5

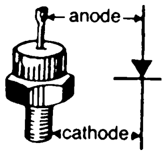
Electronics

Section Outline Page

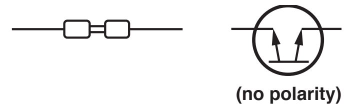
5.1 SEMICONDUCTORS AND TRANSISTORS

SYMBOLS AND CONNECTIONS

DIODE

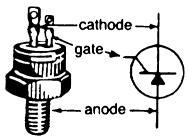


DIAC

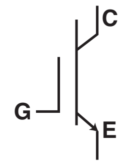


MOV

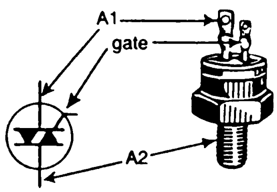
LOW CURRENT SCR (THYRISTOR)



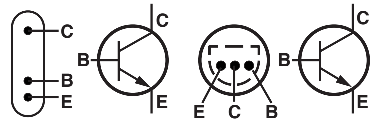
INSULATED-GATE BIPOLAR TRANSISTOR



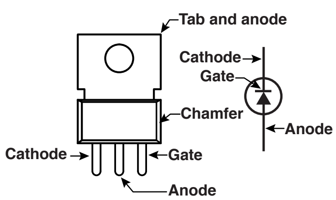
TRIAC



NPN TRANSISTOR



POWER-TAB SCR



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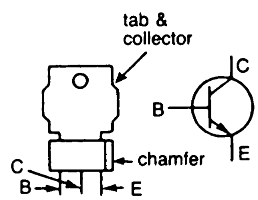
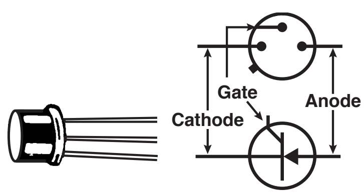
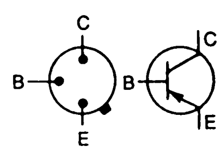


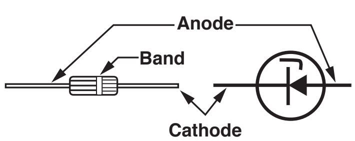
LIGHT ACTIVATED SCR



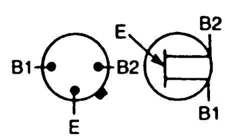
PNP TRANSISTOR



ZENER & SIGNAL DIODE



SILICON UNIJUNCTION TRANSISTOR



5.2 RESISTANCE TEMPERATURE DETECTORS (RTDs)

Metal	Characteristic	TCR (Ω/Ω/°C)*
Copper	10.0Ω @ 25°C	0.00427
Platinum	100Ω @ 0°C	0.00392
Nickel	120Ω @ 0°C	0.00672

* TCR is the temperature coefficient of resistance.

TABLE 5-1: RTD TEMPERATURE VS. RESISTANCE CHART*

PLATINUM : PA

TCR = 3.92E-3 R_0 = 100

A = 0.0039848 B = -5.87E-07 C = -4E-12

(Values are in ohms)

Temp °C	+ 0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9
0	100.000	100.3984	100.7967	101.1949	101.5930	101.9909	102.3888	102.7865	103.1841	103.5816
10	103.9789	104.3762	104.7733	105.1703	105.5672	105.9640	106.3607	106.7572	107.1536	107.5499
20	107.9461	108.3422	108.7381	109.1340	109.5297	109.9253	110.3208	110.7162	111.1114	111.5066
30	111.9016	112.2965	112.6913	113.0859	113.4805	113.8749	114.2692	114.6634	115.0575	115.4514
40	115.8453	116.2390	116.6326	117.0261	117.4195	117.8127	118.2059	118.5989	118.9918	119.3846
50	119.7773	120.1698	120.5622	120.9546	121.3468	121.7388	122.1308	122.5226	122.9144	123.3060
60	123.6975	124.0889	124.4801	124.8713	125.2623	125.6532	126.0440	126.4347	126.8252	127.2156
70	127.6060	127.9962	128.3863	128.7762	129.1661	129.5558	129.9454	130.3349	130.7243	131.1136
80	131.5027	131.8917	132.2807	132.6695	133.0581	133.4467	133.8351	134.2235	134.6117	134.9998
90	135.3877	135.7756	136.1633	136.5509	136.9384	137.3258	137.7131	138.1003	138.4873	138.8742
100	139.2610	139.6477	140.0342	140.4207	140.8070	141.1932	141.5793	141.9653	142.3512	142.7369
110	143.1225	143.5080	143.8934	144.2787	144.6639	145.0489	145.4338	145.8186	146.2033	146.5879
120	146.9723	147.3567	147.7409	148.1250	148.5089	148.8928	149.2766	149.6602	150.0437	150.4271
130	150.8104	151.1935	151.5766	151.9595	152.3423	152.7250	153.1076	153.4900	153.8724	154.2546
140	154.6367	155.0187	155.4005	155.7823	156.1639	156.5454	156.9268	157.3081	157.6893	158.0703
150	158.4513	158.8321	159.2128	159.5933	159.9738	160.3541	160.7344	161.1145	161.4945	161.8743
160	162.2541	162.6337	163.0132	163.3926	163.7719	164.1511	164.5301	164.9091	165.2879	165.6666
170	166.0452	166.4236	166.8020	167.1802	167.5583	167.9363	168.3142	168.6919	169.0696	169.4471
180	169.8245	170.2018	170.5790	170.9560	171.3330	171.7098	172.0865	172.4631	172.8395	173.2159
190	173.5921	173.9682	174.3442	174.7201	175.0959	175.4715	175.8471	176.2225	176.5978	176.9729
200	177.3480	177.7229	178.0978	178.4725	178.8471	179.2215	179.5959	179.9701	180.3442	180.7182
210	181.0921	181.4659	181.8395	182.2131	182.5865	182.9598	183.3330	183.7060	184.0790	184.4518
220	184.8245	185.1971	185.5696	185.9419	186.3142	186.6863	187.0583	187.4302	187.8020	188.1736
230	188.5452	188.9166	189.2879	189.6591	190.0301	190.4011	190.7719	191.1426	191.5132	191.8837
240	192.2541	192.6243	192.9945	193.3645	193.7344	194.1041	194.4738	194.8433	195.2128	195.5821
250	195.9513	196.3203	196.6893	197.0581	197.4268	197.7954	198.1639	198.5323	198.9005	199.2687

* Note: The above temperature and resistance values were calculated using Minco's Products online RTD Calculator (www.minco.com).

TABLE 5-2: RTD TEMPERATURE VS. RESISTANCE CHART*

COPPER : CA

TCR = 4.27E-3 R_0 = 9.035

(Values are in ohms)

Temp °C	+ 0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9
0	9.0	9.0736	9.1122	9.1509	9.1895	9.2281	9.2667	9.3053	9.3439	9.3826
10	9.4212	9.4598	9.4984	9.5370	9.5757	9.6143	9.6529	9.6915	9.7301	9.7687
20	9.8074	9.8460	9.8846	9.9232	9.9618	10.0005	10.0391	10.0777	10.1163	10.1549
30	10.1935	10.2322	10.2708	10.3094	10.3480	10.3866	10.4253	10.4639	10.5025	10.5411
40	10.5797	10.6184	10.6570	10.6956	10.7342	10.7728	10.8114	10.8501	10.8887	10.9273
50	10.9659	11.0045	11.0432	11.0818	11.1204	11.1590	11.1976	11.2362	11.2749	11.3135
60	11.3521	11.3907	11.4293	11.4680	11.5066	11.5452	11.5838	11.6224	11.6610	11.6997
70	11.7383	11.7769	11.8155	11.8541	11.8928	11.9314	11.9700	12.0086	12.0472	12.0858
80	12.1245	12.1631	12.2017	12.2403	12.2789	12.3176	12.3562	12.3948	12.4334	12.4720
90	12.5106	12.5493	12.5879	12.6265	12.6651	12.7037	12.7424	12.7810	12.8196	12.8582
100	12.8968	12.9354	12.9741	13.0127	13.0513	13.0899	13.1285	13.1672	13.2058	13.2444
110	13.2830	13.3216	13.3602	13.3989	13.4375	13.4761	13.5147	13.5533	13.5920	13.6306
120	13.6692	13.7078	13.7464	13.7851	13.8237	13.8623	13.9009	13.9395	13.9781	14.0168
130	14.0554	14.0940	14.1326	14.1712	14.2099	14.2485	14.2871	14.3257	14.3643	14.4029
140	14.4416	14.4802	14.5188	14.5574	14.5960	14.6347	14.6733	14.7119	14.7505	14.7891
150	14.8277	14.8667	14.9056	14.9446	14.9835	15.0225	15.0614	15.1004	15.1393	15.1783
160	15.2172	15.2561	15.2951	15.3340	15.3730	15.4120	15.4509	15.4899	15.5288	15.5678
170	15.6067	15.6457	15.6846	15.7236	15.7626	15.8015	15.8405	15.8794	15.9184	15.9574
180	15.9963	16.0353	16.0743	16.1132	16.1522	16.1912	16.2301	16.2691	16.3081	16.3470
190	16.3860	16.4250	16.4639	16.5029	16.5419	16.5809	16.6198	16.6588	16.6978	16.7368
200	16.7757	16.8147	16.8537	16.8927	16.9317	16.9706	17.0096	17.0486	17.0876	17.1266
210	17.1656	17.2045	17.2435	17.2825	17.3215	17.3605	17.3995	17.4385	17.4775	17.5165
220	17.5554	17.5944	17.6334	17.6724	17.7114	17.7504	17.7894	17.8284	17.8674	17.9064
230	17.9454	17.9844	18.0234	18.0624	18.1014	18.1404	18.1794	18.2184	18.2574	18.2964
240	18.3354	18.3744	18.4135	18.4525	18.4915	18.5305	18.5695	18.6085	18.6475	18.6865
250	18.7255	18.7646	18.8036	18.8426	18.8816	18.9206	18.9596	18.9987	19.0377	19.0767

* Note: The above temperature and resistance values were calculated using Minco's Products online RTD Calculator (www.minco.com).

TABLE 5-3: RTD TEMPERATURE VS. RESISTANCE CHART*

NICKEL : NA

TCR = 7.72E-3 R_0 = 120

(Values are in ohms)

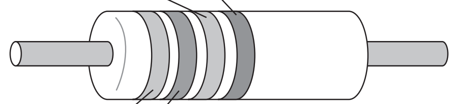
Temp °C	+ 0	+ 1	+ 2	+ 3	+ 4	+ 5	+ 6	+ 7	+ 8	+ 9
0	120.000	120.7088	121.4193	122.1317	122.8457	123.5616	124.2792	124.9987	125.7199	126.4430
10	127.1678	127.8945	128.6231	129.3534	130.0857	130.8197	131.5557	132.2935	133.0333	133.7749
20	134.5184	135.2638	136.0112	136.7604	137.5116	138.2648	139.0199	139.7770	140.5360	141.2970
30	142.0600	142.8250	143.5920	144.3610	145.1320	145.9050	146.6800	147.4571	148.2362	149.0173
40	149.8004	150.5857	151.3729	152.1622	152.9536	153.7470	154.5425	155.3401	156.1398	156.9416
50	157.7454	158.5513	159.3594	160.1695	160.9818	161.7962	162.6127	163.4313	164.2521	165.0750
60	165.9000	166.7272	167.5565	168.3880	169.2216	170.0574	170.8953	171.7353	172.5775	173.4218
70	174.2682	175.1167	175.9674	176.8202	177.6751	178.5321	179.3912	180.2525	181.1159	181.9813
80	182.8489	183.7186	184.5904	185.4643	186.3402	187.2183	188.0985	188.9807	189.8651	190.7515
90	191.6391	192.5297	193.4224	194.3172	195.2140	196.1130	197.0141	197.9173	198.8226	199.7300
100	200.6396	201.5513	202.4652	203.3812	204.2994	205.2198	206.1423	207.0670	207.9939	208.9229
110	209.8542	210.7877	211.7233	212.6612	213.6013	214.5436	215.4882	216.4350	217.3840	218.3353
120	219.2900	220.2458	221.2039	222.1642	223.1268	224.0917	225.0588	226.0281	226.9998	227.9737
130	228.9499	229.9283	230.9090	231.8920	232.8773	233.8648	234.8545	235.8466	236.8409	237.8375
140	238.8364	239.8375	240.8409	241.8466	242.8545	243.8648	244.8773	245.8920	246.9091	247.9284
150	248.9500	249.9739	251.0001	252.0286	253.0594	254.0927	255.1283	256.1664	257.2069	258.2499
160	259.2954	260.3435	261.3941	262.4472	263.5030	264.5614	265.6225	266.6862	267.7526	268.8218
170	269.8937	270.9684	272.0459	273.1263	274.2095	275.2956	276.3845	277.4764	278.5713	279.6691
180	280.7700	281.8739	282.9808	284.0908	285.2039	286.3202	287.4396	288.5621	289.6879	290.8169
190	291.9491	293.0845	294.2233	295.3654	296.5108	297.6596	298.8117	299.9673	301.1263	302.2887
200	303.4546	304.6240	305.7969	306.9734	308.1535	309.3371	310.5244	311.7153	312.9098	314.1081
210	315.3092	316.5149	317.7243	318.9375	320.1544	321.3751	322.5996	323.8278	325.0598	326.2957
220	327.5353	328.7787	330.0260	331.2771	332.5320	333.7908	335.0534	336.3199	337.5903	338.8645
230	340.1426	341.4246	342.7105	344.0004	345.2941	346.5918	347.8934	349.1989	350.5084	351.8218
240	353.1400	354.4614	355.7867	357.1160	358.4493	359.7864	361.1275	362.4726	363.8215	365.1743
250	366.5310	367.8916	369.2561	370.6244	371.9966	373.3726	374.7525	376.1361	377.5236	378.9149

* Note: The above temperature and resistance values were calculated using Minco's Products online RTD Calculator (www.minco.com).

5.3 RESISTORS AND CAPACITORS

TABLE 5-4: RESISTOR COLOR CODE

Color	1st & 2nd Significant Figures	Multiplier	Tolerance
Black	0	1	—
Brown	1	10	±1%
Red	2	100	±2%
Orange	3	1000	±3%
Yellow	4	10000	±4%
Green	5	100000	—
Blue	6	1000000	—
Violet	7	10000000	—
Gray	8	100000000	—
White	9	—	—
Gold	—	0.1	±5%
Silver	—	0.01	±10%
No Color	—	—	±20%



RESISTOR COLOR BAND SYSTEM

- Various special characteristics may be denoted by a fifth color band in various positions along the resistor body.
- Resistors with black body color are composition, non-insulated.
- Resistors with colored bodies are composition insulated.
- Wire-wound resistors have a double width color band for the first digit.

TABLE 5-5: MICA CAPACITOR COLOR CODE

Color	Characteristic*	Capacitance: 1st & 2nd Significant Figures	Capacitance: Multiplier	Capacitance Tolerance	DC Working Voltage	Operating Temperature Range
Black	A (EIA)	0	1	±20% (EIA)		-55° to +70°C (MIL)
Brown	B	1	10	±1%	100 (EIA)	
Red	C	2	100	±2%		-55° to +85°C
Orange	D	3	1000		300	
Yellow	E	4	10000 (EIA)			-55° to +125°C
Green	F	5		±5%	500	
Blue		6				-55° to +150°C (MIL)
Purple		7				
Gray		8				
White		9				
Gold			0.1	±1/2% (EIA)	1000 (EIA)	
Silver			0.01 (EIA)	±10%		

*Denotes specifications of design involving Q factors, temperature coefficients, and production test requirements.

EIA stands for Electronic Industries Alliance (EIA) Standards; MIL and MIL-STD stand for the standard used by the United States military.

5.4 ELECTRONIC VARIABLE-SPEED DRIVES

Electronic variable-speed drives improve control, cut power needs

By Richard W. Fugill and Gregory L. Rinehart
Drives & Systems Division
Siemens Energy & Automation, Inc.

Adjustable-speed motor drives are used not only to provide varying speed for the driven equipment but also to control tension, torque, position and other variables.

Adjustable-speed drives are often applied to variable torque loads such as centrifugal pumps, compressors and fans to reduce operating costs.

Figure 5-1 (Page 5-8) shows curves of input power requirements for a fan with dampers driven at a fixed speed compared with one driven by an electronic adjustable-speed drive. The resulting power and cost savings shown are significant.

Electronic adjustable-speed drives are efficient and reliable. Because of the low losses of solid-state conversion devices, modern electronic drives are the most efficient adjustable-speed drives on the market today. Many other drives require heat exchangers or other means for removing the heat produced by inefficient components. The power losses in this auxiliary equipment must be included in the power requirements of the total drive. Electronic drives are designed with protective circuitry to prevent line and load disturbances from having an adverse effect. With this protection and adequate thermal design, solid-state devices have an extremely long operating life, which makes them among the most reliable devices on the market.

DRIVE TYPES

Several basic types of electronic adjustable-speed drives are very popular today: DC drives; current source inverters with induction motors; voltage source inverters with induction motors; load commutated inverters with synchronous motors; slip energy recovery system, wound-rotor motors; cycloconverter drives.

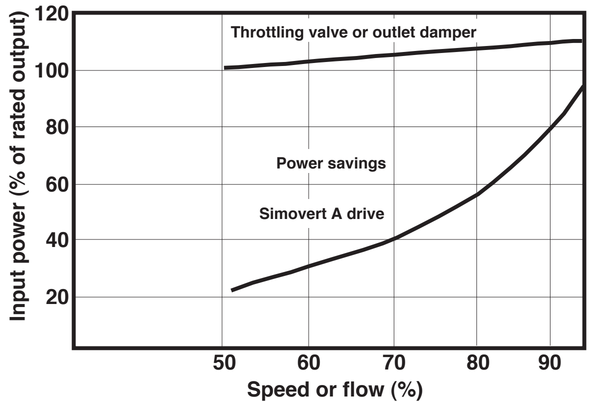
These drives have similarities as well as obvious differences. Table 5-6 provides a quick reference comparison among these drives. Specific applications require careful consideration of the characteristics of the particular drive types. The following sections describe the most important features of each drive type.

DC drive. The DC drive is the workhorse of the adjustable-speed drives. It is the oldest and most used of the electronic drives and usually is the basis for drive comparisons. The power conversion circuitry is the simplest of the industrial electronic drives.

TABLE 5-6: COMPARISON OF ELECTRONIC ADJUSTABLE-SPEED DRIVES

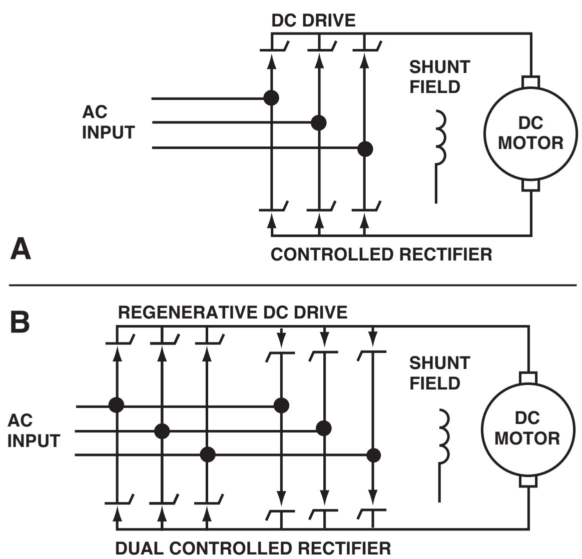
Drive type	DC drive	Current source inverter	Voltage source inverter	Wound rotor slip recovery	Load commutated inverter	Cycloconverter
Motor Type	Commutated direct-current	Squirrel-cage induction	Squirrel-cage induction	Wound-rotor slip-ring	Synchronous (brushless)	Synchronous or Squirrel-cage
HP range (Typical)	1 to 10,000	100 to 2500	1 to 1000	400 to 20,000	1000 to 50,000	1000 to 50,000
Speed range (typical)	50 to 1	10 to 1	10 to 1	3 to 1	50 to 1	50 to 1
Method of torque control	Armature current and field current	Stator frequency and current	Stator frequency and voltage	Rotor current	Stator current and field current	Stator current
Method of speed control	Closed outer loop speed controller					
Speed feedback source	Armature voltage or tachometer	Inverter frequency or tachometer	Inverter frequency or tachometer	Rotor voltage or tachometer	Inverter frequency or tachometer	Converter frequency or tachometer
Converter type	Phase-controlled Line-commutated	Current link Force-commutated	Voltage link Force-commutated	Current link Line-commutated	Current link Machine-commutated	Phase-controlled Line-commutated
Features	Simplest control Low converter cost Wide speed range	Simple control Good reliability	High output frequencies Multiple motors	Lower cost for smaller speed ranges	Simple control Wide speed range	Wide speed range Fast response
Applications	Extruders Conveyors Machine tools Winders Process machinery General purpose industrial drive	Pumps Fans Compressors Medium power industrial drive	Conveyors Machine tools General purpose industrial drive	Large pumps and fans with limited speed range	Large pumps and blowers Starting sets	High power, low-speed drives Ball mills Cement mills Mine hoists

FIGURE 5-1



A fan with dampers driven at a fixed speed vs. one driven by an electronic adjustable-speed drive.

