutator.

TURNING THE COMMUTATOR

	ft/min = 0.26 x D x rpm where D (commutator diameter) is in inches	m/min = 0.00314 x D x rpm where D (commutator diameter) is in mm
SURFACE SPEED		
Single point carbide tool	300-500 ft/min	90-150 m/min
Synthetic diamond tool	Max 750 ft/min*	230 m/min*
DEPTH OF CUT	0.007 – 0.010 in	0.18 – 0.25 mm
FEED RATE	0.005 – 0.007 in/rev	0.13 – 0.18 mm/rev

*Or follow recommendations of manufacturer.
Note: Use a flat file to chamfer the ends of the commutator bars (0.040 in/1 mm).

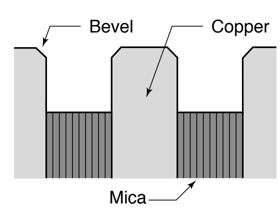
COMMUTATOR RUNOUT AND FINISH

	Peripheral speed	
	≤ 5000 ft/min	**> 5000 ft/min**
Maximum total indicated runout	0.0030" (0.076 mm)	0.0015" (0.038 mm)
Maximum total indicated runout in any quadrant	0.0015" (0.038 mm)	0.0010" (0.025 mm)
Maximum between adjacent bars	0.0002" (0.005 mm)	0.0002" (0.005 mm)
Maximum taper (in/ft)	0.0020"/ft (.051 mm/m)	
Surface finish	40 to 60 micro-inches (1.02 to 1.52 microns)	

UNDERCUTTING THE COMMUTATOR

1. Type of undercut:	U-shaped and beveled, as shown in Figure 3-44. (Note: In certain cases, the shop manager may determine that a different type of undercut should be used.)
2. Depth of undercut:	Factory specifications vary. A good rule to follow: make the depth equal to 1 - 1½ times the slot width.
3. Cleaning of slots:	Use slotting files and hand scrapers to eliminate mica fins along the sides of slots. Bevel the bar edges 0.015" (0.4 mm). Clean the slots using clean, oil-free air.
4. Polishing of commutator:	Polish the commutator with a fine-grit stone or sandpaper to eliminate any minor burrs. The surface finish should be no more than 40 to 60 micro-inches (1.02 to 1.52 microns). Note: Never use emery paper. Electrically conductive particles can lodge in the surface of the commutator bars and cause arcing.
5. Testing:	Growler and bar-to-bar test.

FIGURE 3-44



U-shaped undercuts and bevels.

The commutator and its maintenance

By Preben Christensen, EASA Staff Engineer (retired)

(Based on a presentation made by Glen Goebl of Kirkwood Commutator Company at the 1989 EASA Convention in San Francisco.)

It has been said that the commutator is the heart of the DC machine. Functioning as an electromechanical switch, it provides the means of conducting electrical power to or from the armature. The commutator is made primarily of copper bars that are insulated from each other and held together mechanically to resist the stresses imposed during the manufacture and operation of the armature.

COMMUTATOR DESIGN

Several different commutator designs are used in DC machines today, the oldest of which is the steel core or "cap and cone" commutator. Commutators of this type, which may either be arch-bound or vee-bound, consist of a specific number of wedge-shaped copper bars, separated by mica segments. The bars and segments are stacked to form a cylindrical assembly that is held together mechanically by a dovetailed anchorage of insulated steel vee-rings (see Figure 3-45).

The dovetail clamp angle, typically 30 degrees, provides contact area and retaining strength for the steel vee-rings, which are held tightly against the insulated bar clamp angle by rivets, bolts or a large tightening nut.

The arch-bound anchoring design (see Figure 3-46 on Page 3-42), which is used in virtually all steel core commutators and in *all* traction motor commutators, has a small gap at the clearance angle of the insulating vee-rings. This gap allows the bars to be pulled inward and prestressed when the commutator assembly is being tightened. Prestressing the bars neutralizes centrifugal forces that develop as the commutator rotates. The gap at the clearance angle is always maintained and must be sealed (usually with a string band).

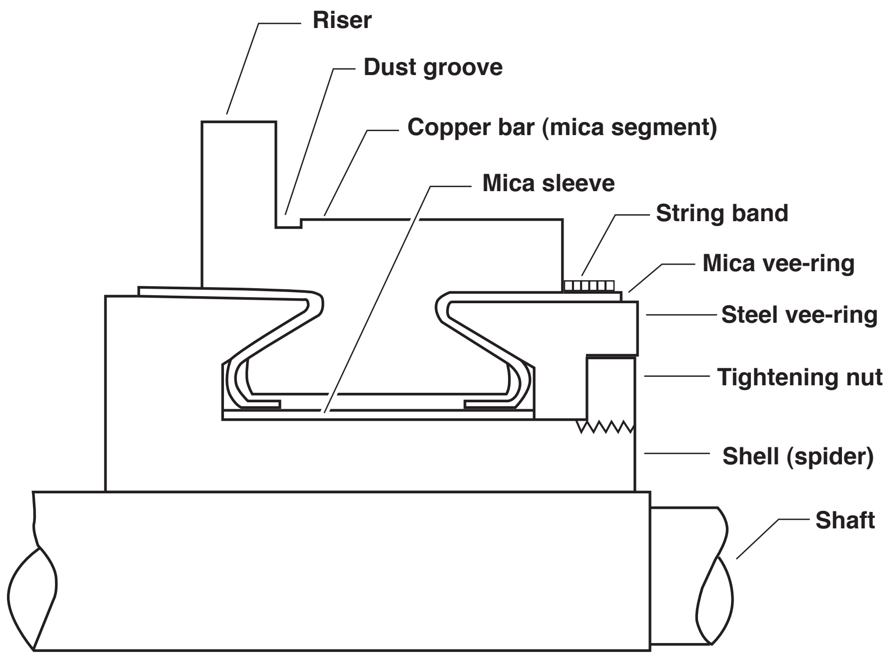
The vee-bound or wedge-bound commutator has an anchoring design similar to the arch-bound commutator except that no gap is provided at the clearance angle of the insulating rings (see Figure 3-47 on Page 3-42).

Some commutators are designed without dovetails. In these, the copper and mica assembly is prestressed and held in place with either glass bands or steel shrink rings on the OD of the assembly. Glass-banded commutators obtain radial squeeze by controlled winding tension. Shrink-ring commutators obtain radial squeeze by contraction as the heated steel rings cool to ambient temperature.

Another design is the molded commutator used on smaller armatures. With this type, the copper bars and the mica segments are held together mechanically with a reinforced thermoset phenolic molding compound.

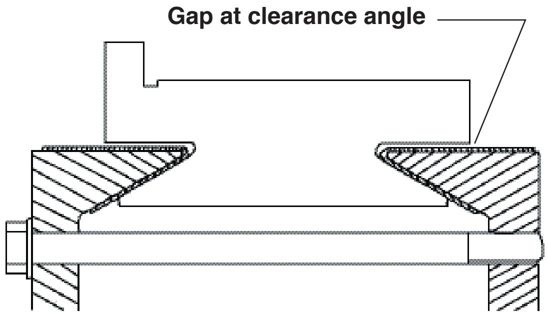
Arch-bound, steel core commutators are more commonly encountered in EASA service centers, however, so the following information pertains to them.

FIGURE 3-45



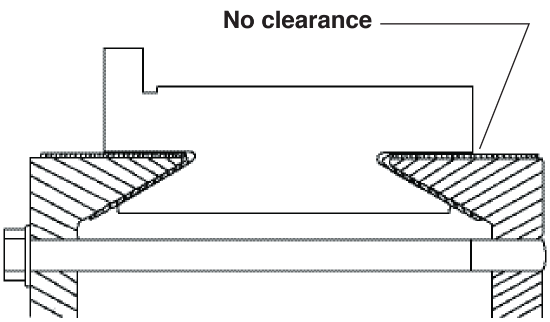
Steel core commutator construction.

FIGURE 3-46



Arch-bound commutator.

FIGURE 3-47



Vee-bound commutator.

MATERIALS USED

The basic materials used in an arch-bound commutator assembly are copper, mica and steel. The bars are drawn to close tolerances from hard-drawn copper to which fixed percentages of silver have been added to increase the annealing temperature. Adding 8 to 30 ounces of silver per ton (250 to 940 grams per 1000 kg) raises the annealing temperature of silver bearing copper to 325°F to 450°F (163°C to 232°C).[1]

The copper bars are terminated at one end with a riser that is either an integral part of the bar or one that must be attached. When the riser and bar are made separately, they are joined by silver soldering, TIG welding or riveting.

Two grades of mica are used in commutators: **segment** mica, which insulates the copper bars from each other; and **molding** mica, which is used for making vee-ring insulators and sleeves. The mica vee-rings and sleeves form the ground insulation for the commutator.

Both grades are made from mica flakes that are bonded together with organic binders such as shellac, epoxy and alkydvinyl. Mica bonded with inorganic binders is also available and is used exclusively where high temperatures are likely to be encountered. (High temperatures can carbonize organic binders and cause associated electrical problems.)

1 CDA Stds. Handbook, Part 2: Alloy Data, 8th ed. (New York: Copper Development Association, Inc., 1985).

Mica segments are punched or sawed from segment plate to match the bars. The segment plate is made of India mica (Muscovite) or of a softer type known as Amber mica (Phlogopite), both of which have comparable electrical properties. Amber mica is used mainly in commutators that are not undercut, since copper and Amber mica wear at a more uniform rate than do copper and India mica.

All mica segments for one commutator are made from segment plate of the same thickness. The thickness of segment plate varies between 0.025" and 0.062" (0.6 and 1.5 mm) with the tolerance being typically ± 0.001" (0.025 mm), nominal reading.

Molding mica, which is used to make the vee-ring insulators and the sleeves, has a higher binder content than segment mica. The higher binder content makes the molding mica pliable and easy to form with applied heat and pressure. When properly cured, the mica vee-rings conform intimately to the 30° clamp angle of the copper assembly and the steel vee-rings. The cured molding mica for the vee-rings measures between 0.045" and 0.062" (1.1 and 1.5 mm) in thickness, while the cured molding mica for the sleeves is between 0.020" and 0.045" (0.5 and 1.1 mm) thick.

Steel vee-rings, which come in many shapes, are manufactured as bars, forgings and castings from various alloy steels and ductile iron. The alloy is selected as much for its ability to be machined as for mechanical strength. The steel vee-rings are designed to withstand the mechanical loads from armature operation. These loads vary with the commutator size, speed requirements and application. When steel vee-rings in good condition are reused in commutators, there is no concern about the alloy steel used.

ASSEMBLY OF COMPONENTS

To successfully withstand the mechanical and thermal stresses incurred during armature operation, commutator components must be assembled to rigid specifications in the proper sequence.

First, copper and mica segments are stacked into a squeeze ring that prestresses the segment assembly and holds it together for further processing. The skew of the segments is then checked and corrected as necessary, and the dovetails are bored. Next, the bar assembly, along with its retaining members (vee-rings and bolts or tightening nut), is assembled. The commutator is then removed from the squeeze ring and "seasoned." This consists of multiple cycles of hot and cold pressing and torquing of bolts (tightening nuts). The baking temperatures reach 450°F (232°C).

After the copper has been turned to finished dimensions and a slot has been cut in each riser, the commutator is balanced. If required, it is then spin seasoned at elevated temperatures at 125 percent of the maximum operating speed of the armature. After spin seasoning, the commutator is again pressed and re-torqued to ensure a tight assembly. Radial movement of bars is checked before and after spinning, with maximum allowable bar-to-bar movement typically being 0.001" total indicator reading (0.025 mm TIR).

CHECKING NEW OR REBUILT COMMUTATORS

When your shop receives a new or a remanufactured commutator, it is strongly recommended that you make the following incoming checks before installing it on the shaft.

First, inspect it for any possible damage incurred in transit or handling. Second, confirm that the riser slot dimensions agree with the wire size being used. And third, after the commutator temperature has stabilized at room temperature, make a bar-to-bar test of 200 to 250 VAC, and a bar-to-ground electrical check of 1000 to 1500 VAC for one minute.

INSTALLING THE COMMUTATOR ON THE SHAFT

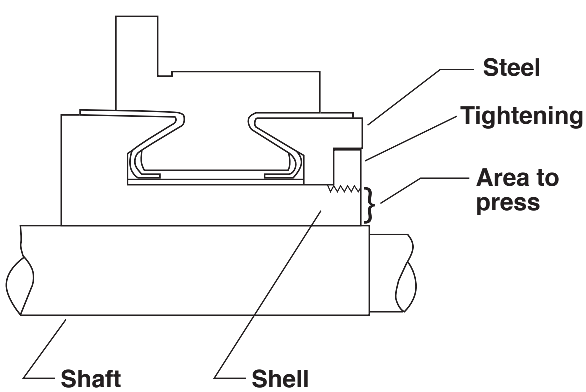
The recommended procedure for installing of the commutator on the shaft is to preheat the commutator and freeze the shaft. The combination of a heated commutator and a frozen shaft reduces the interference fit between the two and minimizes the mechanical stresses on the commutator assembly.

The commutator is usually installed with the armature core assembly already in place on the shaft. The commutator is heated to 200°C (392°F) in a baking oven for a minimum of four hours. A bronze tube is placed over the commutator's fit on the shaft and liquid nitrogen is injected into the tube where it is maintained for five minutes. This drops the shaft temperature to minus 112°C (minus 170°F). *Note: Never use a steel tube for this purpose since it will shatter at this low temperature.*

The heated commutator is then pressed onto the shaft and checked for correct alignment with special fixtures or by referring to a sketch (made before disassembly) of its original position on the shaft.

If the commutator is mounted on the shaft without preheating, be certain that no pressure is applied to the vee-ring or the tightening nut. Pressure must be applied only to the face of the spider or the shell, which normally is the shoulder located immediately above the commutator shaft diameter (see Figure 3-48).

FIGURE 3-48



Pressure must be applied only to the face of the spider or the shell.

CONNECTING THE LEADS

The commutator risers must be slotted correctly to ensure proper fit for the leads. The width of the riser slot should be slightly greater than the wire thickness. The recommended tolerances for wire clearance in riser slots are: +0.002" and - 0 (+0.05 mm and - 0) for risers being TIG welded; and +0.004" and - 0 (+0.10 mm and -0) for soldered connections.

Care must be exercised in staking armature coil leads and equalizers into riser slots. Applying excessive force can push a bar downward and cause unstable commutator operation. The instability occurs after the commutator has been turned and the armature is put into service. In such cases, the sunken bar can rise to its original position, protruding beyond adjacent bars as though it had lifted. Even if the bar rises only a few thousandths of an inch, it can cause brush chipping, chattering and sparking.

The temperature that the commutator may reach during soldering or TIG welding is also of great concern. The temperature should be kept to the minimum needed to achieve a good connection. The 95-5 solder (95% tin and 5% antimony), which becomes liquid at 464°F (240°C), is recommended for most commutators.

Overheating the commutator can anneal the copper and degrade the insulation. If excessive heat is allowed to migrate to the dovetail area, the copper will anneal causing bar movement. For this reason, use a staggered sequence rather than heating consecutive bars when soldering or TIG welding commutator connections.

If care is taken in installing the commutator on the shaft and in making the lead connections, re-torquing the commutator should not be necessary, except to verify nut and bolt tightness. Verify the tightness of the nut-type commutator by drifting the nut. Verify the tightness of the bolt-type commutator with a torque wrench. Torque values for the size and grade of the bolts should conform with the bolt manufacturer's or SAE standards.[2]

SAFEGUARDING THE COMMUTATOR FROM VARNISH DAMAGE

The commutator should not be exposed to varnish or submerged during VPI treatment. If either occurs, uneven distribution of varnish on the commutator may result in an unbalance of the armature. To minimize the unbalance, slowly rotate the armature as the varnish dries. Exposing the commutator to impurities in the varnish can also cause shorted bars.

MACHINING THE COMMUTATOR

The surface of the commutator must be machined to a smooth, polished finish to minimize the wear on copper and brushes. Commutators with flush mica should be machined with a single-point carbide tool at a surface speed of about 500 feet per minute (2.5 meters per second). For commutators with pre-undercut or subflush mica, use a synthetic diamond tool at a surface speed of approximately 750 feet per minute (3.8 meters per second). The approximate amount of metal removed per cut should be 0.007" to 0.010" (0.18 to 0.25 mm) with either carbide or diamond tools. The feed rate should be 0.005 to 0.007 inch per revolution (0.13 to 0.18 mm per revolution).

The tool geometry should be such that you get a clean, sharp break at the trailing edge of the cut. The setup must be rigid and without significant vibration—particularly if diamond tools are used.

[2] Society of Automotive Engineers.

Periodic machining of the bars and wear from operation reduce the OD of the commutator. Check with the manufacturer to determine what the minimum diameter is for that commutator. A commutator diameter that is too small causes increased heating.

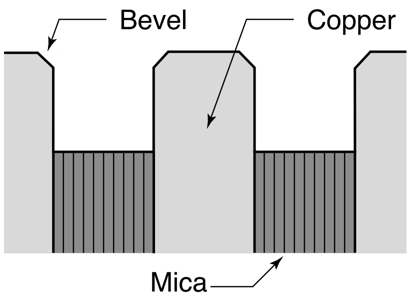
Rewinding an armature may also require facing of the riser, thereby reducing its width. When the riser width becomes less than 1/3 of its original width, consider replacing the commutator.

UNDERCUTTING THE COMMUTATOR

Mica segments must be undercut to compensate for wear of the copper bars. When the copper has worn down below the surface of adjacent mica, firm contact between the brush and the commutator surface is disturbed and sparking may occur.

For most service centers and OEMs, the undercutting procedure usually involves cutting U-shaped grooves between bars to completely remove the mica for the full depth of the cut (see Figure 3-49).

FIGURE 3-49



U-shaped undercuts and bevels.

The depth of the cut is measured from the brush track diameter of the finished commutator. Factory specifications for undercutting vary. A good rule to follow: make the depth equal to 1 - 1 ½ times the slot width.

Slotting files and hand scrapers should be used to eliminate mica fins (thin edges of mica along the sides of the slots) that may remain after undercutting. This operation also chamfers or bevels the edges of the bars (see Figure 3-49). Beveling removes rough spots from bar edges that result from work hardening of the copper during the undercutting process. A 1/64” (0.4 mm) beveled face is usually sufficient to remove any roughness.

U-slots reduce the frequency of undercutting but can trap contaminants that can cause short-circuits between bars. Slow-speed machines are prone to this kind of failure because they do not develop enough centrifugal force to eliminate contaminants.

A number of devices are available for undercutting mica segments–some hand held, others bench type that move on a fixed track. While visual alignment is required for these undercutters, the more sophisticated ones have an optical sensor for tracing the copper and mica. Whichever device is used, centering the undercutter saw between bars is critical.

APPLYING THE STRING BAND

The mica, which insulates the bars from the underlying hub, extends past the bar ends and should be protected by string banding (Figure 3-50), a Dacron-epoxy band or a Teflon band. Procedures for each method are provided below.

FIGURE 3-50

Top: Strings bands in good condition. Bottom: Disintegrated string bands.

After commutator machine work is complete, protect the commutator by wrapping it with heavy paper or similar material (Figure 3-51). When practical, leave the protective wrapping in place until it is time to adjust the brushholder height.

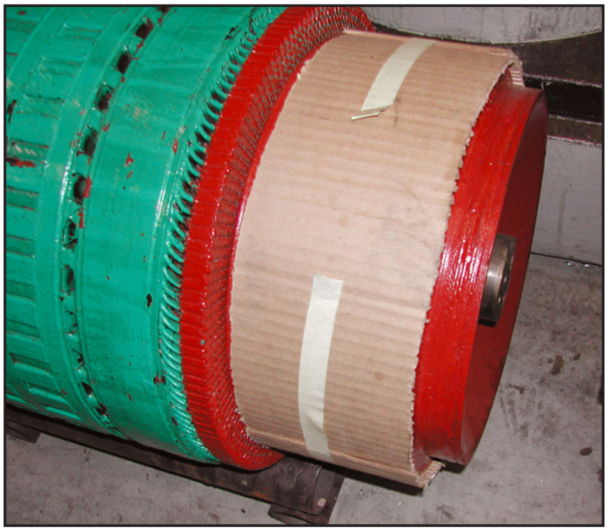
String band

Use round string, not flat, to make the string band. Start by forming a loop at one end of the string and placing it flat on the mica at right angles to the banding area. Point the loop away from the commutator bars, extending it beyond the edge of the banding area about 1/2” (12.7 mm). Extend the end of the string that forms the loop past the banding area towards the risers.

Now, starting at the commutator bars, wrap the string circumferentially around the mica band, covering the loop as you go. Lay each turn against the preceding one until you reach the outside of the mica.