FIGURE 5-2



Power circuit of a basic nonreversing drive (A) and of a reversing, regenerative drive (B).

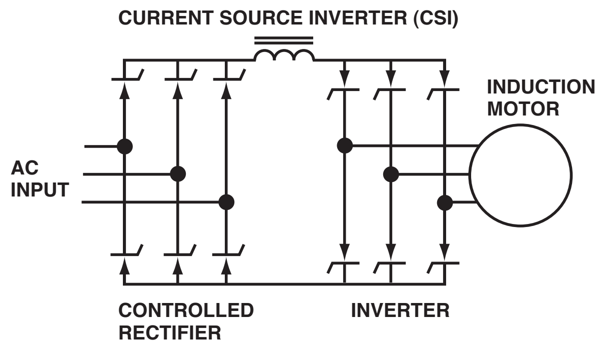
The power circuit of the basic nonreversing unit is shown in Figure 5-2A. A reversing, regenerative drive is shown in Figure 5-2B.

A DC drive provides continuous speed control over a given speed range. The basic control includes a means of starting and stopping the drive and a means for speed control. The speed control can be either manually set with an operator's potentiometer or automatically set from various input signals responding to the process being controlled.

Commutation inherently occurs due to the construction of the motor. This is the major drawback of a DC drive, since the commutator and brushes require regular maintenance.

The DC drive is generally lower in cost than AC drives in the low-horsepower range. The major cost item in DC drives is the motor. If any special motor modifications are required, the cost may increase considerably.

FIGURE 5-3



Power circuit of a current source inverter (CSI).

Current source inverter. The current source inverter is one of the generally applied types in the family of AC adjustable-speed drives. A basic advantage of this class of drive is the use of the widely available squirrel-cage induction motor.

A current source inverter (Figure 5-3) uses a phase-controlled rectifier to generate an adjustable DC voltage, the same as a DC drive. The inverter also has a second inverter bridge to convert the DC into the required controlled-current, variable-frequency power for the motor. A large DC link reactor filters the DC to constant current input to the inverter bridge. A commutation circuit is required for the inverter.

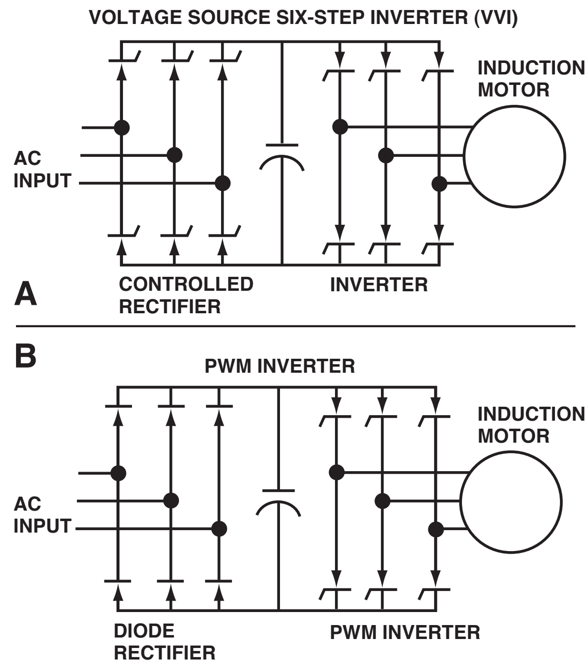
Maximum speed is not limited to the normal synchronous speed for the motor since the inverter can provide higher than 60 Hz when desired. The drive provides a low starting current and has inherent regeneration capability without additional circuitry.

Voltage source inverter. The voltage source inverter also uses a squirrel-cage induction motor. The power circuit of a variable-voltage input inverter is shown in Figure 5-4A (Page 5-9).

As with the current source inverter, variable voltage DC is provided through a controlled rectifier into the inverter bridge. The difference is that a large filter capacitor is used in the DC link rather than a series reactor. This provides a stiff voltage to the inverter, which is voltage-fed rather than current-fed. A commutation circuit is also required.

A second type of voltage source inverter is the pulse-width modulated (PWM) unit. The power circuit of a PWM is shown in Figure 5-4B (Page 5-9). Constant voltage DC is provided by an input diode bridge. The required variable voltage, as well as frequency, is provided in the inverter bridge by pulse width modulation control techniques. A PWM inverter operates at higher switching frequencies than the other types. The front-end diode rectifier provides a better system power factor over the operating range than inverters using controlled rectifiers. PWM circuitry can provide lower motor harmonic losses than basic six-step inverters.

FIGURE 5-4



Power circuit of a variable-voltage input inverter (A) and of a pulse-width modulated (PWM) inverter (B).

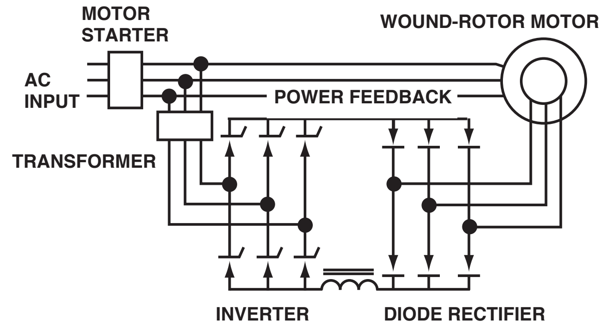
A third type of voltage source inverter is the chopper converter. It uses three power bridges. An input diode rectifier provides constant voltage DC. A controlled rectifier chopper converts this to variable voltage DC, while the output inverter provides variable frequency output. The chopper converter operates as a current source drive by using a large reactor in the chopper output.

Load commutated inverter. The load commutated inverter in combination with a synchronous motor has recently received considerable publicity in the U.S. due to its wide application range in larger horsepower ratings and its high efficiency. The load commutated inverter is a current source AC drive with the advantages of a low inertia AC motor. The motor in this case is a synchronous machine which drives the load and serves to commutate the inverter thyristors.

Two synchronous motor designs may be used for these drives. One is a salient pole design for 1,200 rpm and lower. The other uses a cylindrical rotor capable of high speeds up to 6,000 rpm.

Many advantages of the machine commutated inverter are similar to those of the current source inverter, such as maximum speed not being tied to normal synchronous speeds, low inrush current, and regeneration capability. Since the motor is not directly connected to the power line, this prevents a "contribution" to a system fault and allows economies in the power distribution system. However, because of this isolation, the synchronous motor cannot be used for system power factor correction. The synchronous motors used include a brushless exciter, which eliminates the brushes and slip rings.

FIGURE 5-5



Slip energy recovery drive (static kramer drive).

Slip energy recovery system. The machine commutated inverter uses the counter EMF (electromotive force) from the motor to turn off the thyristors and also determines the frequency of the inverter. Since the motor speed determines the frequency, it cannot pull out of synchronism.

This drive uses a wound-rotor slip-ring induction motor with speed control in the rotor circuit. The power circuit is shown in Figure 5-5.

Originally, wound-rotor motors used in adjustable-speed drives had variable resistors in the rotor circuit. Rotor energy was converted to heat in the resistors and lost in the atmosphere, or cooling equipment was added to remove the heat. The efficiency of the drive was poor, and a method of recovering the energy was needed.

Today, the slip energy from the rotor circuit is rectified to DC and converted to a fixed voltage and fixed frequency to be fed to the motor stator. The inverter for the slip recovery unit is line commutated. The AC power source supplies energy to turn off thyristors, similar to the way a DC drive operates in the regenerative mode. This eliminates the need for a separate commutating circuit.

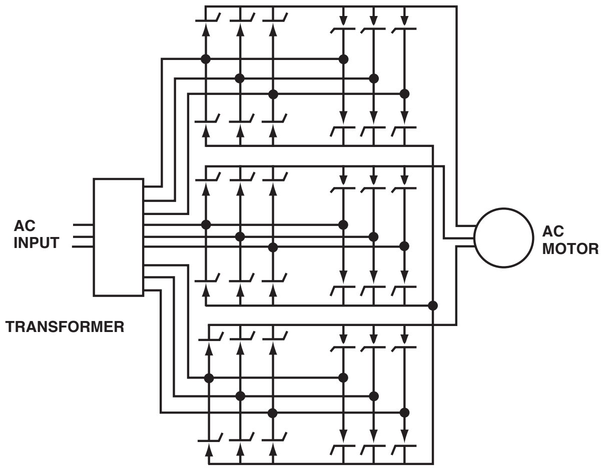
The slip energy recovery drive is of similar or higher efficiency when compared with other electronic drives. The major cost item is the motor, as in the case of a DC drive. Full motor power does not go through the controller, unlike other electronic drives. When a limited speed range is required, the controller can be sized significantly less than the rated motor power, thus allowing use of a lower cost controller. The wound rotor slip recovery drive operates below synchronous speed and cannot operate above it.

Cycloconverter drive. A cycloconverter converts AC input at line frequency to another frequency through a one-step process. One converter is used for each phase winding of the motor.

The power circuit (Figure 5-6) operates in the phase-control, line-commutation mode.

The maximum output frequency applied to the motor is only a fraction of the supply frequency. The cycloconverter may be applied to both synchronous and induction motors. The control system is designed to obtain performance from the rotating field machine equal to that of a DC machine under

FIGURE 5-6



Cycloconverter drive.

current control. The cycloconverter drive is normally furnished for very large-horsepower, low-speed applications, providing high efficiency and fast response.

EFFICIENCY RATINGS

Electronic adjustable-speed drives are highly efficient over their total operating speed range. This contrasts with other methods of modulating process output, such as fan dampers and throttling valves of pumps.

Other types of adjustable-speed drives have significant slip loss, which drastically reduces efficiency at points below full speed. Total energy loss and operating power costs depend not only on drive efficiency but also on the operating load profile of the application.

Efficiency evaluations are normally made between electronic drives and other methods of control. In some cases, a comparative analysis is needed for the various types of electronic drives described in this article. However, a general comparison is not possible. Efficiencies will vary between specific products in each type of drive. These variations are greater than any general differences among drive types. Motor design and the specific operating points for efficiency calculations are the largest contributors to efficiency differences. Power circuit configuration also has an effect.

Different drive types will have various efficiencies, depending on the specific application. Therefore, efficiency comparisons among electronic adjustable-speed drives should be made for each particular application and for the specific equipment involved.

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PWM amplifiers

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A wide range of adjustable-speed technologies is used by industry to achieve better process control, higher productivity and lower maintenance costs. Of these, pulse width modulation amplifiers (PWMs) are now among the most popular, due to their low cost, efficiency, availability of parts and low power factor. They also are quite versatile. By converting fixed AC frequency (single and/or three phase) and voltage to variable DC output for DC motors (typically servo motors) and variable AC voltage and frequency for AC motors (induction and brushless), PWMs make it possible to adjust the torque and/or speed of the motor.

This article describes the main components of PWMs as well as some of the differences among the various types of controls that employ this technology. It also covers the adjustments that may be found on today's controls and explains the advantages of inverters, vector drives and encoderless vectors.

PWM amplifiers are commonly known by such names as:

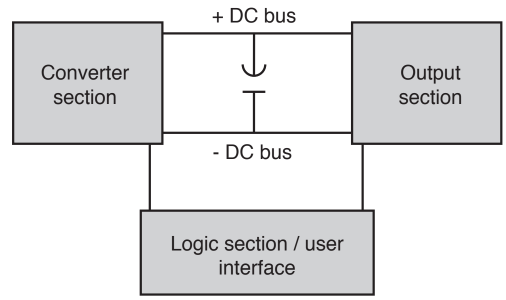
- Servo amplifier
- Inverter
- VFD (variable-frequency drive)
- Encoderless vector
- Vector drive
- ASD (adjustable-speed drive)
- VSD (variable-speed drive)
- Drive
- Control

Although these are all seen as PWM amplifiers, many of them may be other topologies, such as SCR controls or variable-pitch pulley systems.

COMPONENTS

PWM amplifiers generally have three components: the converter section, the logic or control section and the output section (see Figure 5-7).

FIGURE 5-7



Major PWM components.

Converter section

The converter section is the area of the control where the AC input power is converted to DC. There are four primary ways of accomplishing this, each of which has its own peculiarities.

Standard diode bridge. The most common approach is through a diode bridge. This is a series of 4 or 6 diodes–4 for single phase only input and 6 for three-phase input. Basically, the diodes allow either the top or the bottom half of the sine wave to pass through, depending on how they are receiving the power. Facing one diode each way effectively splits the AC power into the "top half" and the "bottom half." This, of course, is now DC.

The level of DC equals the square root of 2 (i.e., 1.414) times the input voltage. The bus for a 460V AC input through a full-wave diode bridge is therefore:

1.414 x 460 = 650V DC

This voltage has some ripple (i.e., harmonics) to it, so there is normally a smoothing capacitor bank to mitigate the bus ripple. *This means when you open the breaker to the control, there is still enough power on the bus to potentially kill you. Be very careful when working with these controls*. The bus of a UL-listed control will be down to (or below) 50V DC within 1 minute after power is shut off. Always measure the bus before working inside the control.

A modified diode bridge. One approach to help minimize harmonics is to add an isolation transformer with a delta primary and both a delta and a wye secondary. The output of the delta secondary goes into one diode bridge, and the output of the wye secondary goes into another diode bridge feeding the same bus. This effectively creates a voltage phase shift, so the harmonic currents are reflected into the primary at different times. This smooths out the harmonics in the power distribution system as well as in the bus of the amplifier. There is, however, a cost premium associated with this technique.

DC drive (SCR) front end. Another successful technique for converting AC power to DC employs a 4-quadrant DC drive. Two SCRs per phase on the input and two SCRs per phase on the output (12 SCRs for a three-phase system) accomplish this. The SCR can convert AC to DC at the rate of 1.08 times the RMS input voltage. Therefore on a 460V AC power distribution system the bus will be 460V AC x 1.08 = 500V DC.

The resultant voltage is not as high as that of the diode bridge for the same output power (volts x amps), so the motor will draw more current. That means additional motor heating and potentially larger transistors in the control.

An advantage of this approach, however, is that the extra SCRs in the control can put regenerative energy back on the line for use by other electrical components. This works well for applications with heavy regenerative loads (e.g., hoists, elevators, dynamometers and unwind stands).

Transistorized front end. Another approach is to have 6 transistors turning on and off as the AC power comes into the control. Additional phase sensing is required to ensure that the transistors are turned on at the correct times, but with an appropriate boost reactor, a constant 750V DC bus is achievable.

The logic to commutate this power back on the line is a vector algorithm. This means the front end (converter section) of the amplifier is effectively a vector drive. While it can be expensive, this approach has several advantages: unity power factor (1.0), very low harmonics back on the line, and line regenerative control. It is excellent for dynamometers, hoists, elevators and unwind stands.

Some notes on the converter section

Single-phase power. It is often possible to run a three-phase rated control on single-phase power. Most manufacturers, however, make you derate the continuous output current 20 - 50 % (especially on higher horsepower ratings). The reason for this is threefold.

The diode bridge, capacitor bank and power supply are not capable of supplying the bus with enough continuous voltage for full three-phase output current for the motor.

Since the AC is only commutated 120 times/second (60 Hz x 2 x 1 ph) instead of 360 times/second (60 Hz x 2 x 3 ph), there is a lot more ripple current in the bus. Pulling full output current will likely weaken the capacitor bank enough that it could eventually explode.

With higher ripple on the capacitor bank, it is more difficult to control the current in the motor and within the amplifier.

Most manufacturers rate their controls for a wide voltage range. Be careful when applying these to voltages outside of the exact ratings. There are pitfalls. If the actual input voltage is lower than the rating (e.g., 208V AC instead of 230V AC), the control will still work; however, it will not put out any more current. This means a larger control will be needed for the same output power. Why? Power equals volts times amps. If volts are down and amps cannot be increased, the control is undersized.

Misfiring SCRs. When using the SCR front end, exercise caution if significant harmonics are present. Harmonics may cause the SCR to misfire due to multiple zero crossings. Although a line reactor will often help clean the power, it is not always the correct solution. A line reactor adds impedance to the system. Once an SCR sees approximately 8% or more impedance, the current is separated far enough from the voltage that this also causes the SCRs to misfire.

Voltage swings. The SCR and PWM front-end controls can modify their input when high or low voltages are present–i.e., they can be turned off. A diode bridge just keeps on converting. During very low power conditions, this may damage a soft-start charging resistor. During high power conditions, it might destroy a regenerative transistor or resistor, or even the bridge and capacitor bank. For protection in such conditions, install a voltage-monitoring device tied into the contactor that feeds the amplifier.

The converter section–conclusion

The front end of the control converts AC single- or three-phase power to DC power using SCRs, transistors or diodes, all of which are much more susceptible to damage from line voltage disturbances than a motor. For this reason, it is generally advisable to add a line reactor (also called a choke or inductor) ahead of the control, especially when power is not clean and when the application is critical. Having learned from experience, most control manufacturers automatically include an input line reactor in any panel they build using their controls.

All four conversion techniques described above are still being used. Each has unique advantages. Let decision makers know that different techniques can accomplish the same purpose, with slightly different results, reliability and performance.

DC bus section

The DC bus carries energy. In just about every PWM control on the market, bus values are continuously measured and decisions are made if the bus is above or below prescribed limits. Many of the controls go from moderate to great care in smoothing out the ripple current to keep the components intact.

Most of the amplifiers on the market today use a capacitor bank to help smooth out the ripple current on the bus. This is a fairly inexpensive and reliable technique. However, capacitors are susceptible to "rapid disassembly" when subjected to high voltages, heat and/or current. There are several methods to keep these forces within acceptable limits.

Soft-start charging. Most of the smaller controllers use a soft-start charging resistor. This circuit passes the bus through a resistor before the voltage enters the capacitor. This minimizes the inrush current into the capacitor bank. Once the bus voltage exceeds minimum limits, a contactor closes, bypassing the resistor and keeping it from overheating.

Another method is to use an SCR to increase the voltage into the bus. Once the bus voltage is above minimum limits, the SCR is turned off and power goes through a diode bridge.

DC bus choke. With this method, an inductor in the bus reduces ripple and inrush current. This also helps the amplifier survive voltage spikes when it is powered from a low-impedance source. The choke, however, adds cost, weight and space.

Some controls allow a DC choke to be an option that can be added as required. Use chokes cautiously, though, because they lower voltage with current, thus reducing output power.

The bus starts from the output of the converter section, routes the power to the capacitor bank and choke (if applied) and ends at the output section.

Output section

The output section is comprised of transistors that turn on and off, thus pulsing DC to the windings.

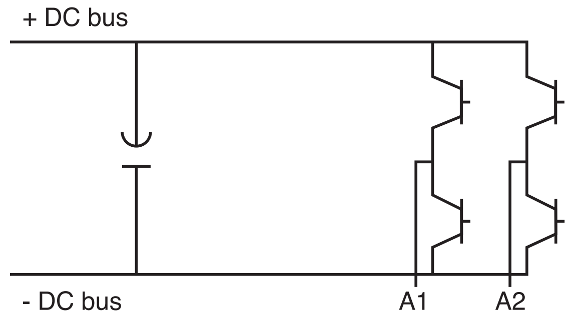
PWM DC. Many of today's servo controllers are PWM output. For the permanent magnet brush-style motors, the output section consists of 4 transistors configured as shown in Figure 5-8 (Page 5-13).

Turning on the top transistor to A1 and the bottom transistor to A2 would rotate the motor in one direction. Turning on the bottom transistor to A1 and the top transistor to A2 would rotate the motor in the opposite direction.

The speed of a PWM DC motor is directly proportional to voltage. The longer and more dense the pulses, the higher the average voltage to the motor (Figure 5-9 on Page 5-13).

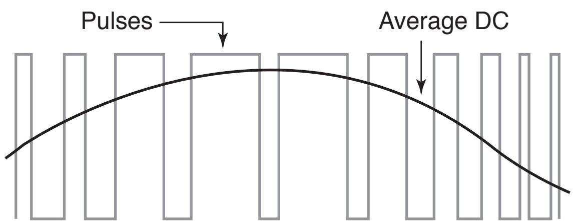
Since the "on" and "off" times can be controlled, so can

FIGURE 5-8



Output section consists of 4 transistors.

FIGURE 5-9



The longer and denser the pulses, the higher the average voltage to the motor.

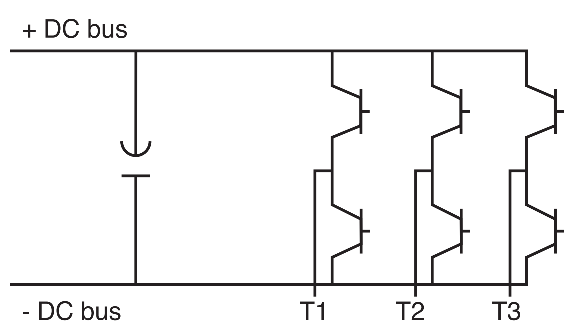
the voltage. If the voltage can be controlled, so can the speed. The polarity of A1 and A2 can also be changed, so it is possible to control motor direction.

If the inductance of the motor is too low, the current that flows through the transistor will be too high. In this case, use an output inductor or increase the current rating of the amplifier. Also, ensure that the rate of voltage rise is not so fast that it flashes the commutator.

PWM AC. Figure 5-10 illustrates PWM AC, which is used in a number of technologies:

- Inverter
- Encoderless vector
- Vector
- Brushless

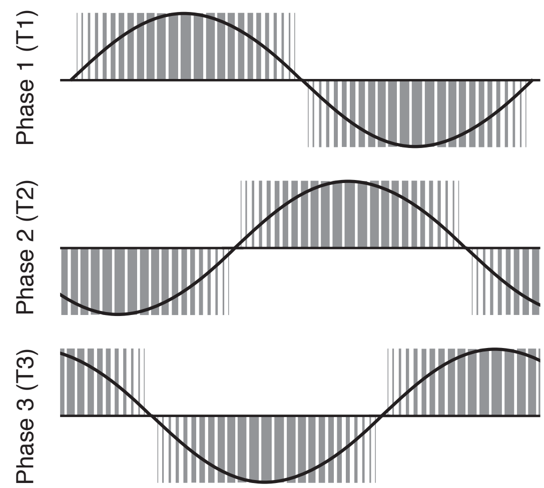
FIGURE 5-10



PWM AC is used in inverter, vector, encoderless vector and brushless technologies.

The positive and negative transistors on the each leg can be turned on, so the frequency can be changed. Because frequency can be changed, speed can also be adjusted. Figure 5-11 shows what the output looks like.

FIGURE 5-11



PWM AC output.

As the illustration shows, the frequency is controlled by modifying the “on” time of the top-to-bottom transistor on each leg. Obviously the phases must remain 120 degrees out-of-phase. Changing the “on” time versus the “off” time also changes the voltage at that frequency, making it possible to maximize the current-to-load ratio.

An increase of voltage to frequency increases the motor’s torque, current and heat until it reaches electrical saturation. A decrease of voltage to frequency decreases the motor’s torque, current and heat (useful for variable-torque loads). Voltage and frequency levels are sometimes controlled by software and sometimes by firmware.

Current can flow through a transistor in either direction. Therefore as a motor regenerates, the energy passes back through the output section and into the bus.

Many of today’s transistors protect themselves from overheat and overcurrent. If heat or current exceed the prescribed limit, an intelligent power module (IPM) “base blocks” the transistor and signals the microprocessor’s central controller that the output devices have shut themselves off for self protection. IPMs are more prevalent in the larger (and more expensive) modules.

The three-phase output section (all six transistors) frequently comes in one integrated module (often called a “six pack”).

Many of the larger transistors are near high voltage input and output power, posing the danger that noise will get into their firing circuits.

Turning on the lower and upper transistors at the same time on the same leg would cause a direct bus short, which may destroy the capacitor bank along with several other components in a potentially explosive manner. Due to this potential problem, many of the devices are gated by fiber optics instead of wire. (Note that you can't "ohm out" fiber optic gating wire. You can, however, place a flashlight on one end and see the light come out the other end.)

Regenerative circuits

There are several ways of handling regenerative energy.

- **DC high.** As the motor is regenerating, the bus voltage will start to increase. Since we continue to monitor this level, when it exceeds the control threshold, we base block the transistor and the control "faults out" on over voltage, DC high, high bus, bus over voltage or some fault to this effect. The actual term is manufacturer selected.
- **Bus leveling frequency change.** As the motor is regenerating and the bus voltage reaches a threshold, the control will increase the free frequency to the motor which will decrease the bus. If the bus voltage eventually reaches the absolute threshold, the control will trip on a DC high fault. If tight speed control is required, this may not be a viable option.
- **Regenerative braking kit.** This is typically built into smaller, full-feature controls and added as an option to larger controls and many mini controls. As shown in Figure 5-12, the circuit has two components. As the bus voltage reaches an internal limit, the regenerative transistor starts to pulse the DC bus through the resistor, turning the excess energy into heat. This is a very effective method of controlling the excess energy and the motor speed.

Some notes on regenerative circuits. Many regenerative assemblies come as a complete package (a transistor and resistor). Typically, a twisted pair shielded wire is used for the transistor and power wiring for the bus.

Some regenerative kits have independent transistor and resistor assemblies. If the ohm value of the resistor kit is too low, the current through the transistor will be too high and may destroy the output transistor. If this shorts to ground, it will also take the bus to ground, possibly destroying the capacitor bank and converter section.

The lower the ohm value of the kit, the greater the braking "torque." The braking current can be calculated by dividing the bus voltage at time of regeneration by the ohm value (Ohm's law).

Example: A 200 hp 460V AC input control that regenerates from 780V DC to 800V DC with a 7.9 ohm resistor.

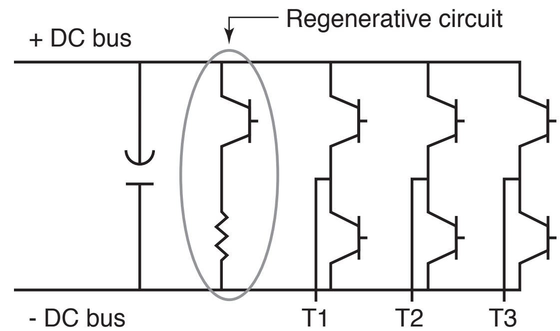
- Average bus voltage during deceleration = (780 + 800)/2 = 790V DC
- Average braking current = (790V DC) / 7.9 ohms = 100 amps regenerative DC current.

Hoisting load calculations

The watts relate to the total amount of braking over time required. Calculate watts as follows.

1. Calculate braking duty cycle:
2. Duty cycle = Lowering time / Total cycle time
3. Calculate braking watts to be dissipated in dynamic braking resistors:

FIGURE 5-12



Regenerative braking circuit.

Watts = (Duty cycle x lbs x FPM x Efficiency) /44

Where:	Ibs	=	Weight of load
	FPM	=	Feet per minute
	Efficiency	=	Mechanical efficiency (i.e., 95% = 0.95)
	Time	=	Seconds

General machinery load calculations

1. Calculate braking duty cycle:
   Duty cycle = Braking time / Total cycle time
2. Calculate deceleration torque:
   T_{Decel} = {(rpm change x Wk^2) / (308 x time)} - Friction (lb ft)

Where:	T_{Decel}	=	Deceleration torque (Ib-ft)
	Wk^2	=	Inertia (lb ft^2)
	Time	=	Seconds
3. Calculate watts to be dissipated in dynamic braking resistor:
   Watts = T_{Decel} x (S_{max} - S_{min}) x Duty cycle x (0.0712)

Where:	S_{max}	=	Speed to start braking
	S_{min}	=	Speed after braking
4. Multiply watts calculated in Step 3 by 1.25 to allow for unanticipated loads (safety factor).

If the ohm value of the kit is too high (not enough braking torque), the amplifier will experience high bus faults. If the watts are too low, the control may calculate that too much regenerative energy is going into the resistors and shut off the circuit. If the control does not calculate this, the kit may have a normally closed bipolar thermostat that can be wired into the control circuit for shutting down if over temperature is sensed. Unless both of these options are implemented, too much energy may cause a fire.

Line regeneration. Both the SCR and transistor front-end control allow the regenerated energy to be passed back onto the power distribution system. This is highly efficient as well as cost effective for applications like the following that experience a lot of regeneration.

- Dynamometers
- Hoists
- Elevators
- Unwind stands

- Electric vehicles
- Downhill conveyors

The control section

The control section is where everything gets tied together. It may be run on low-voltage AC or DC power, each of which has advantages. AC logic, for example, is not as susceptible as DC logic to current ripple on the bus or noise and harmonics that make their way into the supply. On the other hand, DC logic can stay up longer than an AC logic supply during a power dip.

The following circuits typically feed into the logic card (control section).

- **DC bus voltages.** Determines when to close the contact around the soft-start resistors (or to turn off the SCR).
- **DC bus current.** Samples the DC bus current and compares it to input and output to determine if current is nearing capacitor and converter thresholds.
- **Output current.** Samples output current to determine if one or more legs are open and current is balanced. It also determines slip frequency and modifies PWM for smoother acceleration.
- **Input current sum.** Often a current transducer is wrapped around the power (three-phase) lines. This is just on the other side of the customer end of the terminal block. If current is fairly balanced in all three legs, the output is nulled (0). If one leg is going to ground, the output is high and the control trips off on a ground fault.
- **Temperature switch or thermistor.** If present, the temperature switch or thermistor on the backplane of the control's heat sink is fed into the control card to turn off the control due to internal over temperature.

Additionally, the control section is where the user sets up the control for his application. This may be as simple as turning a couple of potentiometers or as complex as connecting the control as a node on a factory network so that it can be monitored over phone lines or a multi-drop system.

The control section is also where the device is told how to operate (e.g., start, stop, accelerate to X speed, reverse, etc.). Some popular ways of doing this include:

- Keypad control
- Start/stop push-buttons and a speed potentiometer
- Speed selection switch (a digital potentiometer)
- Motorized electronic potentiometer
- PLC interfaced to the amplifier
- Building management system interfaced to the amplifier
- Setpoint controller interfaced with the amplifier
- Computer communication with the control
- Networkable control
- Positioning controller doing coordinated motion

In closed-loop, velocity-controlled drives, the feedback comes into the control board for sampling. The typical feedback elements for PWM amplifiers are:

- **PWM PMDC**
  - Tachometers for amplifier velocity control
  - Encoders for the positioning controller
  - Motor current
- **Inverters**
  - Motor current
- **Encoderless vector**
  - Motor current
- **Vector drives**
  - Encoder
  - Resolver
  - Motor current
- **Brushless drives**
  - Resolver
  - Hall effect
  - Motor current
  - Motor current

To summarize, feedback elements for PWM amplifiers provide:

- Information about the inside of the control;
- Programmed instructions telling the control how to operate;
- Analog inputs and outputs, digital inputs and outputs, serial inputs and outputs (I/O);
- Velocity feedback

Control status. Information about the inside of the control comes from protective circuits that monitor temperatures, voltages and currents within the control. These are strictly for self-preservation. The only time anyone even knows these circuits are working is when they exceed their limits and the control shuts down. When that happens, people often think the control "failed." On the contrary, it succeeded in identifying a problem and prevented the control from self-destruction.

Common adjustments. Programmed instructions, either digital or analog, tell the control how to operate. They control many common adjustments (analog) or parameters (digital), including:

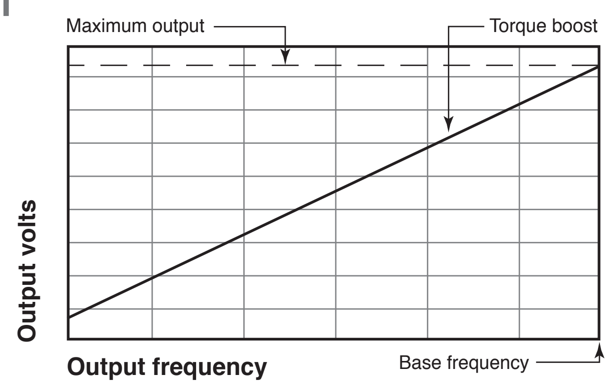
- **Preset speeds.** Allows the setup operator to preset a speed (typically a frequency for inverters and a rpm for brushless and vector drives).
- **Acceleration.** Allows the setup operator to set the ramp rate from 0 to maximum speed. This is not the time from any speed to any other speed, just the time from 0 (or minimum speed) to maximum speed.
- **Jog speed.** Allows the setup operator to set the speed during a jog. Usually this is a normally open switch that closes momentarily to jog something into place (e.g., a hoist), or to jog reverse to "unjam" something (e.g., a jammed conveyor).
- **Braking type.** Allows the setup of coast-to-a-stop, regeneration-to-a-stop, DC injection brake-to-a-stop, or maybe a combination of these. Coast-to-a-stop may be useful to determine if machine vibration is electrically or mechanically induced.
- **Keypad setup.** Allows assignment of specific functions to keys on the keypad. This is useful on applications like pumps or fans where a reverse command could be disastrous.
- **Operating mode.** This sets up the digital inputs in typical configurations. Many controls offer the flexibility to assign several inputs to a few operating modes; others have

many predefined operating modes. The simplest analog controls will allow some of this flexibility through option cards or jumpers.

- **Analog command.** Allows the scaling of the input. Most common are:
  - Potentiometer
  - 0 - 5V DC
  - 0 - 10V DC
  - 4 - 20mA
  - ± 0 - 5V DC
  - ± 0 - 10V DC
  - ± 4 - 20mA
- **Digital outputs.** Digital outputs may control an optocoupler or a relay. These outputs are typically used for fault indication, setting brakes, under voltage, drive ready, zero speed, at speed, etc.
- **Analog outputs.** Analog outputs tie the speed or current of two controls together electrically, or as a source for indication meters, information back into PLCs, etc. These are typically:
  - 0 - 5V DC
  - 0 - 10V DC
  - 4 - 20mA
- **Minimum speed.** When commanded to run, this will be the speed with minimum analog input.
- **Maximum speed.** The speed commanded when analog input is at maximum.
- **Peak (or maximum) current.** Limits the amount of current, hence torque, to the motor.
- **Restart.** This is an important parameter for safety. It allows the control to start automatically after a fault has been cleared (and sometimes as power is applied) or to require the operator to push a run button to start the unit.
- **Security control.** This allows use of a password to keep operators from changing items without authorization.
- **Regenerative braking.** May be used to set the PWM output to a resistor. Provides parameters for setting the regeneration watts in order to prevent fires.
- **DC injection braking.** Parameters for setting the braking voltage (used to set braking torque), the frequency at which braking starts, whether to brake during starting (to fight antiwindmilling), braking on a reverse (good for simple fillers) and brake on stop.
- **Process control.** Used to control a process through feedback and setpoint. The many parameters and different ways to control a process vary from manufacturer to manufacturer.
- **Motor amps.** Used to set the electronic thermal; also used in many of the motor's algorithms.
- **Motor speed (or poles).** Used to calculate speed (for open loop) and to set the frequency (or voltage for DC) to feedback ratios.
- **Motor voltage.** Used to set the base speed on DC and the volts/Hertz for AC.
- **Motor frequency.** Used only on AC to set the volts/Hertz and pole count.
- **Magnetizing current.** The same as no-load amps. Used to set up a motor model and in slip-compensation calculations.
- **Encoder count.** Used to scale the speed of the motor. Usually programmed in pulses per revolution.
- **Tachometer volts.** Used to scale the speed of the motor. Usually programmed in volts per 1000 rpm (v/krpm).
- **Resolver speeds.** Used to scale the speed of the motor. Usually programmed in speeds. Some controls program in poles. The conversion is:

  Resolver speeds = Resolver poles / 2
- **Base frequency (AC) or base speed (AC or DC).** Programs the speed at which you run out of stator (or armature) voltage.
- **Torque (or voltage) boost.** Raises the voltage at the low end to increase low-end torque.
- **Dynamic boost.** A momentary increase in voltage as current bumps up.
- **Slip compensation.** Increases the frequency as current goes up from magnetizing current to full-load current to attempt to maintain motor speed (open loop).
- **Volts/Hertz.** Used to set the profile for torque (saturation levels) at frequencies between 0 frequency at torque boost setting and base frequency full voltage. Too high of a torque boost or any excessive volts/Hertz profile will saturate the lamination and increase current and heat above desirable levels. It also may increase current to trip levels (see Figure 5-13).

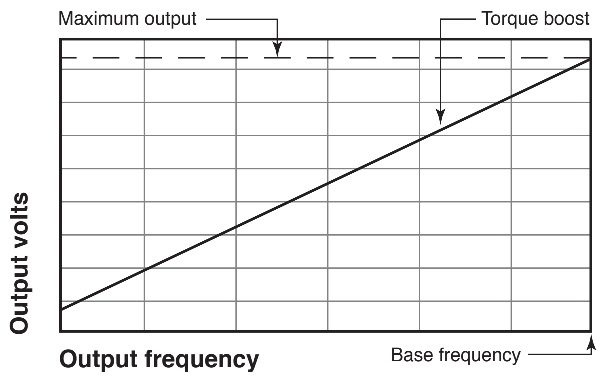
FIGURE 5-13



Linear V/Hz curve.

- If the torque boost or any low volts/Hertz profile is too low, the motor will be too weak, and the load will run too slow (see Figure 5-14 on Page 5-17).
- **Synchronized start.** Used to measure the speed to start the rotating electrical frequency at the mechanical rotating frequency.
- **Auto tuning.** Many of the digital amplifiers have "auto-tuning," which sets the gains for current, velocity and potentially position.
- **Current proportional gain.** Allows the resistance and inductance of the motor to determine how hard to force current into the motor due to velocity or torque error.

FIGURE 5-14



Square law V/Hz curve.

- **Current integral gain.** Allows for the acceleration of current for longer-term errors; somewhat limited by microprocessor speed. Typical values are between 50 and 150 Hz.
- **Proportional speed gain.** Allows for velocity acceleration due to error from speed setpoint; adjustable for inertia and mechanical machine compliance.
- **Proportional Integral gain.** Allows for the velocity acceleration due to steady-state error from the speed setpoint; adjustable for inertia and mechanical machine compliance.
- **Proportional differential gain.** Allows for the velocity acceleration due to the slope of the error from the speed setpoint; adjustable for inertia and mechanical machine compliance.
- **Slip frequency.** Helps control the slip angle for setting the proper relationship (rotor pole to stator pole) for maximum torque.

These adjustments are some of the most popular and universal for typical general-purpose PWM amplifiers.

Analog inputs

For most inverter applications, if an analog input is used for speed command, it is typically unipolar. Bipolar speed command is more popular for many of the encoderless vector, vector drive and brushless DC drives.

- **Unipolar input** compares a positive voltage to a common. Speed (or torque if in torque mode) is proportional to the input command. Direction of speed (or torque) is commanded by a switch closure.
- **Bipolar input** compares positive or negative voltages to each other (instead of comparing to a common). The output speed (or torque, if in torque mode) is proportional to the input command. Direction of speed (or torque) is commanded by the polarity of the analog input. There is generally a forward and/or reverse enable (for an end of travel or emergency-stop command).