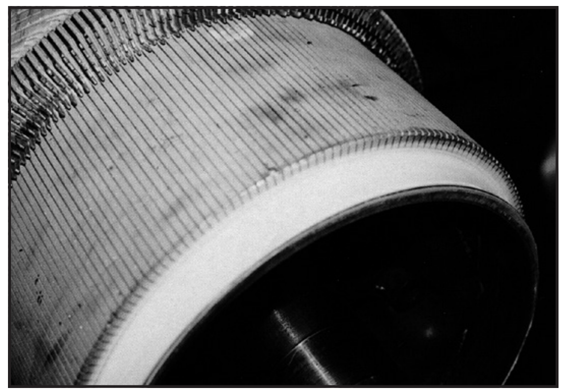
Next, thread the free end of the string through the loop created earlier, and pull the starting end of the loop until the

FIGURE 3-51



This commutator has been wrapped with cardboard to protect it from damage.

FIGURE 3-52



Top: Limitrack (UH 100) is an epoxy used to protect and seal string bands while also minimizing carbon tracking and preventing flashover. Bottom: ARS (Arc Resistant Sealant) silicone seals and insulates the commutator.

Courtesy of Chem-Spec Corp.

finished end is drawn under the string band. Trim the protruding ends flush with the edge of the banding.

The last step is to apply varnish, an epoxy coating designed for the armature model, or a pre-formed Teflon band. Ideally, the material covering the string band should have a smooth surface to minimize carbon tracking and prevent flashover. Several options are available, including Limitrack (Sterling UH100), Dacron glass tape applied with an epoxy product, brushable Viton, Elecrolok U98-C-12 or other similar products (Figure 3-52).

Chamfering should be done before applying protective material to the string band. If chamfering is done afterwards, use shim stock or hose clamps to protect the smooth epoxy finish.

When applying a protective coating to the string band, avoid getting material on the commutator surface or in the slots between bars. One trick is to wrap the edge of the commutator with electrical tape (sticky side up), stretching it slightly so that it forms over the bar ends and seals them (see Figure 3-52, top photo).

Protective banding

The mica can be covered by a protective banding instead of the traditional string band. The resin-rich fiberglass banding material is not suitable for this, because the surface finish must be smooth to prevent carbon tracking. Dacron armor tape can be used, when a two-part epoxy is brushed onto the layers as they are applied.

With the armature rotating at low speed (15 to 40 rpm, depending on the diameter) in a lathe, start wrapping the Dacron tape flat on the mica and brush two-part epoxy between layers. A heat lamp or heat gun mounted on the toolpost will accelerate curing. The slow rotation will ensure a smooth, even coating and cause a slight radius to form as the epoxy tries to migrate up the end of the bars.

When enough material has been applied, cut the Dacron and brush on just enough epoxy to create a smooth coating.

Teflon band

Teflon bands are available for traction armatures and must be purchased for the exact armature. They are shipped on cardboard rings, expanded oversized for mounting. Do not remove a Teflon band from the shipping ring until completely ready to install it. The Teflon will return to its "memory" size quickly and cannot be conveniently restretched for installation.

To install the ring, place the armature vertically in a stand and tightly wrap the mica with underlayment tape. Underlayment tape should be a resin-rich narrow material [approximately 1/8" (3 mm) wide].

Brush excess resin from the underlayment tape onto the lower face of the bar ends, so that the radiused edge of the Teflon band will adhere to the bar ends.

Slide the Teflon band from the cardboard tube directly onto the prepared mica. The radius edge should contact the end of the bars.

Use a preheated steel ring, sized for the band, to simplify installation. The inside diameter of the ring should be slightly larger than the Teflon band, with a slight chamfer so that it will rest against the radius of the band. This preheated ring reduces the curing time for the underlayment tape, while holding the Teflon band in position during curing. To make the ring easier to handle, some repairers weld handles on opposite sides of the ring.

Next, bake the entire armature to fully cure the resin beneath the Teflon band.

After the resin has cured, inspect the Teflon band to make sure it is tightly bonded to the bar ends and solid. If the Teflon band is loose, it will not be effective and may come off. If there are voids between the Teflon and the ends of the bars, carbon can become trapped in them, resulting in shorting between the bars.

PLATING THE COMMUTATOR

Commutators on machines that operate in corrosive atmospheres may require platinum plating to function properly. Platinum plating of the commutator may also be necessary for machines placed in storage for long periods of time. Caution: Never use a commutator stone on a plated commutator.

Most OEMs plate commutators after the armature has been wound and finished by applying two or three thin layers of liquid platinum to the brush riding surface. Service shops normally follow this same procedure on machines at the job site.

COMMUTATOR FIELD PROBLEMS

Overspeeding or overheating the commutator during operation of the machine can cause bar movement and result in a rough commutator surface. This condition will adversely affect the brush riding ability and can cause severe dusting or, in the worst case, break the brushes.

The commutator film that is so vital for good commutation could be disturbed on units operating in the acidic atmosphere of paper mills. Machines located in areas where silicone solvents are present will have rapid brush wear, particularly totally enclosed units.

Finally, applying power to the commutator with the armature locked could result in selective overheating of the commutator. If this condition lasts for an extended time, bars spaced the same distance apart as the brushes will be softened by the heat developed, damaging the commutator.

CONCLUSION

To summarize, the commutator, though seemingly simple in construction, must be designed well if it is to function properly. It must also be built of quality materials: copper capable of maintaining stability at elevated temperatures; mica that provides excellent insulating properties; and steel of sufficient mechanical strength.

The commutator is manufactured to rigid specifications, ensuring its ability to withstand the mechanical and thermal stresses encountered during the manufacture and operation of the armature.

When an armature is rewound or reconditioned, all work must be done in such a way that the commutator will remain stable and serviceable.

Finally, ample care must be taken that the operating conditions for the machine will not adversely affect the usefulness of the commutator.

Note: This article was originally published as *EASA Tech Note 14* (December 1991). It was reviewed and updated as necessary in October 2020.

TIG-welded commutator connections

By E. Steve Darby (deceased)
Darby Electric Co., Inc.
Anderson, SC

A modern method of connecting armature coil conductors to the commutator riser in DC motors is by TIG welding.

TIG (Tungsten Inert Gas) welding is also known as heliarc welding and also as GTA (Gas Tungsten Arc) welding. GTA is more accurately descriptive overall since inert gas is not the only type used. Sometimes a reactive gas such as 5% hydrogen may be used. For the purpose of this paper, however, we will use the term TIG.

New insulation systems enabled manufacturers to work DC motors and generators at higher temperatures; and this increased the frequency of thrown solder. Two alternate methods of connections were developed to overcome this problem. One is heat staking, which is a production process not suitable for the repair service industry. The second method is TIG welding, which is suitable for both manufacturing and repair as long as some general rules are known and followed.

With TIG welding, a pinpoint accurate arc between the tungsten electrode and the copper conductor and riser produces a molten puddle of metal that joins or connects the commutator and conductor without the addition of filler material. The inert gas shields the arc and molten metal to prevent contamination and to eliminate the need for a flux. One advantage of this process is that heat is generated fast enough to complete the weld before the heat is conducted away from the area by the copper conductors. Another major advantage is the total absence of corrosive material, such as acid base solder paste that is sometimes used and not totally removed from soldered connections.

JOINT PREPARATION

Joint preparation is very important in TIG welding. Carelessness here will prevent a successful completion of the joining operation. The copper conductors must be clean. They must be free of insulation, grease, oil, and oxides; and they must not be tinned. If the commutator is being reused, it must be totally free of solder. Solder boils at welding temperature and will splatter out the back of the riser, causing shorts. It also will contaminate the weld puddle, resulting in a soldered joint rather than a solid copper welded joint.

After making certain that the conductors are clean, place them in the slots. It is important that they fit the slot in the risers exactly, so care must be taken to ensure that there is no gap. After the conductors are placed in the slots, the commutator should be faced in a lathe to give a perfectly flat and true surface for welding. It is neither necessary nor advantageous to let the conductors extend through the commutator face.

EQUIPMENT

In TIG welding, the equipment is equally important as joint preparation. The welder should be designed for controlling the flow of inert gas and for regulating the supply of cooling water to the torch tip. It must be direct current, and it must be connected "straight polarity," which means that the tungsten electrode is negative and the workpiece is positive. This concentrates approximately 70% of the heat into the workpiece.

If the welder is connected for reverse polarity as in MIG welding, 70% of the heat will be concentrated into the tungsten, which will produce a very shallow weld and consume the tungsten electrode. In MIG welding, you want the heat concentrated in the filler metal, while in joining by TIG welding, you want the heat in the two or more pieces to be joined together.

Helium gas gives more heat for a given current, and that is what you want when welding thick metal with high heat conductivity like copper. Although argon gas requires you to play the arc too long, it does give you a smoother arc. Consequently, if you cannot control the arc with 100% helium, try 75% helium and 25% argon. **Do not use 100% argon** in TIG welding commutators.

Another important factor in using helium is to double the gas flow. That is, use about **30 cu. ft./hour for helium** (.85 cu. meters/hour).

The **electrode should be 2% thorium alloyed tungsten,** which increases the current-carrying capacity and also prevents the tungsten from forming a round ball on the end. The electrode should be ground to a sharp point before it is used; it must also hold a point during the welding operation. In addition, the electrode should protrude past the end of the shielding gas cup, so that the operator can see the arc while welding. This requires the electrode to **protrude approximately 1/8"** (3 mm) and necessitates the increased flow of gas previously discussed.

Following these basic simple rules will give you deep and narrow welds with no distortion of the riser, whereas changing any of the criteria–such as polarity, gas or electrode–or not having the joint clean, invites disaster. If a mistake is made and a riser is ruined, the commutator is also ruined. In such a case, the entire rewind must be done over, including the installation of a new commutator.

OPERATOR SKILL AND PROPER WELDING PROCEDURES

Operator skill is the next requirement for success in TIG welding DC commutators. First of all, it is extremely important that the operator be aware of the amount of heat being conducted into the winding. **This can be controlled by welding every third riser and making three turns around the commutator.**

The operator should also weld one side of wide conductors and then the other side. Proceeding in this way will prevent the arc from being held long enough to form a puddle across the wide conductor. If the arc is held too long, the riser will puddle and sag or flow, ruining the commutator.

SUMMARY

The purpose of this paper is to give the experienced welder a few tips that will enable him to do a quality job without going through a long period of trial-and-error welding. Perhaps it would be best to restate the criteria for TIG welding commutators as follows:

1. A qualified, experienced welder
2. Proper joint preparation
3. TIG welding equipment
4. Helium gas
5. Thorium alloyed tungsten electrode

The above list puts the importance of a qualified, experienced welder in its proper perspective–for the operator is the most important aspect in TIG welding commutators.

Note: This article was originally published as *EASA Tech Note 9* (September 1986). It was reviewed and updated as necessary in October 2020.

3.8 FROG-LEG WINDINGS FOR DC MACHINES

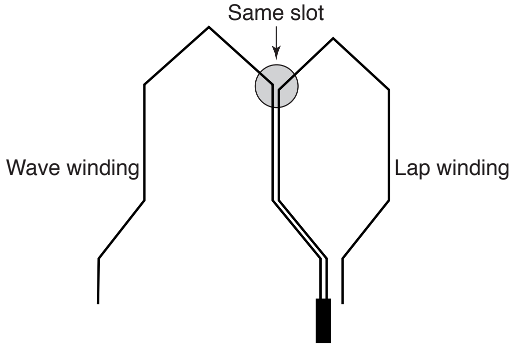
By Preben Christensen, EASA Staff Engineer (retired)

The frog-leg winding is a combination of a lap and a wave winding, principally used on medium and large size direct-current machines. Developed by the Allis-Chalmers Manufacturing Company around 1925, its primary advantage is that it eliminates the separate equalizer winding normally required in a lap-wound armature. This departure from conventional winding design made the manufacture of self-equalizing armatures possible. Other variations of wave windings are covered in EASA's *Fundamentals of DC Operation and Repair Tips*.

The lap and wave sections of frog-leg coils are wound in the same slots of the armature and connected to the same commutator. The photo at right shows a typical one-turn frog-leg coil. The lap and the wave sections are insulated from each other and are usually wound on the armature as separate coils. This makes installation much easier than if the coils are tied together and placed in the slot as a single unit.

The key to the frog-leg armature is simple as shown in Figure 3-53. Look at any slot and select the coil side of the lap and wave windings that exit the slot in the same direction toward the commutator. In the illustration above, the right side of the wave winding and the left side of the lap winding that share the same slot must connect to the same commutator bar.

FIGURE 3-53



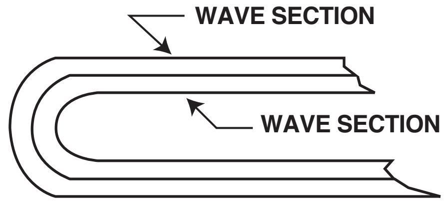
Key to frog-leg winding.

Figure 3-54 shows the lap section of the coil sandwiched in between the wave section.

Assuming that the number of slots equals the number of commutator bars, the position of the sides of a one-turn frog-leg coil in a slot would be as shown in Figure 3-55. While an armature wound with either a lap or a wave winding has two coil sides per slot, a frog-leg winding has four, as is also illustrated in Figure 3-55.

Instead of the customary two leads, in a frog-leg winding four leads are connected to each commutator bar, two from the lap section and two from the wave section. The characteristic manner in which the coil ends are bent gives the coil the frog-like appearance from which it gets its name (see photograph).

FIGURE 3-54

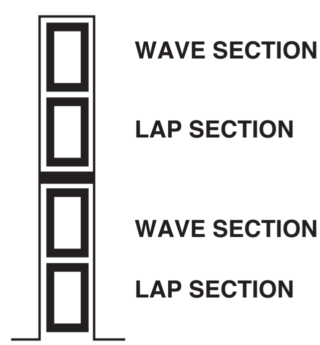


Relative position of lap and wave sections of a frog-leg coil.

The lap section of most frog-leg windings is a simplex winding, wound progressively. For this reason, all calculations referred to here are based on this type of lap winding. The wave section of the frog-leg winding, on the other hand, is wound retrogressively, because the lap and the wave sections in a frog-leg winding must not both be connected alike. If the lap section is progressive, the wave section must be retrogressive, or vice versa.

The coil of a frog-leg winding is formed by combining a lap and a wave coil into one coil. These combined coils are wound (and connected to the commutator) in the same manner as separate lap and wave coils. The same rules that are used

FIGURE 3-55



Position of lap and wave sections of a one-turn frog-leg coil in an armature slot.

for calculating coil and commutator pitch for ordinary lap and wave windings, therefore, also apply to the frog-leg winding:

1. The lap and the wave sections of the frog-leg coil both span a pole pitch.
2. The commutator pitch of the simplex lap winding is always equal to one bar. The coil leads, therefore, are connected to adjacent commutator bars.
3. The commutator pitch of the wave winding is always in accordance with the following equation:

$$\text{Commutator pitch} = \frac{\text{Bars} \pm \text{"Plex"}}{\text{Poles} \div 2}$$

(Using the **positive value** will result in a **progressive** winding. Using the **negative value** will produce a **retrogressive** winding.)

In order to calculate the commutator pitch of the wave section in a frog-leg winding, the multiplicity or "plex" of this section must first be determined. The lap and the wave sections of the frog-leg winding are connected in parallel. Successful operation requires both winding sections to be made with an equal number of parallel paths.

While the simplex lap section has as many parallel paths or circuits as there are poles, the simplex wave section has only two circuits regardless of the number of poles. For this reason, the wave section is always a multiplex winding, having the "plex" equal to the number of pairs of poles, so that the number of circuits of the two winding sections will be equal.

For example, a four-pole frog-leg winding having a simplex lap section will require a duplex wave section in order to make the circuits in both sections equal. Table 3-3 indicates the correct lap-wave "plex" combination for 4-, 6- and 8-pole machines.

TABLE 3-3: COMBINATION OF LAP-WAVE "PLEX" AND PATHS FOR FROG-LEG WINDINGS

Winding Section		No. of Poles	Number of Paths		
Lap Section	Wave Section		Lap Section	Wave Section	Frog-Leg Coil
SIMPLEX	Duplex	4	4	4	8
	Triplex	6	6	6	12
	Quadruplex	8	8	8	16

As mentioned above, both winding sections must have an equal number of parallel paths. In order to share the armature current equally, the coils also must be wound with the same wire size and the same number of turns per coil.

Figures 4 and 5 show typical frog-leg winding diagrams for both 4- and 6-pole armatures. Notice that in these armatures the lap coil has the same coil span as the wave coil. Also, while the lap sections are connected progressively, the wave sections are connected retrogressively.

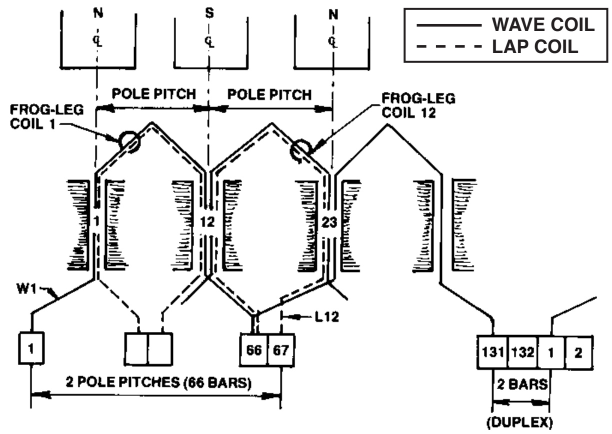
The "plex" of the wave section in the frog-leg winding is equal to the number of *pairs of poles*. The "plex" can also be verified by tracing the wave winding once around the armature and noting the connections to the commutator bars.

The commutator pitch of the 4-pole, retrogressive duplex wave winding (Figure 3-56) is calculated to be 65 bars. Tracing this winding once around the commutator (1-66-131), we arrive **two** bars behind the starting point. Similarly, the commutator pitch of the 6-pole, retrogressive triplex wave winding (Figure 3-57) is calculated to be 39 bars. Tracing this winding once around the commutator (1-40-79-118), we arrive **three** bars behind the starting point. Notice that the "plex" of the wave section is equal to the number of bars we arrive at behind the starting point when tracing the wave winding once around the armature. The number of paths of these windings also conforms with those shown in Table 3-3.

In a frog-leg winding commutator bars located exactly two pole pitches apart will always have equal electrical potential (just as in a lap-winding).

The distance between the commutator bars referred to above is the same as that spanned by cross-connectors in an ordinary lap winding. In the frog-leg winding in Figure 3-56, for example, commutator bars 1 and 67, located exactly two

FIGURE 3-56



$$\underset{\text{(WAVE SECTION)}}{\text{COMMUTATOR PITCH}} = \frac{\text{BARS -"PLEX"}}{\text{POLES/2}} = \frac{132\text{-}3}{4/2} = 65 \text{ BARS}$$

$$\text{2 POLE PITCHES} = \frac{\text{BARS}}{\text{POLES/2}} = \frac{132}{4/2} = 66 \text{ BARS}$$

$$\text{RATIO} \quad \frac{\text{SLOTS}}{\text{POLES}} = \frac{44}{4} = 11$$

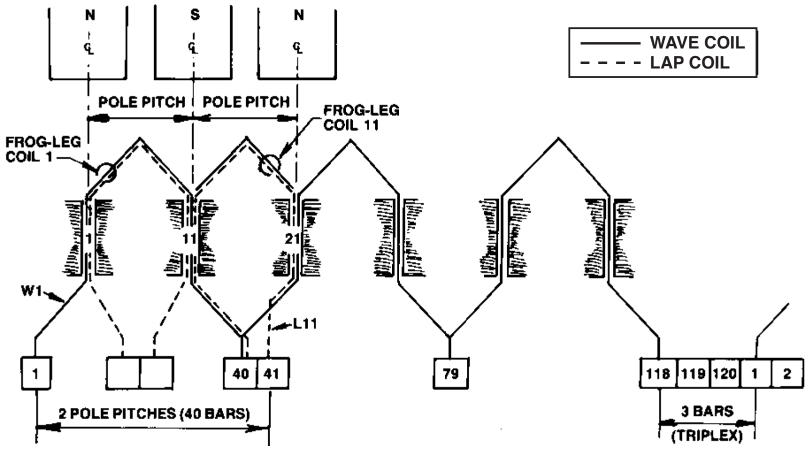
THIS RATIO IS A WHOLE NUMBER. THEREFORE THE COIL PITCH MUST BE THE SAME FOR BOTH WINDINGS.

SUMMARY OF WINDING DETAILS

	Lap	Wave
Type of Winding	Simplex, Prog.	Duplex, Retrog.
Number of paths	4	4
Coil pitch	11 Slots	11 Slots
Coil span	Slots 1-12	Slots 1-12
Commutator pitch	1 Bar	65 Bars
Succession of bars when tracing winding	1-2	1-66-131

Frog-leg winding diagram (4 poles, 44 slots, 132 bars).

FIGURE 3-57



COMMUTATOR PITCH (WAVE SECTION) = $\frac{\text{BARS - "PLEX"}}{\text{POLES/2}} = \frac{120-3}{6/2}$ = 39 BARS

2 POLE PITCHES = $\frac{\text{BARS}}{\text{POLES/2}} = \frac{120}{6/2}$ = 40 BARS

RATIO $\frac{\text{SLOTS}}{\text{POLES}} = \frac{60}{6}$ = 10

THIS RATIO IS A WHOLE NUMBER. THEREFORE THE COIL PITCH MUST BE THE SAME FOR BOTH WINDINGS.