Since most PWM controls have general-purpose analog and digital inputs and outputs, they generally are easily integrated for work with a PLC, building management system, operator station, etc. The requirements of the front-end controller must be reviewed for each integration.

Some notes on the control card

A typical problem with the input card is noise getting in on the analog and digital signals. This sometimes shows up as an incorrect speed reference or as a fault from noise getting into the fault integrated circuit.

For analog noise use an input electronic filter (sampling) and analog deadband and wrap the analog input around a ferrite bead. Separate the logic and power wires by at least 6” (more if possible). If power and logic wires must cross, it should be at right angles.

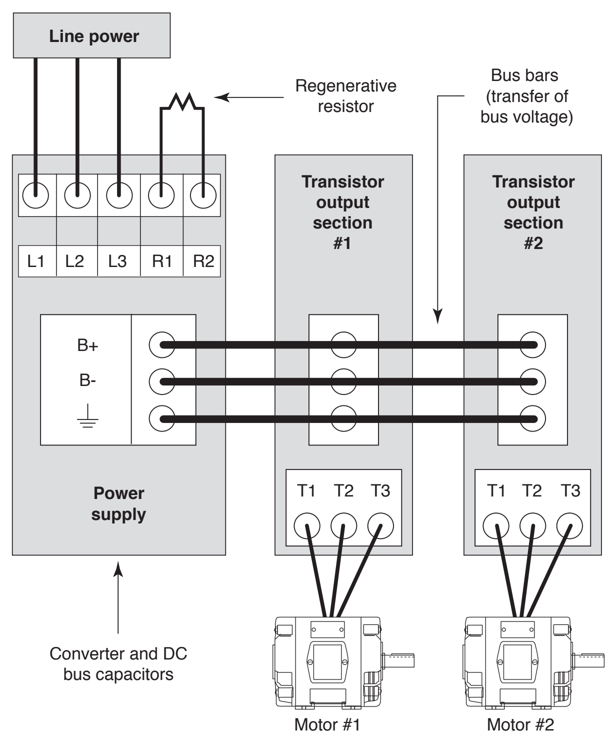
For digital noise, check wire routing as for analog above. If the circuit includes relays or coils, suppress the inductive “kick” by using flyback diodes on the DC coils and snubbers on the AC coils.

Multi-axis controllers

It is possible to mix and match controller parts if there is more than one axis. Basically, this requires a power supply (converter and DC bus) capable of providing the continuous output current for all the axes, as well as the peak current required at any time (see Figure 5-15).

The output sections can be inverter, DC, brushless, encoderless vector or vector drive. Additionally, the outputs can be mixed or matched. As Figure 5-15 shows, Output

FIGURE 5-15



Multi-axis controller.

Section 1 may be a vector drive, and Output Section 2 may be a brushless amplifier. This could be used, for example, in a cut-to-length application.

A big advantage of such a package is that if one motor is regenerating while the other is motoring, the regenerative energy can be used to run the other motor instead of just heating the resistor.

Some differences among inverters, encoderless vectors and vector drives

Inverters control motor speed in an open-loop fashion, typically providing speed ranges from 3:1 to 20:1. The speed range usually is motor dependent, although the quality of the amplifier output as well as several parameters affect the control of (and heat generated in) the motor.

An inverter produces a fixed volts/Hertz pattern that is programmed in either firmware or software. In either case, as a specific frequency is injected into the motor, it is at a fixed voltage that was programmed for that frequency. This prevents the power supplied to the motor from changing with load. It also prevents changes in the stator frequency or voltage coordinating with rotor pole velocity, position and load.

The rotor slipping behind the rotating magnetic field in the stator creates the current in the rotor. This in turn generates magnetic poles in the rotor and attraction to the stator.

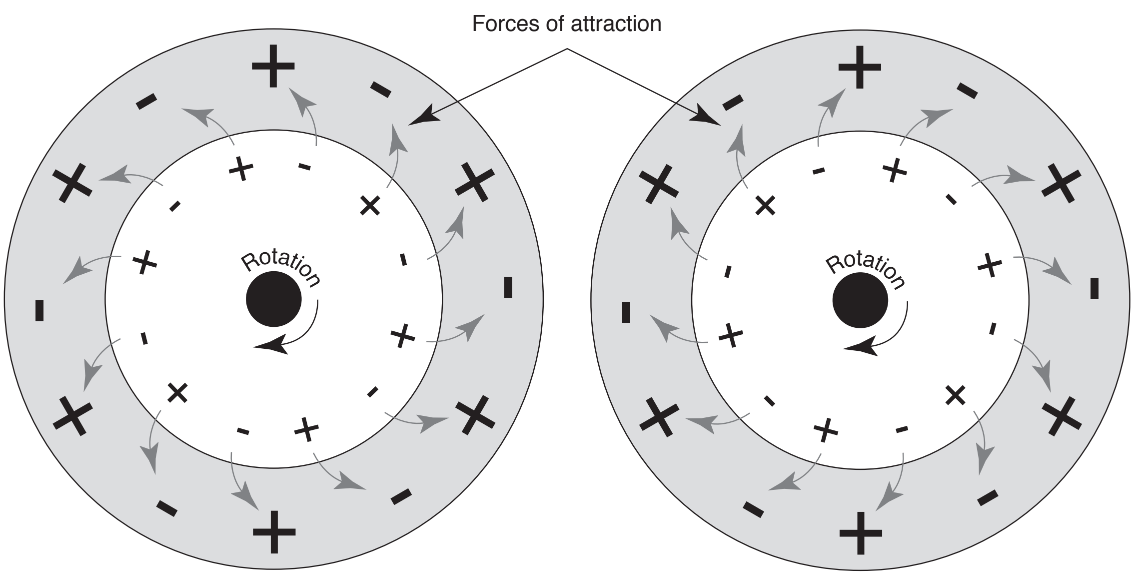
At low speeds, there is little inertia and torque. As Figure 5-16 shows, there will be rotor positions where the stator will attract the poles in the rotor in the direction of rotation. Since the inverter supplies a fixed frequency (independent of rotor position) to the stator, there will also be rotor positions where the stator will attract the poles in the rotor in the opposite direction of rotation. This is known as "cogging".

The **vector drive** solves this issue by putting a feedback device on the rotating member. This is typically an encoder, although many drives also use resolvers as standard or an option. In either case, it provides rotor positional feedback to the control that is used to coordinate the location of the stator pole to achieve the optimum torque angle to the rotor. An appropriate voltage is simultaneously pulsed into the stator to generate the magnetic field strength appropriate to the load induced on the motor shaft.

This approach has several advantages over the inverter. For example, because vector drives provide velocity feedback, the speed and strength of the stator field can be changed in order to force the rotor to rotate at the commanded speed. Since this is a closed-loop system, speed regulation is very good. An inverter typically achieves 2 - 3% of base speed, whereas a vector control can achieve 0.1 to 0.01 % of set speed. How much of an effect does this have? See the following chart.

Commanded speed	2% of base speed	0.1% of set speed
1800	36	1.8
1200	36	1.2
900	36	0.9
500	36	0.5
200	36	0.2

FIGURE 5-16



Point of cogging on an inverter. Forces of attraction are *opposite* of the direction of rotation.

Point of good rotation on an inverter. Forces of attraction are in the *same* direction as the direction of rotation.

At low speeds, where there is little inertia and torque, "cogging" may occur–i.e., in some positions the rotor poles will be attracted to the stator in the *opposite direction of rotation*.

Vector drives can also use torque rather than speed to control the drive. In that case, a command (generally ±10V DC) represents the amount of torque that will be produced. If the load is great, the speed will be low; as the load decreases, the speed increases. This is useful for dynamometer and some winder applications. It also may make tuning with a front-end controller easier by closing this loop in the front-end controller instead of the amplifier.

Since the stator pole can be positioned in relation to the rotor pole, full torque can be generated at 0 speed. This will generate full-load current at 0 speed, so the cooling package needs to provide adequate cooling to the motor if this condition is present.

Vector drives can run at very, very low speeds. It is quite common to run at 1 rpm with full torque. With an 1800 rpm motor, this means we can have a constant-torque speed range of 1800:1. With many of the vector motors on the market good for 6,000 rpm, it is possible to have a speed range of 6000:1. With very special motors 50,000:1 can be achieved.

Among other advantages of vector drives is that they control current and phase angle, making them able to handle reciprocating loads with less difficulty than inverters. Encoder output can also be buffered into master pulse reference cards for electronic gearing.

With vector drives it also is possible to bring a buffered encoder output into a front end positional controller to do coordinated motion with other vector controls, brushless controls, servo DC controls, even hydraulic servos.

Encoderless vectors are the newest things on the market. Like vector drives, they also change the stator voltage and frequency to compensate for load-related speed fluctuations and to maximize the torque/amp of the motor. This is done by a strong motor model (inductance, reactance, resistance, etc.) allowing the control to know as the vector of current changes with relation to voltage and frequency, the location of the rotor poles and the magnitude of the load. The control then orients the stator field to the rotor field.

The encoderless vector has not met market hopes as of yet. The lack of a feedback device to contend with and the absence of wiring and noise issues are big pluses. However, dynamic control during deceleration, low speeds (below 30 - 50 rpm) with good full torque and full zero-speed torque have been somewhat disappointing when compared to a full vector control. Still, it is significantly better than an inverter. Most vector controls can also run encoderless, which is a great troubleshooting technique if the encoder is suspected as the culprit.

CONCLUSIONS

Various motor technologies are powered by PWM amplifiers. These amplifiers have several different topologies, each of which has its own advantages. What they share, however, is the ability to control the speed and often torque of a motor in order to maintain better process control, save energy and reduce maintenance costs through smoother operation of mechanical devices.

Most of the continuing work in this field is being done in two areas: better control of the motor (with and without feedback) and network communications (making the amplifier a node in the communication bus of the factory automation system). As factories continue to automate processes and communications we will continue to see an increase in the use of the PWM amplifiers. They suit these goals well.

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Simple troubleshooting of amplifiers in the field

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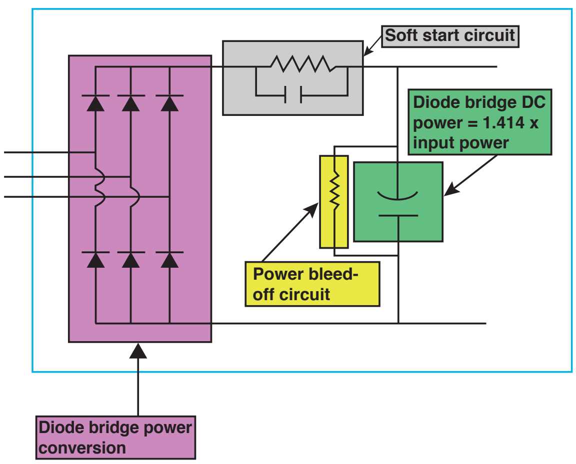
As more and more inverters, vector controls, brushless controls, and DC controls are installed, the opportunities to help customers set up and troubleshoot drives increase.

SAFETY, SAFETY, SAFETY

Drives and controls operate on enough power to be very dangerous–even fatal. Be extremely careful. Do not touch anything that is unfamiliar to you, and always measure the power first to make sure it is safe.

FIGURE 5-17



Control converts AC input power to DC and charges the capacitor.

Figure 5-17 shows how the control converts the input power (typically three-phase AC but could be single-phase) to DC. The power is usually brought through a soft-start resistor to the DC bus. When the power is high enough, a contactor closes to bypass the soft-start resistor and charge the capacitor. Some controls use an SCR for soft charging the capacitor.

The input voltage determines the voltage of the fully charged capacitor:

1.414 x 230VAC = 328VDC

1.414 x 460VAC = 650VDC

1.414 x 575VAC = 813VDC

Important: Even if the power into the amplifier is discontinued, **power still exists inside the amplifier!**

Notice that there is a bleed-off circuit that should decrease the power to safe levels. However, if the resistor is burned out or the trace is destroyed, the voltage will remain in the capacitor. Use a DC voltmeter to make sure the voltage has dissipated before working inside the control.

UL-recognized controls are required to dissipate the bus voltage to 50VDC or below within one minute after power is shut off. This assumes the bleed-off circuit is functional. *Don't assume anything! Measure it.*

Many controls will have a bus power LED (light emitting diode) inside. You can trust these when they are "on" but not when they are "off." A good analogy is a light bulb that doesn't "turn on" when you flip the switch; it doesn't prove there is no power on the circuit. **If the LED is off, do not assume bus power is off**.

TROUBLESHOOTING

Start the troubleshooting with questions. You can get lots of useful information about the power conditions of the facility from the machine operator and the maintenance crew. Some common questions to ask include:

1. Has the machine ever worked–correctly?
2. What changed between the time when it was working and when it stopped working?
3. Did anything unusual happen before or during this occurrence?
4. How do you want this machine to operate, and how is it set up to operate?
5. What are the problems with the machine?
6. Is there a similar machine operating elsewhere in the facility?
7. Where is the manual for the amplifier–especially the one with any machine wiring and programming information?
8. Have you been having any power problems in the facility?
9. Is the problem continuous or intermittent?
10. Can you demonstrate the problem (assuming this won't damage the equipment or injure personnel)?

What to look for when the motor does not start.

1. Is power going into the amplifier?
2. Is the power at the appropriate level?
3. Has the logic power come up?
    - Can you read the keypad?
    - Is the logic power up (power on terminal strip)?
    - Is there a power board with LEDs?
4. Can you measure the power on the bus to see if it is correct?
5. Will the motor run from a keypad? If so, check the I/O programming and the logic wiring.
6. If the motor does not run from the keypad (or a hard-wired input if a keypad is not available), use a clamp-on AC RMS ammeter to determine if there is current in all legs of the motor, and if it is balanced.
7. Is there an interconnected brake on the motor? If so, disconnect power from motor, disconnect the internal

connection and feed power into the brake in an appropriate and safe manner. The brake has to be separately connected to power–not through the motor–when operated from an amplifier.

8. If there is balanced full-load current to the motor, disconnect the power. Disconnect the load. Reconnect the power and try to start again. If it runs, the load is greater than the drive (motor and amplifier combination) can start. Is this a normal condition?
9. If so, can the current be increased (programming) or the torque boost (AC) or field forcing (DC) be increased without other damaging effects? Is the acceleration time too quick, increasing the current beyond the capability of the amplifier?
10. If no current was measured on the motor, try to identify an open contactor between the amplifier and the motor.
11. The output power can be measured with a voltmeter, but be cautious on 460VAC and higher amplifiers. With the potential of reflective waves, the voltage spikes may be greater than the most common voltage probes can handle. **Caution**–this can rapidly disassemble your probe!

What to look for if the control trips out.

Although it is often considered a "failure of the amplifier" when the control trips off, it is actually a success. The amplifier has successfully identified a problem and then protected itself, the motor, the operator and/or the equipment

Ask the operator for information.

1. Does the control trip during a particular machine operation?
2. Are any buttons or knobs tweaked before the fault occurs?
3. Does it happen during acceleration, running, decelerating or idle?
4. Do you "hear anything" when this occurs? If so, what does it sound like?
5. Does this happen at a particular time of day?
6. Can you demonstrate the condition–as long as it does not cause any harm?

Find the fault log and see if a generated pattern gives some clue.

What to look for from an overcurrent fault.

Try to determine if it occurs instantaneously or over time. Many controls will differentiate. Many of the larger controls will also have intelligent transistors that will turn themselves off with an instantaneous overcurrent fault and then send a signal to the main amplifier processor.

Things to look for:

1. Is there any motor slamming? Motor slamming is what happens when you close a contactor on the amplifier's output with the output voltage and frequency (if AC) already part way up. This would be somewhat like putting a motor across the line, and the inrush would be enough to "trip" the amplifier.
2. Is there a clutch on the output of the motor? If so, discuss the need for the clutch. If it is required, and you can run the motor across the line, do so and engage the clutch. Measure the peak current with a fast clamp-on ammeter with peak hold. Make sure the peak current of the amplifier is at or above this measured load.
3. Is the amplifier set up for the proper peak current, and can it be increased safely?
4. Remove the motor leads and try to run the control. If an overcurrent fault still exists, there is probably a damaged output device in the amplifier.
5. Is this is a longtime overload? Are the motor and control sized correctly? Could it be changed from a constant-torque setting to a variable-torque setting? Does increasing the speed of a variable-torque load to allow for "higher output" also increase the electrical load?
6. If the overcurrent fault occurs during acceleration, try to increase the acceleration time if the application allows this.
7. Is the torque boost set correctly? Too high will saturate the winding and create an overcurrent condition. Too low will make the motor make up in current what it didn't get in voltage.
8. If it is a closed-loop AC control, ensure that the slip frequency is correct for a vector drive and that the feedback to the magnets is proper for a brushless motor. To avoid a flashover on a DC control, make sure the rate of current rise is not too quick. On DC motors, also make sure the commutator and brushes are in good shape.
9. Measure the actual current with a clamp-on meter to make sure it agrees with the readout. This should help ensure that the current feedback inside the control is accurate.

What to look for when there is a high bus fault.

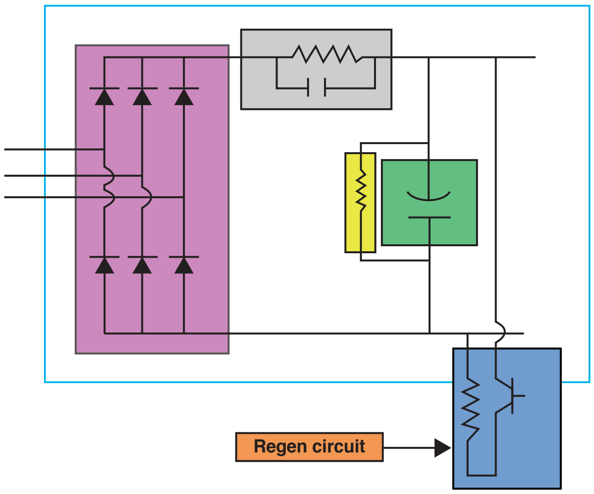
Ask the operator what he knows.

1. Has anything changed?
2. Does this happen during running, accelerating or decelerating?
3. What is happening in the operation when this occurs?
4. Did it always trip off?

As Figure 5-18 (Page 5-22) shows, some of the regenerative circuits are "built into" the control–typically 15 hp (11 kW) and lower), while others are a separate "add-on" kit. Sometimes the transistor and resistor are in the same kit. Sometimes they are in separate kits. Sometimes the transistors are built into the amplifier, and the resistors are separate.

1. Ensure that the transistor is still intact. You can probably do this with a digital voltmeter. Also check the resistor and replace it if it burned out.
2. Make sure the regeneration is "turned on" in the software.
3. Make sure the regeneration kit is wired and connected correctly.
4. Has the load increased? If so, try to decrease the load during deceleration–or increase deceleration time.
5. Increase deceleration time.
6. Some controls have an overhauling load–a DC bus circuit that will increase the frequency to the motor stator if the

FIGURE 5-18



Some regenerative circuits are "built into" the control; others are "add-on" kits. Sometimes the transistor and resistor are in the same kit; sometimes they are separate.

bus starts to go up–which decreases the regenerative energy from the motor.

7. Is there a pulsating load–e.g., punch presses, pulsating air pressure from bends in duct work, etc.? You may be able to detect current pulses with a true RMS ammeter. It may necessary to add a regeneration kit.
8. Ensure that input power is at proper levels.

What to look for if DC is low.

Ask the operator what he knows about this.

1. Does this happen upon power up?
2. Does this only happen on power down?
3. Does this happen on acceleration?
4. Does this happen during deceleration?
5. Is anything else happening in the plant that may "bring down" the supply voltage?
6. Is there a reactor in front of the amplifier?
7. Is the amplifier powered from single-phase or three-phase power?

Look for the following:

1. If DC is low on power up, try to remove the regen kit. The transistor may be shorted to ground, keeping the bus low.
2. If DC is low on power down, it is not a problem
3. If DC is low during acceleration, try to extend the acceleration time.
4. If DC is low during deceleration, look for the regeneration output to be shorted to ground.
5. If DC is low on single-phase power, try to decrease the "power requirements" to the motor, or use a larger amplifier.
6. Check input power for proper level.
7. Look for a delta secondary on the feed transformer. It may be necessary to change to a wye secondary and tie the neutral to earth.

What to look for if the control keeps tripping off on over-temperature (internal).

Ask the operator if he knows anything about this?

1. Is there anything that may add to the temperature in the amplifier?
2. Are there any heat-generating devices in the cabinet under the control?
3. Is the cabinet sized correctly?

Check for the following:

1. What is the temperature in the cabinet? Is the fault real?
2. Is the cabinet near a steam trap, oven, heater, etc.? Discuss additional cooling or moving the cabinet.
3. Have any fans stopped working in the amplifier or cabinet?
4. Can the customer safely keep the cabinet door open while operating the system to see if the fault goes away? If it does, can the cabinet be moved or additional cooling be added?

What if the motor does not reach full speed?

Ask the operator his opinion of the problem.

1. Has this always occurred?
2. Has anything changed?
3. Is the problem that the motor is not going the correct speed, or that the load is not going the correct speed?
4. How do you know the motor is not reaching full speed?

Look for the following:

1. What is the maximum speed in the setting versus the maximum speed expected (ensuring that the speed ratio of output speed to command is correct)?
2. Can maximum speed be reached from the keypad? If so, study the I/O for problems in wiring, device output or programming (set for 4-20mA vs. 0-10VDC).
3. Is the load too large for the motor, slowing down the motor? Current should be up if this is happening.
4. Does the control have a fold-back option. If so, turn it off and see if the control trips (indicating too much load).
5. Is there any belt slippage between motor and load? Maybe the motor is running the right speed, but the load is slipping.
6. Is a current limit keeping the motor from reaching maximum speed?

What if the motor does not stop?

Ask the operator if he has noticed anything about this?

1. Has this always occurred?
2. Has anyone been doing any programming on the amplifier or front-end controller?
3. Could anything be overhauling the motor?

4. Has anyone "played with" the wiring?
5. Where does the speed signal come from? Where is it physically located?

Look for the following:

1. If the circuit is a ±5VDC or ±10VDC, try to do an offset trim to zero-out the analog input.
2. Is a minimum speed programmed?
3. Is the speed signal sent via a shielded twisted pair? Is the shielding connected to common? If it is connected to earth ground, remove the shielding and put it into common.
4. Is there noise on the feedback?
5. Is the control programmed for the correct feedback?
6. Jumper the analog common to input. Then reset the command offset trim and see if it can be zeroed out.

What to look for if the motor runs away.

Ask the operator:

1. Is this something new?
2. Has something changed?
3. Has someone worked on the wiring or programming?

Check for the following:

1. Is the drive in the torque mode versus the speed mode?
2. Is the feedback versus the motor in the same direction?
3. Do the op amps (operational amplifiers) need initialization?
4. Look for noise.

ELECTRICAL NOISE CONSIDERATIONS

The following information may be helpful for understanding some of the noise and wiring issues commonly associated with amplifiers.

All electronic devices are vulnerable to significant electronic interference signals (commonly called "electrical noise"). At the lowest level, noise can cause intermittent operating errors or faults. From a circuit standpoint, 5 or 10 millivolts of noise may cause detrimental operation. For example, analog speed and torque inputs are often scaled at 5 to 10VDC maximum with a typical resolution of one part in 1,000. Thus, noise of only 5mV represents a substantial error.

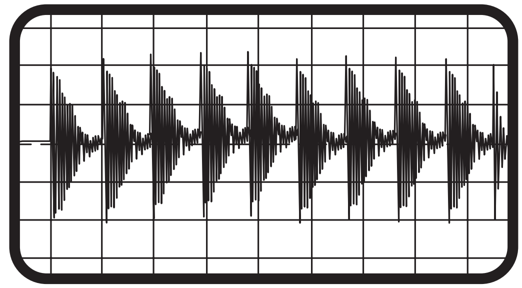
At the extreme level, significant noise can damage the drive. Therefore, it is advisable to prevent noise generation and to follow wiring practices that prevent noise generated by other devices from reaching sensitive circuits. In a control, such circuits include inputs for speed, torque, control logic, and speed and position feedback, as well as outputs to some indicators and computers.

Causes and cures

Unwanted electrical noise can be produced by many sources. Depending upon the source, various methods can be used to reduce its effects and its coupling to sensitive circuits. All methods are less costly when designed into a system initially than if added after installation.

Figure 5-19 shows an oscilloscope trace of noise induced in a 1-ft (30 cm) wire next to the lead for a size 2 contactor coil as the coil circuit is opened. The scope is set at 20V/div. (vert.) and 1µsec/div. (horiz.). The maximum peak voltage is voltage more than 40V. The scope input impedance is 10kΩ for all scope traces.

FIGURE 5-19

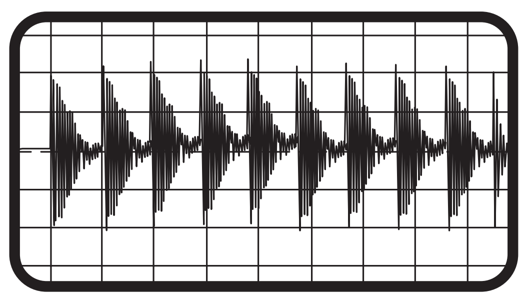


Electrical noise display

Relay and contactor coils. Among the most common sources of noise are the ever-present coils of contactors and relays. When these highly inductive coil circuits are opened, transient conditions often generate spikes of several hundred volts in the control circuit. These spikes can induce several volts of noise in an adjacent wire that runs parallel to a control-circuit wire.

To suppress these noise generators, add an R-C snubber across each relay and contactor coil. A snubber consisting of a 33 ohm resistor in series with a 0.47µF capacitor usually works well. The snubber reduces the rate of rise and peak voltage in the coil when current flow is interrupted. This eliminates arcing and reduces the noise voltage induced in adjacent wires. In the example shown in Figure 5-20, the noise was reduced from over 40V peak to about 16V peak.

FIGURE 5-20



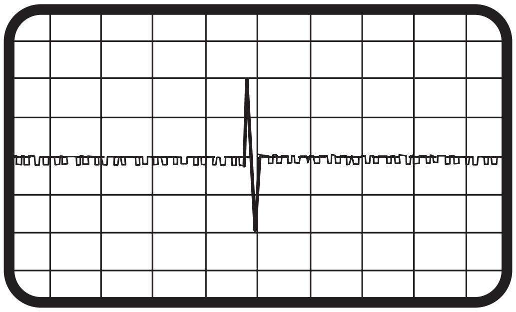
R-C snubber circuit.

Combining an R-C snubber and shielded twisted pair cable keeps the voltage in a circuit to less than 2V for a fraction of a millisecond (Figure 5-21 on Page 5-24). Note that the vertical scale in Figure 5-21 is 1V/div. rather than the 20V/div. in Figure 5-19 and Figure 5-20.

A reverse-biased diode across a DC coil achieves the same result as adding an R-C snubber across an AC coil (Figure 5-22).

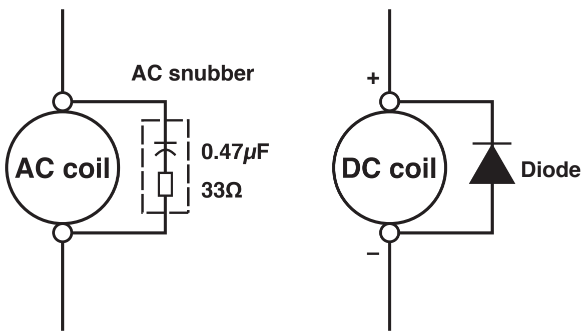
Wires between controls and motors. Output leads from a typical 460VAC drive controller contain rapid voltage rises

FIGURE 5-21



R-C snubber circuit and twisted pair.

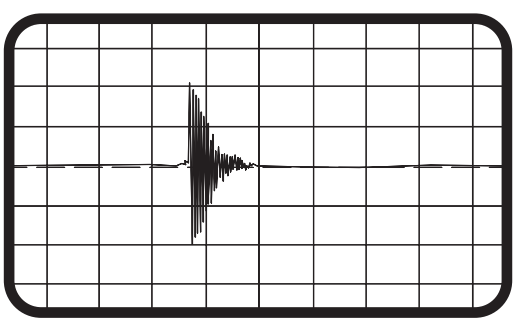
FIGURE 5-22



Diode with DC coil.

created by power semiconductors switching 650V in less than a microsecond, 1,000 to 10,000 times a second. These noise signals can couple into sensitive drive circuits as shown in Figure 5-23. For this waveform, a transient is induced in 1 ft (30 cm) of wire adjacent to the motor lead of a 10 hp (7.5 kW), 460VAC drive. The scope is set at 5V/div. and 2µsec/div.

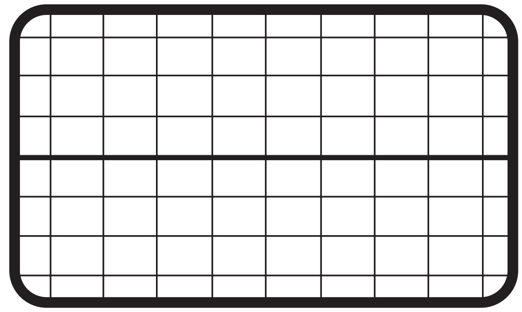
FIGURE 5-23



10 hp (7.5 kW), 460VAC drive.

If the shielded-pair cable is used, the coupling is reduced by nearly 90% (Figure 5-24).

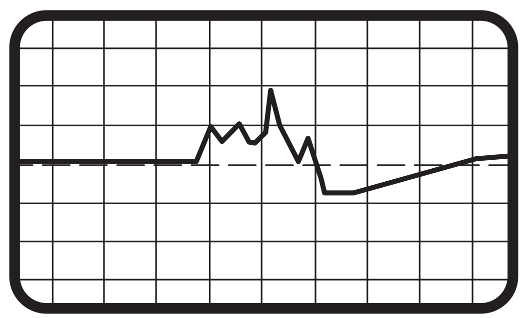
FIGURE 5-24



10 hp (7.5 kW), 460VAC drive, shielded.

The motor leads of DC motors contain similar voltage transients. The switching rate is about 360 times a second. These noise transients can induce about 2V of noise in a wire adjacent to the motor lead. The noise induced by a 30 hp (22 kW, 500VDC drive is shown in Figure 5-25. The scope is set at 1V/div. and 5µsec/div.

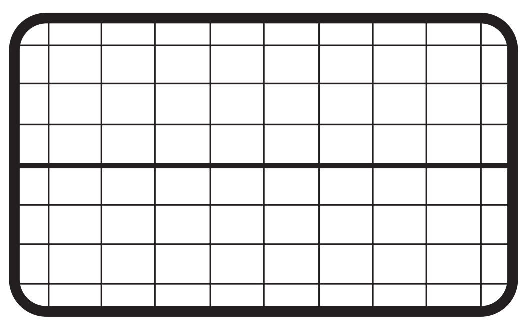
FIGURE 5-25



30 hp (22 kW), 500VDC drive.

Again, replacing a single wire with a shielded-pair cable reduces the induced noise to less than 0.3V (Figure 5-26).

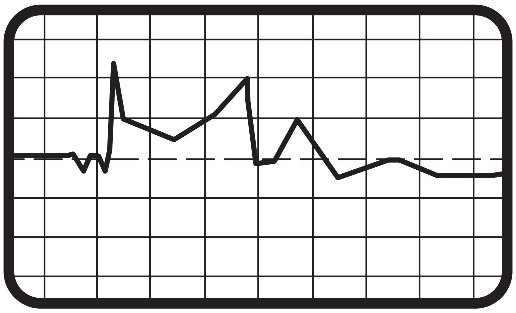
FIGURE 5-26



30 hp (22 kW), 500VDC drive, shielded.

Even input AC power lines contain noise and can induce noise in adjacent wires. This is especially severe with SCR-controlled DC drives, and current-source and six-step inverters. Figure 5-27 shows a transient induced in a 1-ft (30 cm) wire adjacent to the AC input power wire of a 30 hp (22 kW) DC drive. The scope is set at 500mVdiv. and 2µsec/div.

FIGURE 5-27



30 hp (22 kW), 500VDC drive, shielded.

To prevent induced transient noise in signal wires, all motor leads and AC power lines should be contained in rigid metal conduit or flexible metal conduit. The conduit should be grounded to form a shield to contain the electrical noise within the conduit path. Signal wires–even ones in shielded cable–should never be placed in the conduit with motor power wires.

If flexible non-metallic conduit is required, the wires should be shielded twisted pair. Although this practice gives getter protection than unshielded wires, it lacks the protection offered by rigid metal conduit.

Special drive situations. For severe noise situations, it may be necessary to reduce transient voltages in the wires to the motor by installing load reactors between the control and motor. This is often required where a motor housing lacks the necessary shielding (typically linear motors mounted directly to machine frames) or where the power wires to motors are contained in flexible cables.

Reactors are typically 3% reactance and are designed to the frequencies encountered in PWM drives. These reactors also reduce ripple current in the motor windings and often improve motor life. For maximum benefit, the reactors should be mounted in the drive enclosure with short leads between the control and the reactors.

Drive power lines. The same type of reactor installed on the load side of the control can also suppress transients on incoming power lines. Connected on the line side of the drive, the reactor protects the adjustable-speed drive from some transients generated by other equipment. It also suppresses some of the transients produced by the drive itself.

Radio transmitters. Although they are not a common problem, radio frequency transmitters–e.g., commercial broadcast stations, fixed short-wave stations, and mobile communications equipment (including walkie-talkies)–do create electrical noise. The probability of this noise affecting an adjustable-speed drive increases with the use of open control enclosures, open wiring, and poor grounding.

Control enclosures. The cure for some electrical noise may be a grounded metallic control enclosure. The enclosure should be grounded to the building ground with a short, heavy-gauge wire. In addition, the power conduit, motor lead conduit and signal wire conduit must be grounded to the enclosure. Sometimes paint and seals prevent electrical contact between the conduit and the cabinet. Sometimes wire or straps are used to ensure good electrical grounding.

Special motor considerations. Motor frames are also on the required grounding list. As with control enclosures, motors should be grounded directly to plant ground with the shortest ground wire possible. Capacitive coupling within the motor windings produces transient voltages between the motor frame and ground. The severity of these voltages increases with the length of the ground wire. Installations with the motor and control mounted on a common frame, and with heavy ground wires less than 10 ft (3 m) long, rarely have a problem caused by these motor-generated transient voltages.

Wiring practices

The type of wire used and how it is installed for specific applications can result in reliable operation or create additional problems.

Power wiring. Conductors carrying power to anything (e.g., motors, heaters, brake coils, or lighting units) should be routed separately from signal and control wiring in conductive conduit that is grounded at both ends.

Control-logic conductors. Typically, operator's controls (push buttons and switches), relay contacts, limit switches, PLC I/Os, operator displays, and relay and contactor coils operate at low current levels. However, switching noise is caused by contact open/closure and solid-state switch operations. Therefore, these wires should be routed away from sensitive signal wires and contained within conduits or bundled away from open power and signal wires.

Analog signal wires. Analog signals generally originate from speed and torque controls, as well as from DC tachometers and process controllers. The following noise-reduction techniques often improve reliability:

- Use shielded twisted-pair wires with the shield grounded at the drive end only.
- Route analog signal wires away from power or control wires (all other wiring types).
- Cross power and control wires at right angles to minimize inductive noise coupling.

Serial communication conductors. Standard serial communication cables are usually made with a shield that is connected to the connector shell at both ends. This usually grounds the data source to the grounded drive chassis. If the data source is floating, such a connection offers good data transmission. However, if the data source is grounded, adding a heavy ground wire (#14 or larger) in parallel with the communication cable between the source and the drive chassis usually reduces noise problems.

Optical isolation

Two optical isolation methods are commonly used: optical couplers and fiber optics.

Optical couplers. Optical couplers, which are commonly called "opto couplers," use a light transmitter and light receiver in the same unit to transmit data while electrically isolating the two circuits. This isolation rejects some noise, the magnitude of which is usually specified by the "common mode rejection dv/dt rating."

Low-cost opto couplers typically have a common mode rejection ratings of 100 to 500V/µsec, which is adequate for most control logic signals. High-performance opto couplers with common mode ratings up to 5,000V/µsec are installed for the most severe noise environments.

Fiber optics. Special plastic fiber strands transmit light over both long and short distances. Because the fibers are immune to electromagnetic energy, the use of fiber optic bundles eliminates the problem of coupling noise in such circuits. These noise-free fiber optic cables can be run with power or motor conductors because noise cannot be inductively or capacitively coupled into the fiber optic strands.

Plant ground. Connecting electrical equipment to a good ground is essential for safety and reliable operation. In many cases, however, what is perceived as a ground is not ground. As a result, equipment malfunctions or electrical shock hazards may exist.

Therefore a good practice in some cases is to retain the services of a licensed electrical engineer with experience in grounding practices to make the measurements necessary to establish if the plant ground is really grounded.

FINAL SUGGESTIONS

When troubleshooting amplifiers in the field, it is important to understand the scope of the work and develop a plan to accomplish it.

Whether the job involves inverters, vector controls, brushless controls, or DC controls, always take time to query the operator and learn as much as possible about the machine and operation–even if the cause of the problem is obvious. You may learn some things that may not be readily apparent. Additionally, if in two minutes you identify a problem that the operator, engineer or maintenance supervisor has invested two weeks to find, he may feel foolish or even get fired. Take your time. Ask a lot of questions and get input. Let the customer help you.

To ensure that nothing will be damaged and no one will be hurt, always ask permission before turning on the power, starting the motor or running the machine. Customers often have rules about who can perform these tasks, and the same circuit might turn on other items that could be dangerous.

Upon completion of the work, ask the person in charge to "sign off" on the job to show that it was completed satisfactorily. Most importantly, though, remember that troubleshooting amplifiers may involve high power and violent motion. Proceed cautiously to keep the people, equipment, and product safe.

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Servo drives

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(Note: This article assumes a basic understanding of motors. Its purpose is to take some of the mystery out of servos.)

Servo motors come in so many types and flavors that it is difficult to define them in a way that is accurate and universally acceptable. It is possible, though, to describe some of the things commonly found in servo drives, as well as typical configurations.

Servo drives are designed to convert electrical power into precision-controlled motion–e.g., controlled torque (torque servo), controlled speed (velocity servo) or controlled position (positioning servo). This typically requires at least three elements: the motor, feedback of some sort, and an amplifier.

THE MOTOR

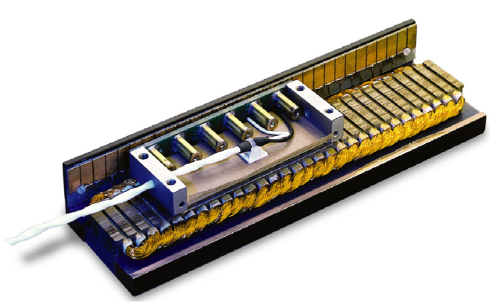
DC brush motors

DC motors can be either rotary or linear. Rotary DC motors typically are long and thin, which allows for quick acceleration due to the lower inertia, as well higher speed due to the lower centrifugal forces of a smaller diameter armature (see Figure 5-28). The armature is skewed to help reduce low-speed "velocity ripple."

FIGURE 5-28

Rotary brush DC servo motor.

FIGURE 5-29



Linear brush DC servo motor.

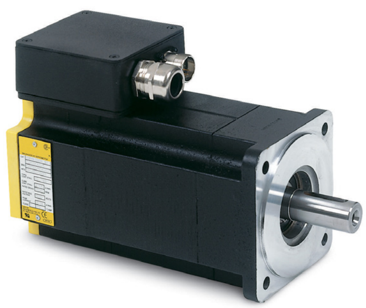
Linear DC motors have the commutator and windings along the path of travel, and power may be supplied to the brushes by a bus bar or an umbilical cord (see Figure 5-29). The "moving short" with the brushes has a permanent magnet, which is attracted to the energized stationary coil. A linear bearing is used to create an air gap and low friction.

DC brushless motors

Brushless DC motors may be either rotary or linear and come in many varieties. They are probably the most prevalent kinds of servo motors due to their quick response time, low inertia-, weight- and size-to-torque ratios, and reasonable cost.