SUMMARY OF WINDING DETAILS

	Lap	Wave
Type of Winding	**Simplex, Prog.**	**Duplex, Retrog.**
Number of paths	6	6
Coil pitch	10 Slots	10 Slots
Coil span	Slots 1-11	Slots 1-11
Commutator pitch	1 Bar	39 Bars
Succession of bars when tracing winding	1-2	1-40-79-118

Frog-leg winding diagram (6 poles, 60 slots, 120 bars).

pole pitches apart, are not connected with a cross-connector as could be the case if the winding had been an ordinary lap winding. Instead, wave coil W1 and lap coil L12 (each having a lead connected to commutator bar 66) are connected in series between bars 1 and 67. These two commutator bars have the same electrical potential because the voltages induced in wave coil W1 and lap coil L12 are equal and opposite at any position of the armature.

The voltages induced in coils W1 and L12 are equal because these two coils are always positioned identically in the magnetic field of the main poles. One side of both W1 and L12 occupy a common slot (slot 12). The other sides of W1 and L12 occupy slots 1 and 23, which are exactly two pole pitches apart. The voltages induced in coils W1 and L12 are not only equal, but also oppose each other because these two coils are connected retrogressively and progressively, respectively. Therefore, the voltage measured between commutator bars 1 and 67 is, theoretically, zero.

The combination of one wave coil connected in series with one lap coil serves as the cross-connection or equalizer in the frog-leg winding.

Figure 3-56) shows wave coil W1 and lap coil L12 serving as a cross-connector. Similarly, any other pair of wave/lap coils connected in series between commutator bars spaced exactly two pole pitches apart can also be thought of as a cross-connector in the frog-leg winding. The frog-leg winding, therefore, is self-equalizing and requires no separate equalizer winding.

SPLIT-PITCH COILS

When the ratio of slots/poles is a whole number for an armature with a frog-leg winding, as in Figure 3-56 and Figure 3-57, the coil pitch of both winding sections is made equal. If, however, the ratio of slots/poles is a mixed number (such as $12^1/_2$), the coil pitch of the lap and the wave coils must be made equal to the nearest whole numbers of the slots/poles ratio.

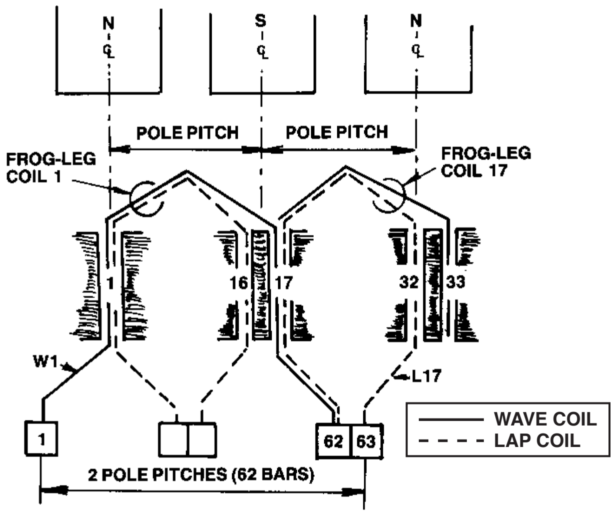
With a ratio of 12½, for instance, the nearest whole numbers are 12 and 13. The lap coil is usually made with the shorter pitch (e.g., 12, slots 1-13); the wave coil is made with the longer pitch (e.g., 13, slots 1-14). This type of frog-leg coil is known as a "split-pitch" coil. It is made very much like the one previously described, except that only one coil side of the lap section and one coil side of the wave section are placed in the same slot. The other side of each of the two coil sections are placed in adjacent slots.

The following example shows how split-pitch coils should be connected. A four-pole, frog-leg winding in an armature with 62 slots and 124 commutator bars has a slots/poles ratio of 62/4, or 15½. Since this ratio is not a whole number, the lap and the wave coils must be made with different slot spans, as shown in Figure 3-58 on Page 3-52.

The lap section of frog-leg coil 1 is placed in slots 1 and 16, while the wave section (W1) spans slots 1-17—one slot larger. The lap section (L17) of frog-leg coil 17 is placed in slots 17 and 32, while the wave section of this same coil spans from slot 17 to slot 33. One side of wave coil W1 and lap coil L17 occupy a common slot (slot 17). A lead from each of these coils is connected to commutator bar 62. Both coils are connected in series between bars 1 and 63, which are two pole pitches apart.

Wave coil W1 and lap coil L17 are therefore serving as a cross-connector because the voltages induced in these two coils neutralize each other at any position of the armature, as explained earlier.

FIGURE 3-58



$$\text{COMMUTATOR PITCH (WAVE SECTION)} = \frac{\text{BARS - "PLEX"}}{\text{POLES}/2} = \frac{124-2}{4/2} = 61 \text{ BARS}$$

$$\text{2 POLE PITCHES} = \frac{\text{BARS}}{\text{POLES}/2} = \frac{124}{4/2} = 62 \text{ BARS}$$

$$\text{RATIO } \frac{\text{SLOTS}}{\text{POLES}} = \frac{62}{4} = 15\tfrac{1}{2}$$

THIS RATIO IS A *MIXED* NUMBER. THEREFORE THE COIL PITCH MUST *NOT* BE THE SAME FOR BOTH WINDINGS.

SUMMARY OF WINDING DETAILS

	Lap	Wave
Type of Winding	**Simplex, Prog.**	**Duplex, Retrog.**
Number of paths	4	4
Coil pitch	15 Slots	16 Slots
Coil span	Slots 1-16	Slots 1-17
Commutator pitch	1 Bar	61 Bars
Succession of bars when tracing winding	1-2	1-62-123

Frog-leg winding diagram (4 poles, 62 slots, 124 bars).

SUMMARY

1. The frog-leg winding, a combination of a lap and a wave winding, requires no separate equalizers.
2. Frog-leg windings have balanced armature circuits because of the equalizing effect of the combined lap and wave sections.
3. In a frog-leg winding any series-connected lap/wave pair of coils are connected to commutator bars which are spaced exactly two pole pitches apart.
4. Both lap and wave coils of a frog-leg winding are wound with the same wire size and with the same number of turns per coil. The two winding sections also have an equal number of parallel paths.
5. The lap section of a frog-leg winding is usually a simplex winding, wound progressively, while the wave section is a multiplex winding, wound retrogressively.
6. Frog-leg windings require the use of split-pitch coils when slots/poles is a mixed number.

Note: This article was first published as *EASA Tech Note 4* (July/August 1984). It was reviewed and updated as necessary in October 2020.

3.9 TROUBLESHOOTING A DC MOTOR AT THE JOB SITE

Note: Never energize the armature unless the field is energized.

INTRODUCTION

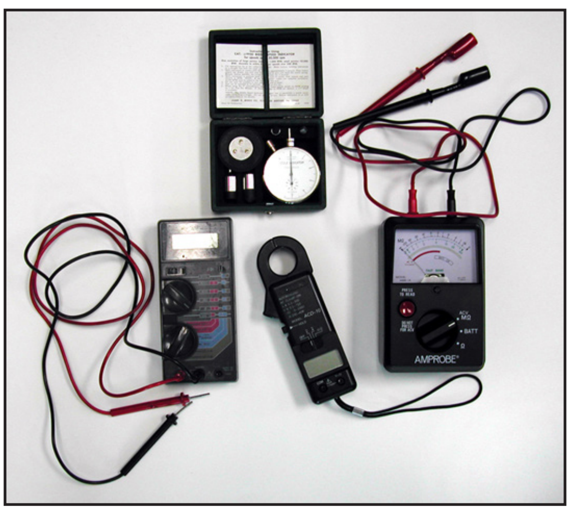
Troubleshooting a DC machine at the job site can be challenging, especially for those with limited drive/control experience. It is possible, however, to perform effective, on-site troubleshooting using basic testing equipment. The first step is to find out whether the problem is in the motor or somewhere else.

This section outlines procedures for determining the cause of DC machine problems, as well as methods for diagnosing common DC machine control problems. In some cases, these methods and procedures can save the technician from removing the motor from service.

Basic testing equipment (Figure 3-59) needed for troubleshooting DC machines includes:

- Megohmmeter
- AC/DC voltmeter
- DC clamp-on ammeter
- Ohmmeter
- Tachometer
- Jumper leads with alligator clamps

FIGURE 3-59



Typical test equipment includes (clockwise from top): tachometer, megohmmeter, DC clamp-on ammeter, and AC/DC voltmeter.

Before proceeding, record all nameplate data of the machine, noting especially the rated rpm and the voltage and current ratings of the field and armature circuits (Figure 3-60).

Base speed is a good reference point when troubleshooting a DC machine. When full field current and rated armature voltage are applied to a shunt motor, the no-load speed should be slightly faster than the base speed.

The next step is to find out how long the motor has been in operation. The list of likely problems, and therefore the things to check, depends on whether the machine was put into service recently or has been running faultlessly for years. This is the point where the right question can make all the difference. If the motor has been in for years, but the drive was just replaced, treat it as if the machine was just installed.

Some troubleshooting procedures require that power be applied to the motor. Because of the possible danger involved, do not apply power to the motor until after taking these precautions:

- Inspect the motor for obvious defects that could prevent safe testing. Look for damaged windings, loose connections, broken or missing parts, and defective brushes or brushholders.
- Use the megohmmeter to measure the insulation resistance of each winding and record the readings. If the readings indicate a winding fault, do not apply power to the motor.

Failure to follow these precautions could result in injury, or further damage to the motor.

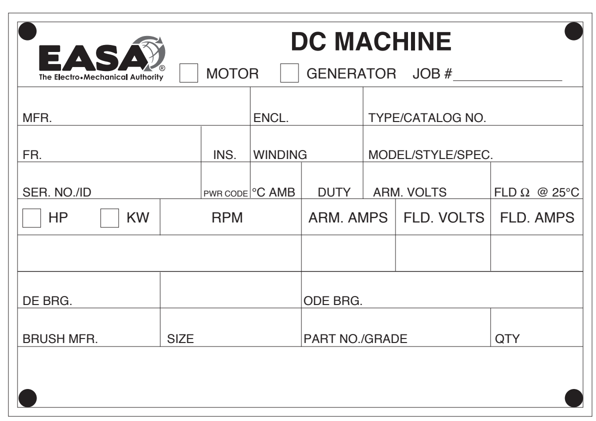
NEWLY-INSTALLED MOTORS

If the motor failed, was repaired and has just been reinstalled, the initial failure may have also damaged the controls. The same is true if the installed motor is a replacement for a failed motor. Any number of problems with the driven equipment could be responsible for the motor failure, too.