Rotary brushless DC motors have either ceramic or rare earth magnets banded onto the rotor (see Figure 5-30). Ceramic magnets (typically ferrite) cost less but have higher inertia and size per torque than high-performance rare earth magnets (typically samarium cobalt or neodymium-iron-boron).

FIGURE 5-30



Rotary brushless servo motor.

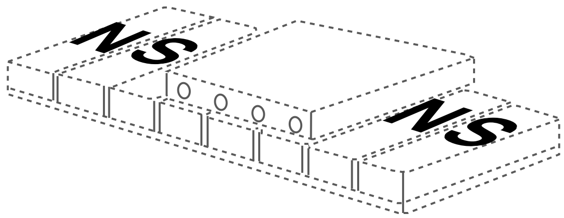
The stators of these motors are wound with basically standard, but low-inductance windings. Some may be epoxy encapsulated for protection from elements (e.g., machine tool coolant) and to provide mechanical rigidity to reduce wire-to-wire abrasion from high current, shock and machine vibration. Rotary brushless DC motors exhibit low inductance and small electrical and mechanical time constants.

There are two main types of linear brushless DC motors–iron core and cog-free. Both types support the moving short with one or more linear bearings, which provide an air gap and reduce friction.

The iron core motor has one or more columns of magnets with alternating poles (north-to-south). Higher force motors may have several rows of magnets (see Figure 5-31, Figure 5-32 and Figure 5-33 on Page 5-28). The coils in the moving short are energized, which attracts them to the magnets and moves them along the column. The payload usually is attached to this piece.

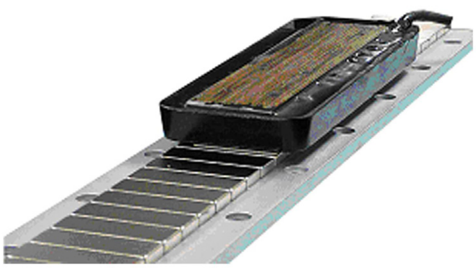
The laminated iron core magnifies the flux density. Since the core is also attracted to the magnets, a velocity ripple will

FIGURE 5-31



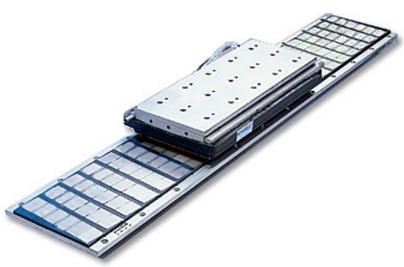
Brushless motor magnet track and moving short (coil with attached payload).

FIGURE 5-32



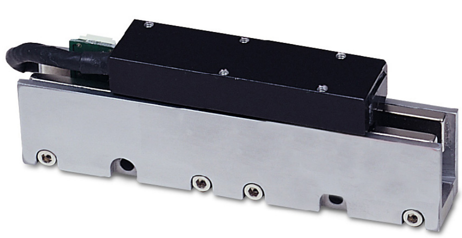
Single row of magnets in a long column.

FIGURE 5-33



Multiple row of magnets in a long column.

FIGURE 5-34



Cog-free brushless linear servo motor.

occur during movement. If this is an issue for the application, a cog-free linear motor may be a better option (see Figure 5-34).

For applications that only require point-to-point moves, cog-free linear motors also provide the most force in the smallest package and at the lowest cost.

A cog-free linear motor consists of a column of two magnets of like polarity attached to either side of a machined channel. As with the iron-core style, polarities along the magnet track assembly of cog-free linear motors alternate north-south-north-south. A coil of epoxied magnet wire supported by a linear bearing rides between the magnets. Energizing the coil creates the attraction to move it along the magnetic track. Since there is no iron core to fight the smooth attraction of the coil, the velocity ripple is minimized.

AC induction servo motors

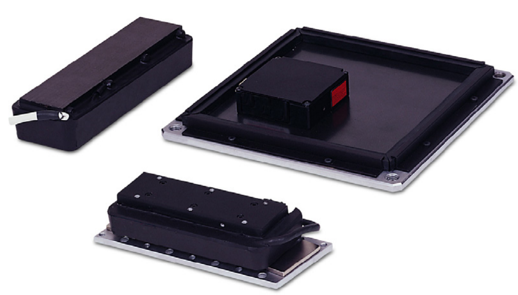
AC induction servo motors can be linear or rotary. The rotary design typically is long and thin, making it suitable for higher speeds and quicker acceleration and deceleration profiles due to the lower inertia. A separate constant-velocity blower motor is often attached to the back of the servo motor for cooling during low-speed operation. The stator has a standard, low-inductance, three-phase AC motor winding, which sometimes has special volts/hertz ratings and/or wye-delta switching (see Figure 5-35).

Linear induction servo motors operate from the same principle as rotary induction motors. They have a three-phase coil (typically on the moving short) powered by an umbilical

FIGURE 5-35

Rotary induction servo motor–standard inertia.

FIGURE 5-36



Linear induction servo motor.

cord or bus bar and ride on two linear bearings above an aluminum “reaction plate” that is mounted on steel (see Figure 5-36 on Page 5-28).

The advantage of linear induction servo motors over brushless servo motors is their maximum speed. Since they do not have to fight the back EMF (electromotive force) of the motor through the magnets, they can reach velocities of more than 2000 in/sec (5080 cm/sec) or 110 miles/hour (177 km/hr) with enough travel.

Feedback

Servo systems receive feedback from the motor and sometimes from the product and/or process. The focus of this article is servo drives, so elements of process feedback are not included.

Brush-style rotary DC servo motors may use tachometer feedback (typically 7 volts/1000 rpm), encoder feedback, and/or resolver feedback. Brush-style linear DC servo motors use encoder or laser feedback.

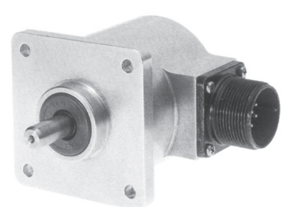
Brushless rotary DC servo motors may use hall feedback and/or encoder feedback, or resolver feedback. Brushless linear DC motors may use linear encoder feedback with halls or sinusoidal commutated linear encoder feedback.

Induction rotary motors use a rotary encoder, whereas induction linear motors use a linear encoder.

Brief descriptions of the various feedback devices can be helpful in understanding how they work.

Tachometers employ a permanent magnet field. The armature, which is coupled to the motor shaft, induces a DC voltage proportional to velocity as the shaft spins (see Figure 5-37). This voltage is brought out through a commutator and brushes to the amplifier for speed and direction information.

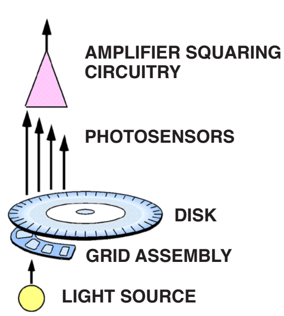
FIGURE 5-37



Tachometer.

Encoders employ an LED to emit light that is directed through a slit called a gate and then through a scale (commonly glass) with very fine, uniformly etched marks. When these marks align, light passes through and hits a photo cell; otherwise, between marks, no light hits the photo cell. As light strikes the photo cell, a pulse (generally 5, 12 or 15 volts) passes back to the amplifier or motion controller (see Figure 5-38).

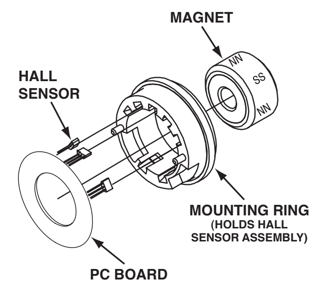
FIGURE 5-38



Encoder.

There are typically 2 or 3 signals. The first is called A; if the signal is differential, A/ will also be present. The second signal, B (and B/), has the same ppr–pulses per revolution (rotary)–or ppi–pulses per inch (linear)–as A, but it is offset 90 degrees. This makes it possible to obtain velocity, direction and position information. The third signal, called C, Z or I (with corresponding C/, Z/ or I/), occurs only once per revolution. This signal is only found on rotary encoders.

FIGURE 5-39



Hall feedback device.

Hall feedback may be part of the encoder or a separate device. A hall device is a magnet with a sensor that indicates the polarity (and therefore the location) of the magnet (see Figure 5-39). It is used for commutation of the brushless motor. When part of the encoder, hall feedback is really just another encoder channel. This is often called “encoder with halls,” “hall tracks” or “comm tracks.”

Hall feedback is used strictly for motor commutation, so the device must be aligned with the magnets according to a timing circuit that the amplifier can use.

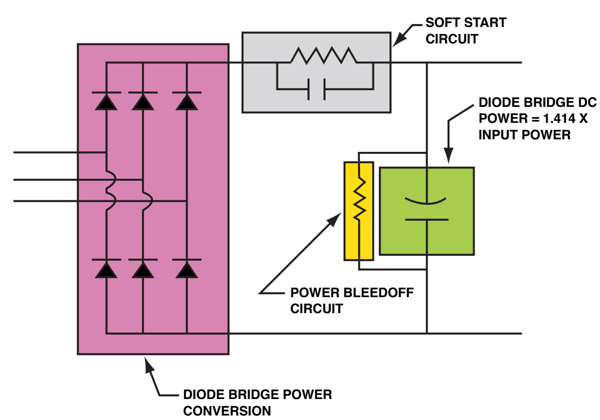
Resolvers are essentially rotating AC transformers that employ a small AC input for the power circuit.

A rotor is attached to the main motor shaft. As it passes through the alternating stator polarities, it generates a voltage that cuts the “output windings” (two windings 90 degrees apart electrically).

The output is two sine waves 90 degrees out-of-phase. The number of sine waves per rotation depends on the number of poles–ranging from 1 to 80 in common, commercially available motors, but going much higher in very special ones. The output goes into the amplifier and is “decoded” to encoder output.

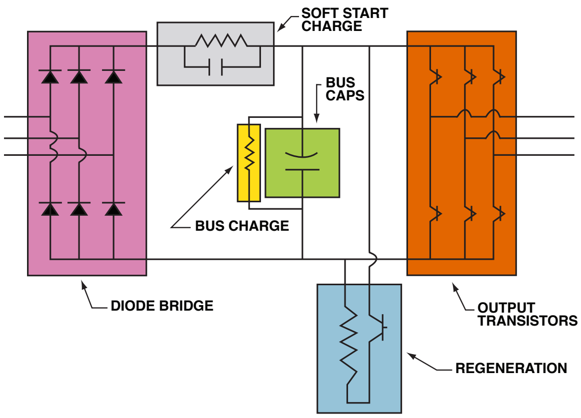
Resolvers are also used for commutation, so the output must be aligned with the magnets using a timing circuit that is compatible with the amplifier. The encoder signal can be brought out to the motion controller.

FIGURE 5-40



Converter section of a single-axis amplifier.

FIGURE 5-41



Typical single-axis, three-phase output. For DC, eliminate one set of transistors.

FIGURE 5-43

Single-axis amplifier.

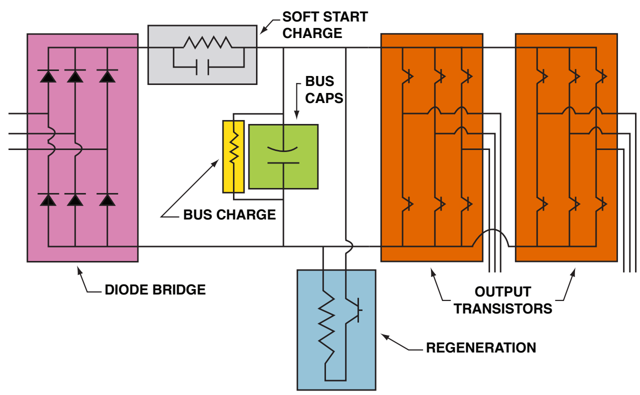
FIGURE 5-44

Multi-axis brushless servo.

FIGURE 5-42

Single-axis AC power amplifiers and motors.

FIGURE 5-45



Multi-axis, three-phase output.

THE AMPLIFIER

The amplifier converts the output power from the distribution panel to controlled output that will cause the motor to move at the correct velocity. Most servo amplifiers are PWM (pulse width modulated) style. x

The converter section of a single-axis amplifier uses a diode bridge to change AC input power to DC power, which is then "smoothed out" by the addition of a capacitor. This DC section is called the bus (see Figure 5-40 on Page 5-29).

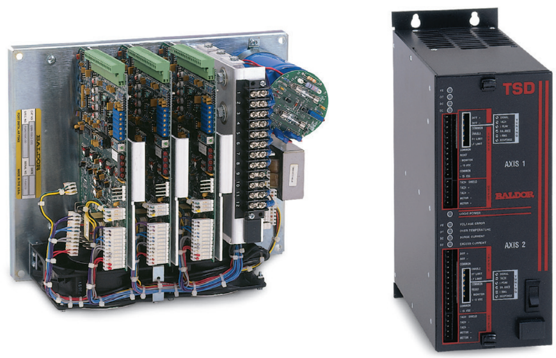
The output is then "chopped up" by transistors (typically FETs or IGBTs). These devices rapidly turn the DC power to the motor on and off. If the transistor is closed for long periods (motor receiving power) with short open periods (motor not receiving power), the average terminal voltage goes up. If the transistor is open for long periods (motor not receiving power) and closed for shorter periods (motor receiving power), the average voltage goes down. The amplifier can close an "upper transistor" in one phase and a "lower transistor" in another phase, creating a path through the winding (see Figure 5-41). If the motor is AC, the polarities can be reversed by switching from an upper to a lower transistor and back on each of the phases (see Figure 5-42 and Figure 5-43).

Another topology called multi-axis essentially splits the amplifier after the bus (see Figure 5-44). The bus is bought out to terminals and then connected to output (transistor) sections. The bus must be sized to handle all axes of continuous and peak current that the application requires.

Notice that two output sections are driven from one power converter. Output sections can be added in series as long as there is enough power–e.g., 2 - 8 axis is very common (see Figure 5-45 and Figure 5-46).

Both single-axis and multi-axis amplifiers have a regeneration section, which is required for stopping quickly. To do so, the motor becomes a generator (the rotating magnetic field bypasses the stationary magnetic field), and the energy is carried to the bus via the lead wires and through the transistors. When the bus voltage is raised to a sufficient level, a regenerative transistor closes to transfer the excess power to a shunt resistor. Another method is to use a transistorized or SCR-based front-end converter to regenerate the power back onto the line.

FIGURE 5-46



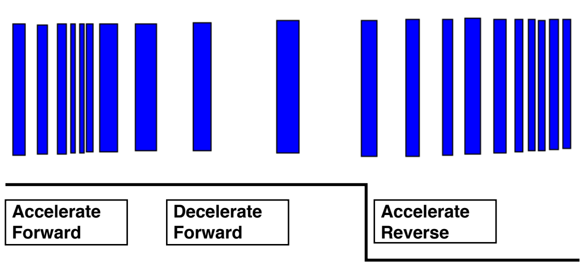
Chassis-mount and NEMA 1 multi-axis brush-type servo amplifier.

The devices described here are called amplifiers because they typically take a control signal from a motion controller or CNC and amplify this command to higher power motion. The signal is almost always a pulse and direction input (from a stepper program), a ±10VDC signal, or a digital command. The prevalent method today is ±10VDC, although digital will probably take over the favorite spot soon.

There are three kinds of control signals: **pulse and direction**; **±10VDC**; and **serial command and feedback**.

- **Pulse and direction** is a pulse train (see Figure 5-47). Each pulse commands a velocity or position, depending on how the amplifier is set up–velocity following or position following. There will be a ratio between the input pulse train and the output velocity or position. The faster the incoming pulses, the faster the motor will move to keep up. There is a second input for direction. This input is either high or low, indicating forward or reverse direction.
- The pulses are generally 5 - 15VDC. This is typical for stepper-indexer output, and today many servo amplifiers can read and run from this type of input. Input of this kind usually gives instructions to the amplifier and lets the amplifier close the velocity and/or position loop. This does not allow for real time trajectory correction. In other words, corrections can be made for speed variations (due to speed feedback to the amplifier) but not for position (because the typical indexer does not take and correct for position feedback).

FIGURE 5-47



Pulse train.

- ±10VDC is a more traditional and popular amplifier input. This can be either a speed command or a torque command, depending on the system configuration.
  - If a speed command, then +10VDC = full speed forward; +5VDC = half speed forward; 0VDC = 0 speed; -5VDC = half speed reverse; and -10VDC = full speed reverse.
  - If a torque command, then +10VDC = peak torque (or force) forward; +5VDC = half torque (or force) forward; 0VDC = 0 torque (or force); -5VDC = half torque (or force) reverse; and -10VDC = full torque (or force) reverse.

One of the amplifier specifications will be analog input resolution, which is typically rated in bits. This is how it works. If a ±10VDC velocity command with maximum speed of 6000 rpm (rotary servo) is used with an amplifier that has 9-bit analog input, the analog signal can be divided in 2^9 parts (or 512 pieces).

10VDC / 512 pieces = 0.01953125 volt pieces

6000 rpm / 512 = 11.71875 rpm increments

Therefore, for every 0.01953125 volt increment, the motor will accelerate another 11.71875 rpm.

When trying to position accurately at low speeds, 11 or 12 rpm may not allow for good, smooth positioning. Additionally, the controller giving the signals will have an analog-out bit resolution. It does no good to go from a 9-bit amplifier to a 16-bit amplifier if the controller is 9 bit.

Serial commands and feedback is increasingly popular.

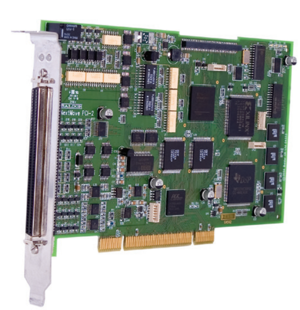
For this to become a mainstream topology, more work will be needed to increase the speed of information transfer. Most servo loops close every 250 microseconds to 2 milliseconds. That means a lot of information must be transmitted very quickly. Most research and development in this area seems to be heading toward a ring topology with fiber transmitters.

THE CONTROLLER

The controller, which ties all parts of the system together, comes in four main flavors.

- **Standalone card**–Requires power supplies, mounting and a place to reside.
- **Resident card**–Resides inside the computer in ISA, VME or PCI format, using the computer's mounting and power supply (Figure 5-48).
- **Standalone box**–Requires a single power supply with the program resident inside of the box (Figure 5-49).
- **Intelligent amplifier**–Resides inside an amplifier package, using the mounting and power supply from the amplifier (Figure 5-50).

FIGURE 5-48



PCI bus-style controller.

At the heart of all these controls is a clock and an encoder reader that determine velocity and position, and software that calculates and relays trajectory information to the amplifier via a ±10VDC signal or digital (serial) command.

Depending on the controller, programming languages range from Basic-like commands to Visual Basic "boxes" to C or C++. The program tells the machine what to do and interfaces with the operator and safety devices (e.g., machine guards and E-stops). It also tells the controller how the servo should perform (tuning the gains for servo motor/amplifier performance, the desired motion, as well as machine compliance). It frequently will take several hours to several days or even weeks to tune a servo system. The software usually costs more than the hardware.

The motion controller mathematically generates a trajectory or path–where the part should be at each specific servo loop (time period). It also receives position feedback (typically encoder or laser) that tells it the actual position. The controller then compares the trajectory with the actual position and generates a change in analog output (±10VDC) to help correct for the difference (or error).

The process of calculating trajectory, comparing it to actual position, and correcting for error is repeated at each servo loop. The amount of change generated will depend on the tuning gains that are programed into the controller.

FIGURE 5-49

Standalone combination amplifier and controller.

FIGURE 5-50

Boxed 4-axis servo controller.

Topology

Feedback can come from the motor to the motion controller; from the motor to the amplifier and the amplifier to the motion controller; or from the work piece to the motion controller. The advantages of having the feedback on the motor are lower cost and a less complicated package. The advantage of having feedback on the work piece is increased accuracy in product positioning.

Consider a motor coupled to a lead screw with the load riding on linear bearings. The screw might rotate a 1/16 of a revolution before the load starts to move (a form of linear backlash and coupling slop). With a 1024 PPR or 4096 quadrature count encoder, 1/16 x 4096 = 256 encoder quadrature counts. (Quadrature counts = 4 times the pulse per revolution.) Having two offset channels makes it possible to read the leading and trailing edges of both channels, which yields four times the resolution.