Problem: the motor does not start or does not run properly

If a newly-installed motor malfunctions the first time it is put in service, first check the control unit and the power lead connections. Also determine if the control has been serviced as a result of the motor failure, or if the control is new. If it is new, confirm that the control ratings match those of the motor. Measure the AC voltage input to, as well as the DC output

FIGURE 3-60



Typical DC motor nameplate.

from, the controller. Be sure the lead connections are correct and are tight. It may be necessary to use an oscilloscope to check the output waveform for evidence of AC ripple. If there is no obvious reason for the malfunction, proceed with the following troubleshooting procedures.

Problem: motor will not start

If the motor will not start, first make sure the control unit is supplying the correct power.

If adequate power is being supplied from the control unit and the motor will not operate, the problem is most likely an open circuit. These circuits include the armature winding, the fields (field loss relay), series and interpoles when present, the cable run between the drive and motor, and parts of the motor control circuit.

Activate the start button and measure the voltage at both the armature and the shunt field terminals. If rated voltage is measured, the problem is in the motor. A zero reading or a very low reading indicates that something is wrong in the control circuit.

Problem in the motor

When the problem is in the motor, first examine the brushes. Make certain they ride firmly on the commutator, and that there are no loose brush lead screws. Also inspect the brush shunts for loose tamping. The motor may not start if there is poor brush or brush lead contact. Replace brushes that are too short or damaged.

If the motor still does not run, disconnect the power supply from the motor and check the armature circuit for continuity. If the ohmmeter measures a reading of infinity, the circuit is open.

An open connection in the armature circuit could be caused by:

- A broken or disconnected jumper between the interpoles or series field coils.
- An open circuit in one or more interpole or series coils.
- Open armature coils.

Problem in the control circuit

If the voltage at the motor terminals is zero (or very low) when the start button is activated, there is a problem in the control circuit. This circuit includes the overload relay, contactors, fuses, and the power leads to the motor. Any interruption of this circuit will prevent the motor from starting. If the problem appears to be in the control circuit, check the following things:

- The overload relay: Has it tripped?
- Fuses: Are any blown? Remove them before testing.
- Contactors: Are they closing properly? Inspect the condition of the contacts.
- Power leads: Do all leads have continuity?
- Connections: Are the bolts tight? Inspect the lugs for poor crimps.

If the control is a solid-state drive, disconnect the motor and verify that the drive supplies rated field voltage, and variable armature voltage from zero to rated.

Problem: overload relay trips or fuses blow when motor is energized

A tripped overload relay or blown fuse(s) can occur when starting a DC motor. Both are caused by excessive starting current. Causes of high starting current include:

- Grounded windings.
- Mechanical problems with the motor or driven equipment.
- Shorted armature winding.
- Defective field winding.
- Drive attempts to accelerate the motor too quickly.

  Notes:

  - Don’t assume that measuring full voltage at the shunt field terminals proves the continuity of the circuit. If readings are taken ahead of an open circuit, the expected voltage will be present. There may still be an open circuit past the meter.
  - For compound-wound motors, use a megohmmeter or ohmmeter to test for shorts between the shunt and the series coils.

Caution: If the main fuse is blown, DO NOT apply power to the motor until the cause of failure has been found and corrected.

Mechanical problems such as damaged bearings could trip an overload relay or blow a fuse when the motor is started. Uncouple the motor and turn the armature by hand. If the armature turns freely, try to start the motor again. If it starts uncoupled, without tripping the overload relay or blowing fuses, the problem is probably in the driven equipment and not in the motor.

To check the armature for shorts while the motor is uncoupled, lift all the brushes away from the commutator and apply rated voltage to the shunt field. Rotate the armature by hand. If the armature cogs as it is being turned, it may have shorted coils. Use a temperature detecting device to check for hot armature coils. Shorted coils will usually be much warmer than the rest.

If no faults are found in the armature circuit, test the field winding for defects like shorts and open circuits that could prevent the shunt field from achieving full strength when the motor is started. Field strength must be 100 percent the instant the motor starts to keep the armature inrush current within the normal range.

To detect shorts or open circuits in the field winding, measure the resistance of the shunt coils with an ohmmeter and compare this reading with the nameplate data. A reading well below nameplate resistance indicates shorted coils, while a reading of infinity indicates an open circuit.

If above procedures do not identify the cause of failure, look for common problems that could result from errors made when the motor was repaired:

- The motor runs at a higher-than-rated rpm.
- The motor runs in the reverse direction.
- There is sparking under the brushes.

Problem: motor runs faster than rated speed

Sometimes a newly-installed motor will operate at a higher than rated speed. A differential series-to-shunt field connection will cause compound-wound motors to run faster than base speed under load. To correct this problem, first determine which leads are incorrect. If possible, operate the motor as a shunt motor (with the series temporarily out of the circuit) and note the direction of rotation. If it is correct per the lead markings, interchange the series leads (S1 and S2). If it is backwards, interchange the shunt field leads (F1 and F2).

A DC motor with a dual-voltage shunt field might also run faster than nameplate rpm if the fields are misconnected. This can happen if the shunt field is connected in series for high voltage, but low-voltage power is supplied. To restore the speed of the motor to its normal range, reconnect the shunt field for the correct voltage.

An incorrectly rewound armature can also cause a DC motor to run faster than its rated speed. The most common error is to increase armature circuits accidentally (e.g., a lap simplex armature is connected lap duplex). If fewer turns were used in the new winding than in the original winding, the speed will also increase. Such a mistake is more likely with armatures having random windings with unequal turns.

A loss of output voltage from a tachometer will send a false signal to the drive, indicating zero speed. The drive will then accelerate the motor until it trips the protective relays or the motor overspeeds and fails.

If the tachometer cable is not shielded, other wiring in a shared conduit may cause electromagnetic interference. Shielded cable should be used for the tachometer leads.

Problem: motor runs backwards

First, verify the lead markings and connections. If those are correct, but the direction of rotation has been reversed, interchange leads A1 and A2 of the armature circuit. (Never change rotation by swapping the field leads! While that method works for shunt motors, it causes problems on compound-wound machines.) If there is also sparking under the brushes, follow the procedures in the next paragraph.

Problem: brushes spark and arcing increases with load

In most cases minor adjustments will correct the problem. First, make sure the brushes are in the neutral position. Adjust the neutral position as follows.

First, unlock the brush rigging so that it can be shifted. To prevent armature movement during this procedure, it may be helpful to insert a wooden wedge between the armature and one of the pole pieces.

Apply single-phase power (115 volts is sufficient) to the shunt field terminals and connect an AC voltmeter to brushes on adjacent brush posts. Observe the voltage induced in the armature winding while shifting the brush rigging. The brushes are on neutral when the voltmeter indicates minimum voltage. Using a digital voltmeter, it should be possible to adjust neutral so that the induced voltage is less than 1/100 of a volt (0.01 volt).

Tighten the brush rigging fasteners and mark the brush rigging and the end bracket to identify the neutral position. Remove the wooden wedge, if used, after completing this procedure.

If sparking still occurs with the brushes set on neutral, there are several other things to check:

- Relative polarity of armature and interpoles: Shift the brushholder assembly off neutral and apply just enough DC voltage to cause the armature to rotate. If the interpole polarity is correct, the armature will rotate in the direction the brushholders were shifted. If it rotates in the opposite direction, interchange the brushholder leads.
- Brushholder spacing: Check that there is equal spacing (within 3/64" or 1.2 mm) between the brushes in each path.
- Commutator runout: Use a dial indicator, with the travel rod contacting one brush, to check commutator runout. The entire commutator should be true within 0.002" (0.05 mm), with no more than 0.0002" (0.005 mm) between adjacent bars. High bars, or camming during rotation, may cause arcing during operation.

Problem: motor runs over temperature

There are several possible reasons for high motor temperature. By inspecting the ventilation system, it should be fairly simple to determine the actual cause of the excessive heat.

Causes of overheating may include:

- An auxiliary blower operating in the wrong rotation.
- Blocked ventilation openings.
- Buildup of material on the exterior of the motor.
- Missing or damaged covers, especially louvered covers.
- Damaged or missing fans.
- An auxiliary blower opposing the airflow produced by an internal fan.
- Drive faults that permit AC through to the armature circuit.
- Shipping covers that should have been removed.

Blower

The auxiliary blower is usually a squirrel cage blower mounted on a small 3-phase motor, so it can be reversed by interchanging any 2 leads. Bump the blower for rotation, and observe the direction of rotation during coastdown. The blower MUST rotate in the direction of the scroll housing or it will not deliver the correct volume of air. There is no substitute for this method for checking rotation.

Covers and gaskets

The next items to inspect are the covers. Covers, and their placement, are important when a DC machine has any sort of cooling airflow. Look for:

- Missing or loose covers
- Blocked openings
- Product restricting airflow
- Clogged filters
- Missing gaskets under solid covers

Missing fans

If the machine has no external blower, it almost certainly should have an internal fan. If the motor has louvered openings, but no blower or internal fan, it is likely that a previous repairer forgot to install the fan or blower.

Drives and controls

DC drives rectify AC power to convert it to DC power. If one or more SCRs are damaged, they may convert the AC to DC until the armature current increases under load. If the SCRs do not gate properly, AC "ripple" will cause armature temperatures to increase and usually result in sparking. Use an oscilloscope to evaluate the DC output from the drive WHILE THE MOTOR IS LOADED.

MACHINES THAT HAVE BEEN IN SERVICE

If the motor has been operating for years, problems such as incorrect hookup or internal misconnection can probably be ruled out.

Problem: motor runs faster than rated speed

If a motor that has been operating satisfactorily suddenly begins to run faster than rated at full load, the trouble is either in the supply voltage or in the motor winding. To pinpoint the problem, measure the armature and the shunt field voltages at the motor terminals. The speed of the motor will increase if the armature voltage is higher than shown on the nameplate, or if the applied shunt field voltage is lower than the value shown on the nameplate.

Find out if the drive has been replaced or adjusted recently. If the drive is current-limiting, the cold performance may be correct with problems only developing as the motor approaches operating temperature. The applied voltage at ambient will be correct, but as the winding resistance increases the applied voltage must increase to keep the current constant.

If applied voltages are in accordance with the motor rating, and the motor still runs faster than rated speed, there is a defect in the winding. The problem could be grounded coils, shorted coils, or an open circuit in the field winding–any of which could cause an increase in speed.

To determine which problem is causing the motor to run at a higher rpm:

- Use a megohmmeter to test for grounds in the field or armature circuits.
- Use a megohmmeter to test for shorts between shunt and series field (if it is a compound-wound motor).
- Use an ohmmeter to test for continuity in shunt and series coils. (High resistance indicates an open circuit.)