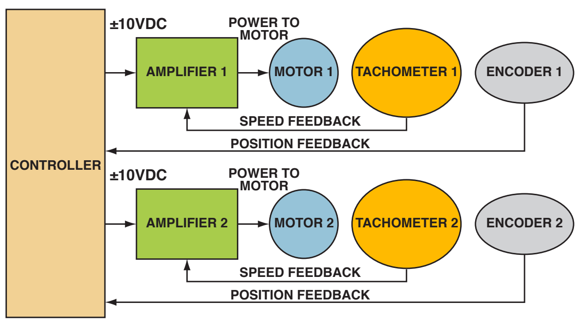
If positioning from the back of the motor, the controller thinks the load has moved a distance of 256 quadrature counts, which in fact has not happened. Since this affects system accuracy, many motion controllers correct for this somewhat in the software with a feature called backlash compensation.

Additionally, ball screws are not perfect, so distances for one revolution will change slightly along the length of the screw. This can also be adjusted for with lead screw compensation, which typically is based on a table in the software that converts the actual move counts to calculated move counts produced empirically.

It is much more difficult to account for thermal growth. Direct feedback makes it possible to locate and position the work piece without making calculations based on testing and tables.

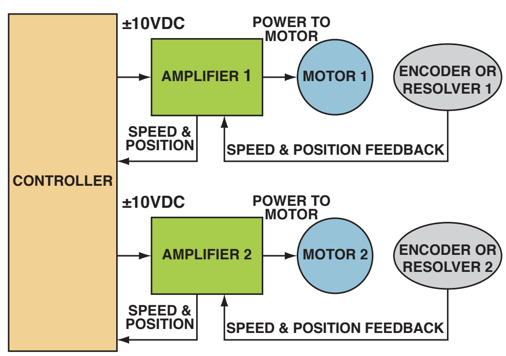
For high-performance servos, the amplifier is set up in velocity control, and the controller demands velocity and closes the position loop. In lower performance servo systems, the amplifier closes the torque loop, and the controller closes the velocity and position loops.

FIGURE 5-51



Tachometer attached to motor; encoder attached to motor or load.

FIGURE 5-52



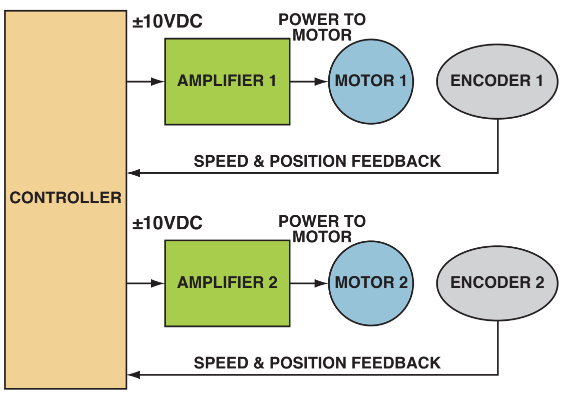
Encoder or resolver attached to motor; amplifier buffers feedback to controller.

As an example, in the topology shown in Figure 5-51 (Page 5-32), the tachometer is attached to the motor, and the encoder may be attached to either the motor or the load.

In Figure 5-52 (Page 5-32), an encoder or resolver is attached to the motor, and the amplifier buffers the encoder information back to the controller. In the case of a resolver, the amplifier converts the sine waves to a digital encoder-like signal and buffers this back to the controller.

With the torque servo in Figure 5-53, the controller governs velocity and position. The encoder may be attached to the motor or the load.

FIGURE 5-53



Torque servo with controller controlling velocity and position; encoder may be attached to motor or load.

Loops

What are the torque, velocity and position loops, how are they "closed" in different areas, and why is this important?

Imagine a person driving a car. The driver knows the destination and needs to steer the car in the right direction to reach it. If the driver notices that the car is veering too close to the line, he corrects by steering back to the middle of the lane. This is "closing a position loop."

The driver also knows where he is going (trajectory), sees where he is (position feedback), compares that with where he should be, and then corrects for the error. Since the driver knows the command, compares to feedback, and corrects for the error, he is closing the position loop.

As he proceeds, the driver monitors the speedometer. He knows how fast he is supposed to be traveling and compares that with the actual speed. If necessary, he changes the commanded torque to the engine to maintain the correct speed. In other words, he is closing the speed loop.

By pressing the accelerator, the driver changes the commanded torque. The car senses the change in accelerator position and delivers more fuel to the engine, causing it to run faster and produce more torque. The car is closing the torque loop.

In this example, the driver functions like a servo controller that closes the position and speed loops (steering and commanding a change in torque to maintain desired speed). The driver also resembles an amplifier that closes the torque loop–i.e., changing engine torque in response to a command from the accelerator.

If cruise control is used, the driver still controls position, but the automobile regulates velocity and torque automatically, like a velocity-controlled amplifier and a position controller. The position controller delivers speed commands to the amplifier, which automatically adjusts torque in relation to load variations in order to maintain demanded speed.

What happens if both the amplifier and the controller try to control speed? They will fight each other, and control will be terrible. Therefore, a critical step during setup is to determine if the amplifier is speed-controlled or torque-controlled. To do so, uncouple the motor from any load and put a small voltage into the command input (approx. 1 volt). If the motor runs up to full speed, the amplifier is torque-controlled; if it runs at about 1/10 of the maximum speed, the amplifier is velocity-controlled. When tuning the servo, it is important to know whether to put in a velocity feedback term or leave that up to the amplifier.

TUNING THE SERVO

Tuning a servo is more of an art using science than pure science. Typically, the amplifier is tuned to the motor for the torque loops (pretty straight forward), and then the motor/amplifier (also called a drive) is tuned to the application (the speed loops). The last step is to tune the motion controller to the customer's desired control (the position loops).

Sometimes it works well to have a very stiff velocity control (whether done in the amplifier or motion controller) with a low position gain setting. At other times, it is better to have a sloppy velocity control and overpower it with higher position gain settings.

Many controllers now have electronic scope features for making a move, recording the resulting encoder counts over time, and graphing the position, velocity and following error. This makes it possible to change tuning parameters and view the effects again and again to obtain the desired performance.

Basic loops and their effects

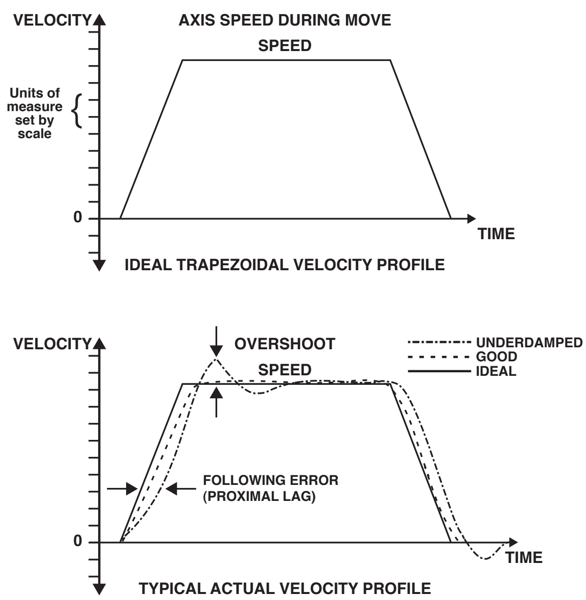
Most loops (but not all) are based on error. For instance, if a motor is not exactly where it should be at a certain time, it is considered an error that must be corrected. Review of the trajectory vs. feedback is done in the summing junction. The output of the summing junction is error, which is amplified through a formula using some of the tuning parameters to determine the magnitude of the correction needed at the motor.

Torque or current gains

The following kinds of parameters are used to correct for errors.

Proportional current gain–is multiplied by the error to determine an immediate step change in current to correct for the error. This gain must be used cautiously (especially on brush-style motors) to avoid flashing the commutator with an extremely abrupt change in current. Setting it too high can also cause torque ringing seen as heat, velocity ripple, and vibration. Proportional current gain is an immediate correction to error.

FIGURE 5-54



Trapezoidal moves.

Integral current gain–this gain corrects for long-term errors. The current needed to correct for the error will increase or decrease relative to how long the error lasts.

Speed or velocity gains

Proportional speed gain–this is an immediate speed change to correct for error. If speed drops from demand due to load changes or voltage sags, this gain controls how much change will be made instantaneously to correct for that error. Immediate correction on a large inertia load will require a large change; making a large change on a small inertia load will create ringing. Figure 5-54 shows an ideal trapezoidal move and how under-damped, good and ideal systems would really look on a scope.

Speed integral gain–adjusts for long-term error. For example, consider the proportional gain that multiplies the value of the error times its gain. As the error gets smaller, so does the product of the gain times the error, which reduces the probability of achieving the target speed. This is where integral speed gain kicks in, because it looks at error over time. The longer the error lasts, the greater the correction that is applied.

Differential speed gain–looks at the slope of the error and multiplies the rate of change times the gain to correct for a radically increasing error. This gain should be treated delicately; otherwise, it will cause oscillation.

Position Gains

Position gain–this multiplies the error times the gain for a velocity command to correct for the error. This gain must be used carefully. Too high of a position gain without damping (especially with a tight speed loop) can cause severe oscillations.

Velocity feedback–is a damping term that allows higher position gains for a stiff system, while decreasing the ringing.

Position integral gain–looks at long-term position error and multiplies by the gain to correct for the inadequacies of only a proportional gain. Again, this gain must be used very carefully. Extremely low numbers (if any) usually will be sufficient. Too high of a gain may create violent action.

Velocity feed forward–This gain is based not on error but on *anticipated error*. Assume, for example, that a motor should accelerate from 0 to 200 rpm. Using the gains previously described, the trajectory would be set but no analog output to the amplifier would occur until an error occurs.

Velocity feed forward (as opposed to feed back) outputs an analog signal (magnitude set by the gain) appropriate to the trajectory speed to create speed as it is supposed to occur–instead of after the speed exceeds 200 rpm and an error occurs.

Tuning procedure

The gains all wrap around each other, so it takes lots of experience to set up a well-tuned servo.

All of the parameters are set in the amplifier or the motion controller. The torque gains will be found in the amplifier, whereas the speed gains may be found in either the amplifier or the controller. The position gains will be found in the motion controller.

The typical procedure for tuning a servo is to set the torque gains first. Speed gains are then tuned to the mechanical system, and velocity feed back is increased until there is good resistance. At this point, position gain is increased very slowly until a tight loop is obtained. The need for position integral gain is then determined with a scope, and velocity feed forward gain is set to minimize following error and overshoot.

File types

Two main files typically are included in the software. The configuration file is the basic setup of the machine. It usually includes the servo gains, scale factors, max and/or positioning speeds, following error, acceleration and deceleration rates, S-curves, and so forth. These items are related to the type and size of machine and motors.

The program file is the operation of the application. This normally includes the operator interface, instructions for movement and process of handling interrupts, as well as fast position latch, error handling, homing routine, and so on. Usually, the program file can be used on different size machines and motor/amplifier combinations with a change of items in the configuration table.

Software vs. firmware

Firmware is the programming done at the factory for the basic operation of the logic. Firmware variants may include different keywords, support for different protocols (such as profibus, can open, RS232, RS485, etc.), and recognition of options like keypads or additional I/Os.

Usually, the appropriate firmware must be selected when choosing the controller. Some (but not all) firmware can be updated in the field (e.g., firmware that is stored in flash memory or on an EEPROM).

The firmware and hardware give the user the tools to do the job. Application software is then written by the user or a systems integrator based on the firmware logic.

CONCLUSIONS

There are many parts to a servo system that are individually critical yet interrelated. The motor is the prime mover; it converts electrical energy into either rotational or linear movement. The speed feedback monitors the velocity of the motor. The current feedback closes the torque loop. The position feedback tracks the location of the load. The amplifier converts the line power to a different voltage and/or frequency to control the current and velocity of the motor and load. The controller is the brain of the operation, calculating the trajectory, comparing with the feedback and correcting for error.

Successful installation and operation of servo systems requires people with good mechanical, electrical, electronic, application and programming experience and capabilities. It also is important to allow time for tuning the system, and to expect programming bugs. They happen; they always happen. These are complicated systems with a lot of interaction–PLAN FOR IT!

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Application considerations of pulse-width modulated inverters and AC induction motors to a total system

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ABSTRACT

The pulse-width modulated (PWM) inverter is one of the newest and fastest evolving technologies used in electric power systems to accomplish speed control. Constant and rapid changes require a continuous evaluation of their impact on the system

The purpose of this paper is to establish the criteria for applying PWM low voltage drives and AC induction motors as a system to the driven equipment.

Emphasis is placed on the impact the PWM waveform has on the motor life and performance. Various laboratory and field tests have been conducted to verify the conclusions. Recommendations are made on insulation systems that will provide increased motor life. The impact of standing waves is explored along with shaft currents. A detailed list of application considerations and constraints is provided to assist in a complete system approach to applying the drives, cable runs, motors, couplings and driven equipment. An important part of this study is the compilation of an extensive bibliography of other related studies.

INTRODUCTION

This article assumes that the traditional fundamental sine wave voltage is (except for starting or outside influences) a steady-state condition, with a maximum and a RMS value.

The voltage waveform supplied by a PWM drive, however, can have significant harmonics and transients that may alter the motor performance characteristics and life expectancy. The effects of the maximum voltage, rate of rise, switching frequencies, resonance and harmonics will all be considered.

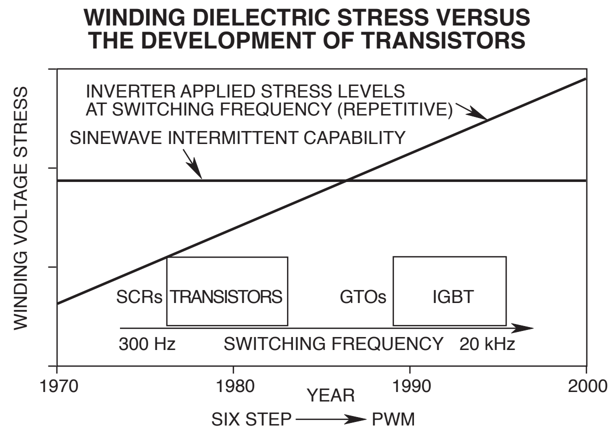
Much has been written over the years about the various types of adjustable-speed drives (ASDs) and their associated impact on motor applications. This paper focuses on the impact of the transient voltage, as defined above, generated by the ASD on squirrel-cage induction motors. The scope of product discussed will be PWM and low-voltage random- wound motors (600 volts or less).

BACKGROUND

The pulse-width modulated inverter is one of the newest and fastest evolving technologies in nonlinear devices used in power systems. Originally the motivating force for its development was speed control comparable to mechanical or DC drives. With the increased emphasis of energy conservation and lower cost, the use of higher performance PWM drives has grown at an exponential rate.

Figure 5-55 shows how drives have evolved over the past 20 years, from silicon-controlled rectifiers (SCRs) at 300 Hz to the current gate turn-off thyristors (GTOs) and the newer insulated gate bipolar transistors (IGBTs) that operate up to

FIGURE 5-55



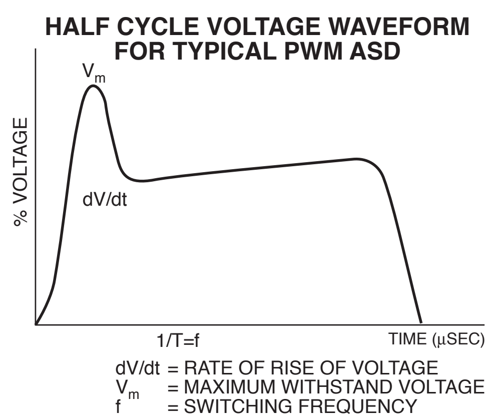
The switching frequency of drives has increased from 300 Hz to about 20 kHz over the past three decades.

the 20 kHz range. IGBTs are now the industry standard. Note how winding stress changes as switching frequency increases.

WINDING INSULATION SYSTEM

Motor winding insulation systems normally are classified according to their thermal capability. Low-voltage systems (600 volts or less) used for drive applications are typically Class F (155°C) or Class H (180°C). Qualification testing subjects the samples (motorette) to a series of cycles of thermal stress, mechanical stress, and moisture. Electrical stress, however, is limited to 60 Hz and 600 volts RMS AC in accordance with IEEE Std. 117-1974 [1]. Unfortunately, these standards do not

FIGURE 5-56



Typical PWM voltage waveform.

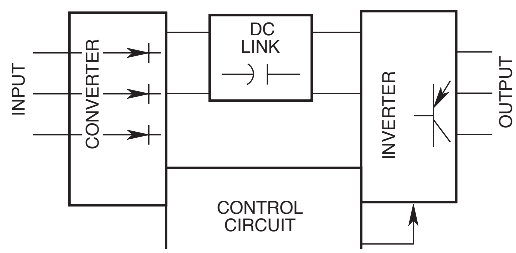
specify the maximum repetitive voltage transients (Vm), the switching frequency (kHz) and the rate of rise (dV/dt) that the winding can safely withstand and still meet the life expectations.

As suggested above, various types of output transistors and modulation schemes have different values of Vm and dV/dt, which in turn have different effects on the life of motor insulation. Figure 5-56 (Page 5-36) shows a typical PWM voltage waveform. This is obviously a much more severe condition than normally experienced when operating on sinusoidal voltage.

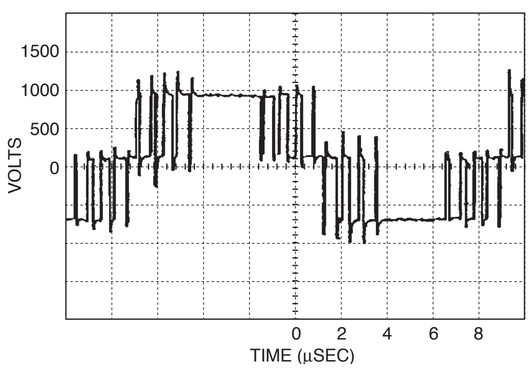
Figure 5-57 shows a typical PWM control circuit and its resulting voltage and current waveforms.

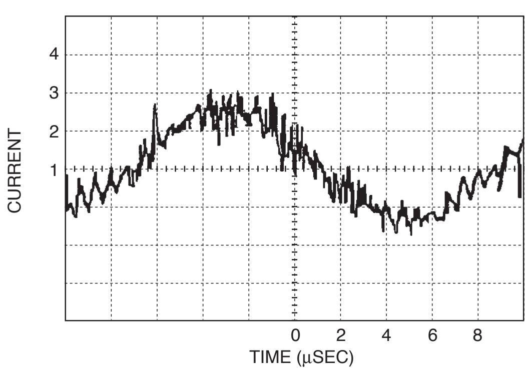
FIGURE 5-57

TYPICAL PULSE-WIDTH MODULATED CONTROLLER



PULSE WIDTH MODULATED VOLTAGE AND CURRENT WAVEFORMS





Typical PWM control circuit and resulting voltage and current waveforms.

Winding damage or failure

Four basic stresses act on the stator winding: [2]

- Thermal
- Mechanical
- Dielectrical
- Environmental

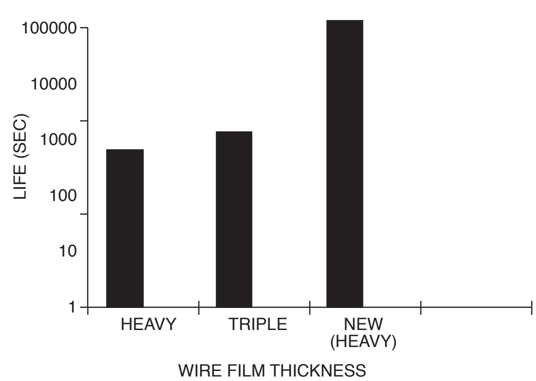
All of these stresses are impacted by ASD voltage waveforms, in that the longevity of the winding is predicated upon the integrity of the whole insulation system. During the early stages of applying six-step ASDs to AC motors, the major focus was on the thermal stress generated by the unwanted drive harmonics passed through to the motor and the associated heating. The other critical factor dealt with the increased heating as a result of reduced cooling capacity at slower speeds. In addition, more attention was given to rotor bar shapes than to the stator insulation voltage withstand capability, since the bar shape significantly influences the speed-torque characteristics of the motor.