Problem: motor runs slower than rated speed

If the motor runs substantially slower than base speed, the problem is probably in the supply voltage or in the armature circuit connections. Measure the armature voltage and compare it with the nameplate value. Reduced armature voltage will decrease the motor speed.

If the applied armature voltage is correct, and the motor still runs at a speed slower than rated rpm, the problem is high resistance in the armature circuit. This problem can be detected by first inspecting all armature circuit connections for high-resistance joints caused by loose connections. Check for hot spots and discolored insulation around the connections. When available, use a thermal scanning device to locate hot spots on the risers, armature lead connections, or brushholder connections.

Next, make sure that all contactors in the controller are making good contact when closed. If there are high resistance joints anywhere in the armature circuit, the motor will run slower than its rated speed.

If the speed of the motor changes continuously with constant voltage applied (i.e., the armature slows down, then speeds up, etc.), the problem is due to shorted armature coils. To detect shorted armature coils, follow the procedures described previously in "Problem: Overload relay trips or fuses blow when motor is energized."

Problem: sparking at the brushes

Sparking at the brushes indicates commutation problems. Although sparking may be due to any one of many seemingly unrelated factors, mechanical problems (rather than electrical ones) are often the cause. To isolate the cause of sparking, concentrate first on the mechanical problems associated with the brushes:

- Make sure all brushes are in place and fully seated.
- Check that all brush leads are intact and fastened properly to the brushholder.
- Check brush springs for correct tension.
- Check the fit of all brushes in their brush boxes.
- Check brushholder mountings for looseness (e.g., loose bolts or damaged brushholder insulation).
- Inspect the brush rigging, and make sure it is tight and secure. Check brush neutral.

If the brushes appear to function satisfactorily, the problem may be with the commutator. Carefully inspect the commutator, making certain there are no raised bars, no flat spots, and no high mica. Be sure there is no foreign material between the commutator bars. If commutator runout is excessive, or any bars are badly burned and rough, the commutator must be machined to a smooth finish.

Severe vibration can also cause brushes to "bounce" and sparking will occur. Apply pressure to the brush post, near the riser. If the arcing stops while pressure is applied, vibration is the cause of the sparking. Determine the source of the vibration by taking comprehensive vibration readings on the motor and driven equipment.

If pressure directly on a brush stops the arcing on that brush, check the spring tension. Vibration-related arcing can be improved by increasing the spring tension to 6-8 psi.

Sparking may also be due to eccentricity of the air gap. Badly worn bearings, or a shaft bent by a jam or stoppage, can displace the armature core and result in uneven air gaps and sparking under the brushes.

If the sparking is caused by an electrical fault in the armature winding, inspect the commutator bars for signs of discoloration. These might include a few burned bars or a few darkened bars. If one or more commutator bars are burned, there probably is an open circuit in the armature winding. To detect this fault, inspect for:

- Broken coil leads behind the risers.
- Thrown solder and loose connections at the risers.

TABLE 3-4: SPARKING CAUSES AND CURES

Symptom	Cause	Cure
Unequal sparking on different brush posts	Brushholders not equally spaced	Move the brushholders so that brushes are in the same path and are equally spaced within 3/64" (1.2 mm).
Sparking may be equally severe on all brushes	Brushholders off electrical neutral	Adjust neutral.
Broken or chipped brushes	Brushholder fails to support or guide the brush properly	Adjust the brushholders so that their nearest point is 1/8" to 3/16" (3 mm to 5 mm) from the commutator surface.
Arcing changes with the load	Flaw in the interpole winding or incorrect spacing of the pole face in relation to the armature	Use field form/black band test to check interpole strength.
Arcing at all brushes, blown brush shunts	Excessive overloads if the interpoles have passed their saturation point	Reduce load or change brush grade.
Rapid brush wear and arcing	Friction increases drastically at very light loads	Lift some brushes to increase current density or change the brush grade.
One or more burned places on the commutator	Defective armature windings	Test the armature and rewind if necessary.
Arcing only at scattered brushes	Brushes carrying a higher pressure will have lower contact drop and will take more than their share of the current	Check spring tension and adjust or replace springs.
Arcing or bar edge burning	High mica, burrs of copper or commutator slots filled with foreign material	Undercut, scrape to remove the excessive side mica, and chamfer the bars.
Sparks, no film on commutator, smeared appearance	Foreign material on commutator surface	Clean the commutator.
Black commutator film	Abnormally dark commutators result from excessive humidity, sulfur and other gaseous materials	Use a commutator cleaning stone and consider a mildly-abrasive brush grade.
Brushes binding in the brushholder	Brushes are not the correct size or the brushholders are damaged	Replace the brushes with the correct size. Deburr the brush boxes.
Restricted brush motion	Shunt stiffness or something interfering with the motion of the spring or hammer	Remove the obstruction.
Arcing, brushes appear to be camming in the brush boxes	Commutator may be out of round or eccentric because of improper finishing.	Check the total indicated runout of the commutator. Remachine if excessive.
High bars or flat spots	High bars will usually be polished and followed by several bars which look rough and pitted or burned. Usually results in a flat spot.	Check the tightness of the commutator fasteners and retorque if necessary. Remachine the commutator and check bar hardness.
Arcing is worse near the risers, or at certain speeds	Vibration of the machine itself may cause brush sparking. Look for armature unbalance, a mounting base problem, mechanical faults or defective bearings.	Correct the source of the vibration. Look for broken welds, a disbonded soleplate, misalignment or a damaged coupling. Inspect the brushholder posts for looseness and correct if necessary. Brace the brushholder posts to improve stiffness.
Severe arcing as load is applied	Interpole polarity is reversed relative to armature polarity	Check interpole polarity. Interchange brushholder leads, if reversed.

- Physical damage to the winding.

The presence of a few darkened bars could indicate one or more shorted armature coils. Shorted coils can be detected by following the procedures described previously in “Problem: Overload relay trips or fuses blow when motor is started.”

Note: A definite pattern of darkened commutator segments (every third or fourth segment, for instance) is often mistakenly assumed to indicate a commutation problem. If the pattern matches the ratio of commutator bars to armature slots, the pattern (with normal brush wear) usually indicates satisfactory commutation.

If the cause of sparking cannot be traced to any of the mechanical and electrical faults outlined previously, measure the load current with a DC ammeter to see if the motor is overloaded. Momentary overload of up to 150 percent of full load is permissible for most DC motors, as long as the sparking does not harm the commutator and brushes. Intermittent sparking indicates rapid surges of load current. It may also indicate that the driven equipment requires a motor of higher rating.

If sparking occurs only when the motor is started, measure the inrush current. If necessary, adjust the relay timing cycle, or drive starting parameters, to reduce the starting current.

See Table 3-4 for a list of common causes of sparking and their cures and Table 3-5 for causes of unusual brush wear.

GENERATORS

Problem: generator does not produce voltage

If the generator is separately excited, check the field excitation voltage supply. If the correct excitation voltage is delivered to the generator, check the fields for open circuits. Next check the lead markings and make sure the connections are correct.

For self-excited generators, it may be necessary to flash the fields to restore the residual magnetism. This is often the case when a generator has been idle for a long period. Use jumper leads to connect a battery to the field leads and operate the unit. There should now be output voltage at the armature leads. If not, there is an open or misconnection in the armature circuit.

Use the DC inductive kick method to verify the armature neutral position. (The AC method, which requires that AC voltage be applied to the shunt field, will destroy the residual magnetism required for self-exciting generators.)

If the generator produces voltage, let it run for a few minutes to restore residual magnetism to the field poles. Reconnect the fields for self-excitation, and run the unit. Voltage should build normally, until the rated voltage is produced.

Note: If the fields were rewound recently, and the generator requires frequent field flashing, the field poles might not have been installed in the correct positions. Residual magnetism should be of alternate polarity, just like field excitation. If the field poles were randomly reinstalled, or the shunt field leads reversed, the building self-excitation voltage may cancel out the residual magnetism. As the generator output voltage starts to build, it cancels the residual magnetism, and the output voltage suddenly drops to zero.

TABLE 3-5: CAUSES OF UNUSUAL BRUSH WEAR

Symptom	Likely Cause
Rapid wear	Low brush current density
Positive brush wearing faster	Weak interpoles.
Negative brush wearing faster	Weak spring tension
Brushes closer to riser are wearing faster	Excessive vibration
Brushes farthest from riser are wearing faster	Lubricant on commutator
Random variation in rate of brush wear	Unequal spring tension or variation in resistance between brush boxes and brush posts (corrosion, insulating paint), loose brush lead screws
One positive and one negative brush row wearing faster	Missing equalizer jumpers at brushholders. Brushholders of like polarity should always have equalizer jumpers.

Problem: generator does not produce the correct voltage

Check that all lead markings and connections are correct. If the output voltage is half or twice rated voltage, verify the field connections. It is likely that the shunt fields are connected for either double, or half, the rated voltage.

Many generator applications include a rheostat for simple regulation of the generator output voltage. Check the condition of the rheostat for shorts or opens. A simple procedure for doing so is to connect an ohmmeter to the rheostat “start” and “finish” terminals and then observe the resistance while adjusting the rheostat through its full range. The resistance should change smoothly, with no sudden swing in resistance. If the rheostat is open or shorted, it must be replaced. Be sure the replacement rheostat is rated for the field current.

If the generator is compound wound, determine whether it should be connected cumulative or differential. Certain applications, such as the swing generator of a dragline, must be connected differentially. If a generator application calls for cumulative connection, a differential connection will cause a dangerous loss of output voltage should the generator suddenly cease to produce voltage when the load is critical.

If the armature was rewound, the connection may be incorrect. For example, an armature that was connected duplex but should be simplex.

Note: This article replaces *EASA Tech Note 18* (May 1993). It was reviewed and updated as necessary in October 2020.

3.10 DC MACHINE DATA SHEET

DC MACHINE DATA SHEET

NAMEPLATE DATA

KW ____ HP ____ RPM ____ MFR. ____ ARM. VOLTS ____ FIELD VOLTS ____ FRAME ____

SER. NO. ____ STYLE ____ MODEL ____ TYPE ____ ARM. AMPS ____ FIELD AMPS ____ FIELD RES. ____

ARMATURE COIL DATA

Slots ____ Bars ____ Turns per coil ____

Coils per slot ____ Wires in mult. ____ Wire size ____

Wire type ____ Wire weight ____

Slot pitch 1 to ____ Commutator pitch 1 to ____

No. of equalizers ____ Pitch 1 to ____ Wire size ____

Knuckle: Standard ☐ Double ☐

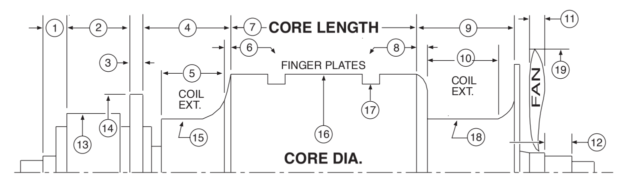
Wound: Flat ☐ Edge ☐

Coils: Left-hand ☐ Right-hand ☐

Compensating winding

Wire size ____

Turns per slot ____



WINDING TYPE

Shunt ☐

Series ☐

Compound ☐

Interpoles: Yes ☐ No ☐

Compensating or pole face: Yes ☐ No ☐

Permanent magnet: Yes ☐ No ☐

Insulation class ____

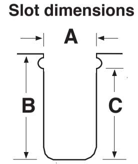
Temperature rise ____

Duty ____

FIELD COIL WINDING DATA

Type	No. coils	No. cir.	Turns per coil	Wire Mult.	Wire Size & type	Coil weight	25°C ohms per coil
Shunt							
Series							
Inter-pole							

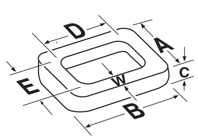
Slot dimensions



A ____

B ____

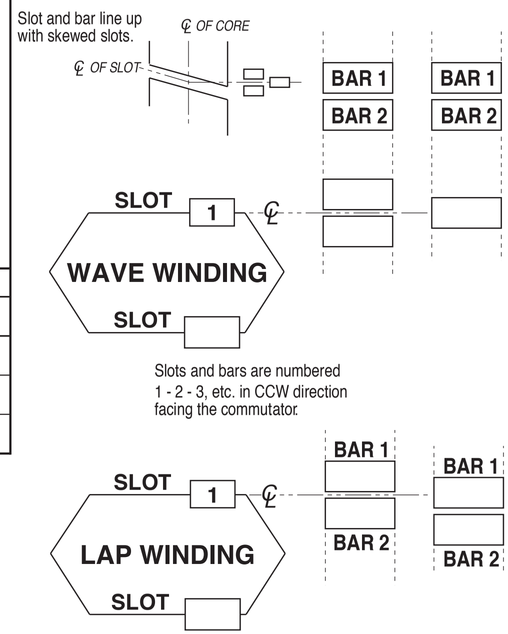
C ____



FIELD COIL DIMENSIONS

Type	A	B	C	D	E	W
Shunt						
Series						
Interpole						

REMARKS



WAVE WINDING

Leads from slot 1 to bar: ____

Leads from slot ____ to bar: ____

LAP WINDING

Leads from slot 1 to bar: ____

Leads from slot ____ to bar: ____

Company ____ **City & State** ____

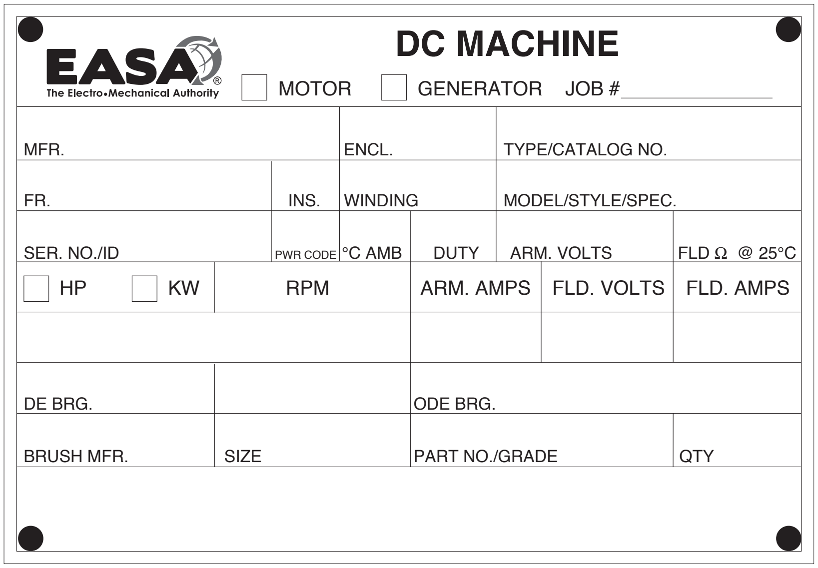
Job No. ____ **Customer** ____ **Date** ____ **Data taken by** ____

EASA® The Electro•Mechanical Authority

PLEASE SUBMIT A COPY OF YOUR COMPLETED DATA FORM TO: EASA, INC. • 1331 BAUR BLVD. • ST. LOUIS, MO 63132 • USA • +1 314 993 2220 • Fax +1 314 993 2998 • www.easa.com 1220RC50-1220

3.11 DC MACHINE NAMEPLATE

SAMPLE NAMEPLATE



3.12 DC MACHINE INSPECTION REPORT

Customer ______________________________ Date ____________

Work order number ____________________ **Priority** ❑ Standard time ❑ Rush ❑ Overtime

Manufacturer ____________________ Model ____________ Frame ____________

Horsepower/Kilowatt ________ rpm ________ Serial number ____________________

Armature
Voltage ________
Amps ________

Fields
Voltage ________ Amps ______ Ohms ______ ❑Series ❑Shunt ❑Compound

Lead labels F1 F____ F____ F____ A1 A____ S____ S____

ELECTRICAL TESTS

		Megohms	Hipot results	Defects?
Armature	Commutator diameter ____________ Minimum commutator diameter ____________ ❑V-ring bolted ❑Clamping nut ❑Glass banded Condition of string band ____________ Other tests: ❑Surge ❑Growler ❑High-frequency bar-to-bar Results of above test(s) ____________ ____________ Bar-to-bar resistance equalized? ❑Yes ❑No Odd turns? ❑Yes ❑No	________ (_____ volts)	________ (_____ volts)	
Fields (Shunt)	Drop test ❑AC ❑DC ________ ________ ________ ________ ________ ________ ________ ________ Connected ❑Series ❑Series-parallel ❑Parallel	________ (_____ volts)	________ (_____ volts)	
Interpoles	Drop test ❑AC ❑DC ________ ________ ________ ________ ________ ________ ________ ________ Connected ❑Series ❑Series-parallel ❑Parallel	________ (_____ volts)	________ (_____ volts)	
Series	Drop test ❑AC ❑DC ________ ________ ________ ________ ________ ________ ________ ________ Connected ❑Series ❑Series-parallel ❑Parallel	________ (_____ volts)	________ (_____ volts)	

Record resistance between series and shunts ______________________________

____

Brushes and brushholders

Quantity of brushholder arms ____________ Brush-to-holder fit ❑OK ❑Loose ❑Tight

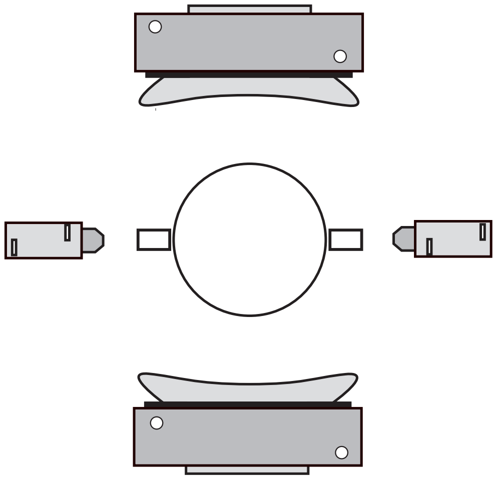
Are brushholders equalized? ❑Yes ❑No Spring tension within tolerance? ❑Yes ❑No

Quantity of brushes ____________ Remarks about spring condition ____________

Part number/grade ________ ________ ____________________

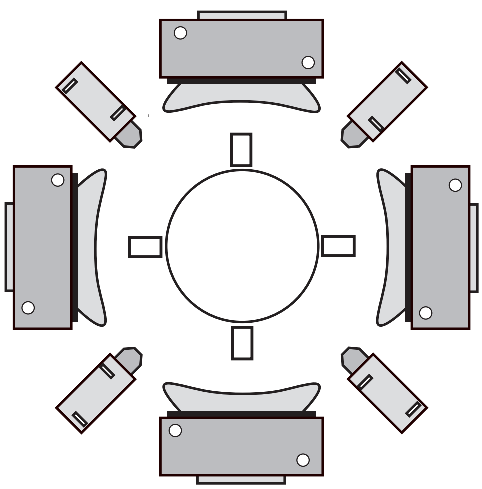
3.13 AS-RECEIVED CONNECTION FORM—2-, 4- AND 6-POLE DC MACHINES

(DRAW AND NUMBER LEADS AND JUMPERS AS RECEIVED)



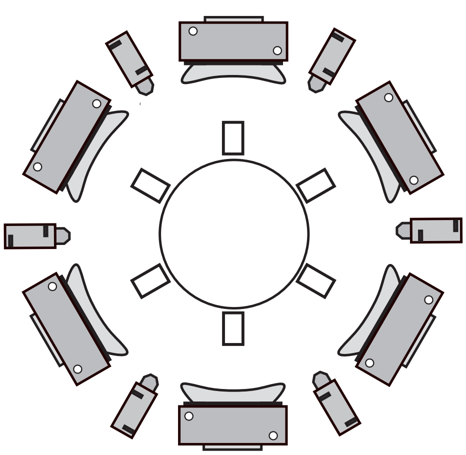
2-POLE TEMPLATE

		Quantity in series	Quantity in parallel
Number of poles	2		
Number of interpoles			
Number of series fields			



4-POLE TEMPLATE

		Quantity in series	Quantity in parallel
Number of poles	4		
Number of interpoles			
Number of series fields			



6-POLE TEMPLATE

		Quantity in series	Quantity in parallel
Number of poles	6		
Number of interpoles			
Number of series fields			

3.14 REFERENCED STANDARDS

The following standards are referenced in this section of the *EASA Technical Manual*.

ANSI/EASA Std. AR100-2020: *Recommended Practice for the Repair of Electrical Apparatus.* EASA, Inc. St. Louis, MO, 2020.

IEC Std. 60034-8:2014, ed. 3.1 b: *Rotating Electrical Machines–Part 8: Terminal Markings and Direction of Rotation of Rotating Machines*, ed. 2. International Electrotechnical Commission. Geneva, Switzerland, 2014.

National Electrical Code: NFPA 70. National Fire Protection Association, Quincy, MA, 2020.

NEMA Stds. CB 1-2000, Rev. 2012: *Brushes for Electrical Machines*. National Electrical Manufacturers Association. Rosslyn, VA, 2012.

NEMA Stds. MG 1-2016 (Rev. 2018): *Motors and Generators*. National Electrical Manufacturers Association. Rosslyn, VA, 2018.

(This page intentionally left blank.)