With the present PWM drive technology, which uses much higher switching rates (sometimes referred to as carrier frequencies), and its increased application, the focus must now turn to the stator winding insulation system. This is not to imply that the rotor designs can be ignored. The phase-to-phase and the phase-to-ground insulation is relatively easy to address. In fact it normally is not the highest stress point as it was when operating on sine wave power where the steady-state turn-to-turn stress was relatively low (usually under 25 volts/turn). The standard magnet wire used by most motor manufacturers is typically a Class H heavy-coated polyester wire (enameled) with a typical build of .0025" per side. According to NEMA Std. MW 1000 [3], this wire under ideal conditions (twisted wire pair test) is capable of a withstand voltage of 5700 volts at a rise time not to exceed 500 volts/second.

Windings designed for definite purpose inverter-fed motors normally use magnet wire with increased build (i.e., triple and quad build). These polyester-based wires demonstrate higher dielectric breakdown strength when stressed by sine-wave voltage or intermittent transients. When stressed with high dV/dt's and fast switching frequencies, however, their withstand capabilities are less effective. The newer inverter grade magnet wires offer significantly increased life capability (see Figure 5-58) [4].

FIGURE 5-58

LIFE AT 2kV, 20 kHz, 90°C

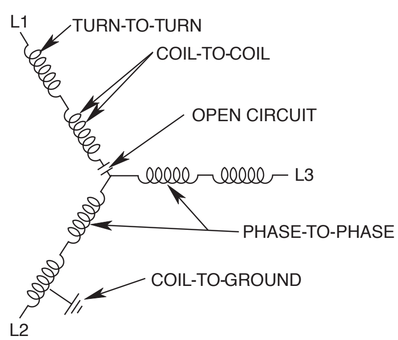


Life capability of inverter grade magnet wires.

These values assume that the wire film is applied concentrically to the copper, and that no damage or depreciation of film thickness occurs in the manufacturing process or operation of the motor. The standards for these films in some cases allows for a max/min ratio of up to 4:1. By reducing this ratio for the same thickness, significant improvement can be made in the voltage withstand capability. At high operating temperatures the turn-to-turn bond strength may decrease significantly. Hence, coil movement and abrasion reduce the thickness of the turn insulation over time, which can cause premature failure of the turn insulation. This condition can be minimized by improving the winding treatment process. Figure 5-59 illustrates the various modes of winding failure for a typical stator. Note that it is possible to have any combination of these modes.

FIGURE 5-59

WYE-CONNECTED STATOR SHOWING POSSIBLE FAILURE MODES



Regardless of the origin of the voltage transient, the highest stress points usually occur in the first or last turns of any given phase. [2] On medium- and high-voltage machines using form coils, additional turn insulation may be added to compensate for this condition. This approach, however, is not practical on low-voltage random-wound windings. On these machines that are specifically designed for inverter-duty applications, some manufacturers have developed special insulation systems that address increased bond strength, lower operating temperature and higher turn-to-turn insulation, along with modified phase and ground insulation. The next section summarizes the various options that can be exercised to improve the insulation system to qualify it for inverter-duty application.

Inverter-grade insulation for ASD motors

The inverter-grade insulation system usually consists of the following key features:

- Magnet wire with increased dielectric strength
- Improved insulation on end turns, in slots and between phases
- Heavy-duty lacing or taping of end turns
- Extra cycles of varnish dip or vacuum impregnation
- Maximized copper content in slots
- High temperature insulation with low thermal rise levels

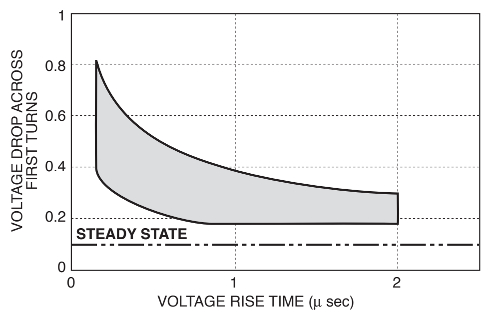
Frequently this system is combined with a premium efficient motor design to increase thermal capability and high torque capabilities. The motor is normally sized to run at less than the full load point without using the service factor.

A number of investigations by motor and insulation manufacturers are in process to determine more accurately the voltage endurance levels of the present and proposed insulations systems. Preliminary results [5] [6] indicate that the transient voltage levels combined with the operating temperatures can exceed corona starting levels, which may result in insulation damage if appropriate precautions are not taken (e.g., line filters or special insulation systems).

Figure 5-60 shows the results of a study conducted to determine the maximum voltage drop across the first turns of the lead coils. [7] [8] It is important to understand that the theory of first or last turn failures is predicated upon the assumption that the other coils are not weaker links but coils of similar dielectric strength.

FIGURE 5-60

VOLTAGE ACROSS THE FIRST TURNS



Maximum voltage drop across the first turns of the lead coils.

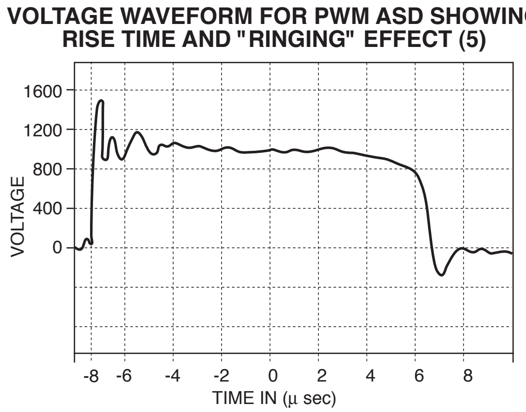
Standing waves or the "ringing" effect

Using the classical line transmission theory [8], it can be shown that, depending upon the cable length between a PWM drive and the AC motor, it is possible to experience a voltage reflection at the motor terminals of up to two times the applied voltage (2Pu). The impedance of a typical induction motor is mostly inductive and at high switching frequencies appears like an open circuit. Hence, the opportunity for a large incident voltage waveform traveling to the motor terminals exists and presents the possibility of serious insulation damage.

Figure 5-61 (Page 5-39) shows the impact of cable length on peak-to-peak voltage values at the motor terminals. [7] Figure 5-62 (Page 5-39) shows the relationship between cable length and the rise time. [9]

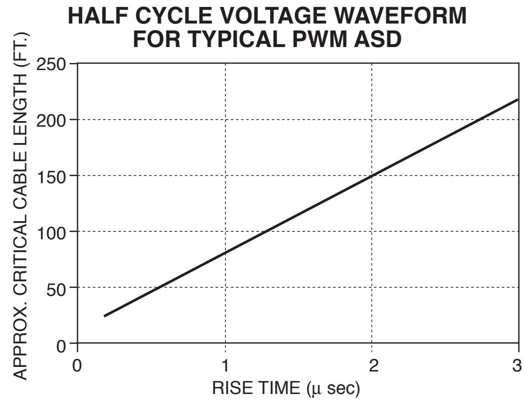
The "ringing effect" can be corrected or minimized with the use of various filter devices that are commercially available, by reducing the cable length (usually to less than 50 feet), or by the use of motors with inverter-grade insulation systems. In some extreme cases more than one of these options must be used. The other alternative when long cable runs are necessary is to apply drives less prone to deliver these high reflected voltages.

FIGURE 5-61



Impact of cable length on peak-to-peak voltage values at the motor terminals.

FIGURE 5-62



The relationship between cable length and the rise time

POWER CABLES

The cables between the motor and the inverter of AC motor drive systems were mostly ignored in the first few years after AC drives became widely used in industrial applications. Since then, inverter switching times have decreased by a factor of at least 20:1, so power cable characteristics are now critical. An informative article on this topic by J.M. Bentley and P.J. Link describes areas of concern regarding power cabling in inverter application, as well as a test program for quantitatively evaluating cable-related remedies for problem areas. [10] The article also provides test results for eight types of power cable and examines connector considerations, interconnection of the cable shield or sheath, NEC ground circuits, and power cable voltage ratings.

Impact of cable length

The impact of long cable runs can be illustrated by the following example of field failures on 8 of 15 standard AC motors (10 hp, 4 pole) on an application powered by typical PWM drives with a switching frequency of 2 kHz. When the motors failed on initial start up (within 30 days), it was concluded that the motors were defective. All 15 motors were replaced with new motors of another make. The new motors also started failing within one week of operation. Next, the user challenged the ASDs as being defective, but no fault could be found. It was then revealed that the cable run between the ASDs and motors was 100 feet.

A simulation test conducted with and without a long cable run demonstrated that there were excessive voltage levels and high dV/dt's. Figure 5-63 and Figure 5-64 show the impact of installing line filters between the drive and motor when operating with the 100-foot cable run. Unfortunately, it was not possible to separate the spikes caused by the ASD from those caused by the cable run. Figure 5-65 and Figure 5-66 (Page 5-40) provide a clear example of the impact of the ringing effect as a function of the cable length.

Numerous examples of this particular problem have been documented with a wide variety of PWM drives and motors. Close inspection of most of the failed units indicated that turn-to-turn shorts occurred in several places without any significant signs of generalized heating. The data, however, does not

FIGURE 5-63

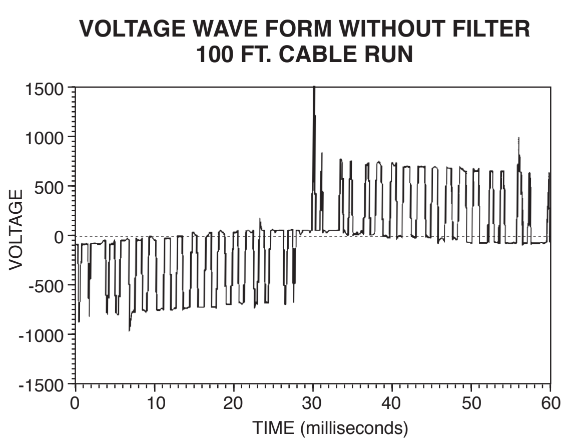
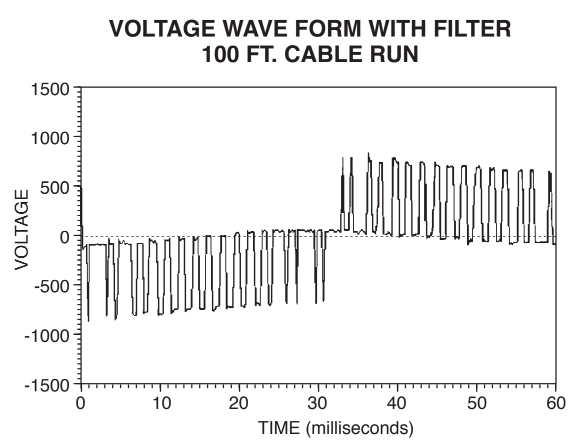


FIGURE 5-64



Impact of installing line filters between the drive and the motor when operating on a cable run of 100 feet.

FIGURE 5-65

COMPARISON OF PWM VOLTAGE WAVE WITH 6 FT. OF CABLE [7]

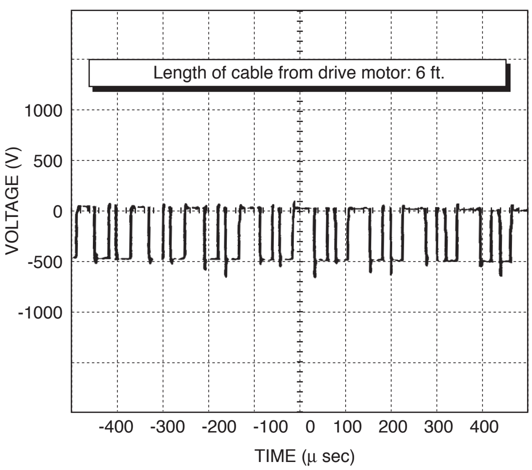
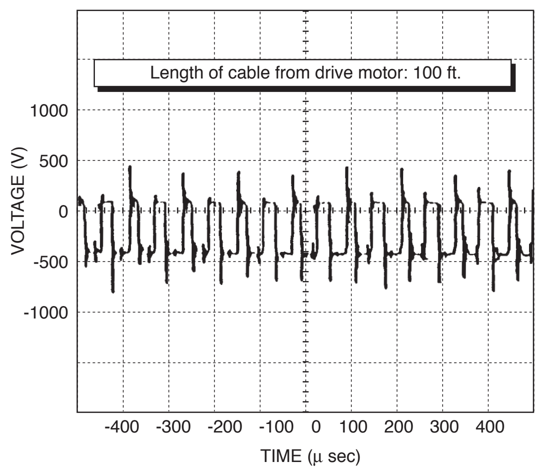


FIGURE 5-66 2

COMPARISON OF PWM VOLTAGE WAVE WITH 100 FT. OF CABLE [7]



The impact of the “ringing effect” as a function of cable length.

provide adequate information to confirm that the turn-to-turn faults were in the first or last coil of a given phase. Note too that there are many successful installations with long cable runs.

Overvoltage and ringing can occur at both the beginning and end of each pulse, [11] as indicated in Figure 5-67. While most “external” voltage line transients occur infrequently, the overvoltage associated with ASDs can occur 20 to 100 times per cycle. These repetitions, along with the rise time, have the most potential for insulation damage. As shown in Figure 5-60 (Page 5-38), which provides an envelope or range, as much as 85% of the peak overvoltage can be dropped across the first turn of the first coil of a phase, depending upon the dV/dt. [7]

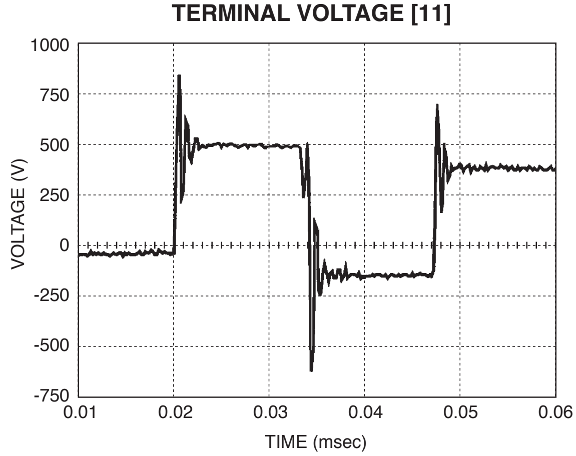
ELECTRICAL HARMONIC IMPACT

Distortion of the fundamental voltage and current waveforms in electrical power systems such as ASDs is becoming more of a concern. The basic problems created by these unwanted harmonics include:

- Heat-related failures of capacitors, fuses, cables and motors.
- Nuisance tripping of overcurrent protective devices.
- Reduced capacity of neutral grounding.
- Excessive noise levels.
- Interference with electrical communications equipment or other sensitive electronic controls.

FIGURE 5-67

MEASURED PHASE-TO-PHASE MOTOR TERMINAL VOLTAGE [11]



Overvoltage and ringing can occur at both the beginning and end of each pulse.

TABLE 5-7: SOUND POWER-LW A-WEIGHTED (DBA) PREDOMINANT NOISE OCTAVE BANDS

4 pole	Noise for blower running with motor powered by inverter								Blower on 60 Hz sinewave	
Speed	6 Hz		15 Hz		30 Hz		60 Hz			
Frame	dBA	Carrier freq.	dBA	Carrier freq.	dBA	Carrier freq.	dBA	Carrier freq.	dBA	Carrier freq.
145			75.3	0.5 - k	73.3	1k	74.6	1k	69.2	.5 - 2k
184			69.2	0.5k	63.8	4k	67.8	4k	67.1	.5 - 2k
215	69.7	4k	73.1	4k	70.0	4k	71.2	4k	68.6	.5k
256	68.9	4k	73.4	4k	74.3	4k	72.0	4k	67.6	1k - 2k

- Circuit resonance.
- Pulsating shaft torques.

Line reactors (chokes)

These harmonics and their impact can be significantly reduced by adding system filters, which usually consist of capacitors and reactors. A combination of filters can be used to attenuate various harmonics.

The application of ASDs can cause distortion on both the "line side" and "load side" of the drive; only the "load side" is addressed in this article. Note that in many cases the distortion caused by ASDs creates little or no problems with equipment connected to either the "line side" or the "load side" of the circuit.

Regardless of the type of drive, cable run or motor employed in a system, when the voltage waveform exceeds the limits specified in NEMA Stds. MG 1, Part 30 or Part 31 [12], it may be necessary to reduce the stress levels by installing line reactors at the drive to assure adequate winding life. The impedance of these devices usually is in the 1% to 3% range, depending on the system impedance. Proper installation of line reactors can provide increased protection for the ASD and the motor. Line reactors reduce line disturbances, attenuate harmonics and minimize nuisance tripping. The reactor acts like a current-limiting device that filters the waveform and reduces the noise associated with the drive output.

Motor noise levels

When induction motors are operated from non-sinusoidal waveforms, the noise emitted by the motor may increase due to the harmonic content of the waveform. Table 5-7 (Page 5-40) illustrates how motor noise levels differ for operation on sinusoidal and non-sinusoidal waveforms. Normal sine wave performance readings obtained from a 60 Hz line are in the column on the right.

It is important to realize that the ASD switching frequency is the source of the motor sound power level (LW) increase at the various frequency levels. Manufacturers of some ASDs can program their drives to minimize this increase. In some cases, filters must be inserted in the output circuit leading to the motor to prevent excessive noise. Consult the ASD supplier if motor noise is unacceptable at frequencies equal to or below 60 Hz sine wave values.

Increased noise levels at 90 Hz and 120 Hz are usually due to the external cooling fan attached to the motor shaft. Since the motor speed increases in proportion to the increase in frequency, the fan speed will also increase. The increased air volume created by the higher fan speed can produce an objectionable noise level.

Newer style ASDs can usually help minimize the motor noise created at 60 Hz and lower frequencies by using higher switching frequencies. Unfortunately, higher switching frequencies can create additional dielectric stress on the insulation system, as previously described.

Shaft currents

During the past few years, a significant increase in problems associated with shaft voltages and currents has been observed. In many cases, these currents have caused bearing failures which are identified as fluting or pitting failures. There are at least three known causes for the phenomena. [13] [14]

- Electromagnetic dissymmetry, which is usually inherent in the design and manufacture of the motor.
- Electrostatic charges (associated with friction) accumulated on the rotor assembly. Also, shaft couplings and air passage are known causes.
- Electrostatic coupling caused by external power supplies such as PWM inverters.

Other abnormalities in sine wave power supply associated with grounding, unbalances, or harmonic [15] content may also result in induced shaft voltages. Additional studies are underway to further identify and quantify this phenomena.

In the case of motors used with ASDs, it is theorized that the terminal motor voltage supplied by the drive is not balanced or symmetrical in some aspect. Additional testing and investigation will also be required to confirm these conditions.

Another possible source of this problem is electrostatic coupling, which induces a voltage into the shaft large enough to cause currents that damage the bearings. The high dV/dt's associated with the GTO and IGBT transistors are the major sources of this problem. The amount of load, rotor speed, method of coupling and type of bearing lubricant can each aggravate the situation. [16] In some cases, insulated bearings may not solve this type of problem

Regardless of the cause of the induced shaft voltage, if its value exceeds 0.3 to 0.5 VRMS sine wave, it may produce currents large enough to permanently damage the bearings. This problem has heretofore been limited to larger motors, usually 500 frame and up (where the stator outside lamination diameters exceed 20"). In most cases, the current passes through both bearings. This condition can be corrected by insulating the outboard bearing on horizontal motors or the top bearing on vertical motors.

This approach is usually not practical on smaller motors. Some bearing manufacturers [17] [18], however, are now offering anti-friction bearings, in a wide variety and sizes, with insulated outer races.

Recognition of shaft/bearing currents in inverter-fed three-phase electric motors has prompted a number of solutions to ward off bearing failures. The simplest approach is to reduce the carrier frequency of the VFD to the 2-5 kilo-Hertz range.

There are three options for insulated bearings:

- Coated outer race
- Coated inner race
- Hybrid bearings

The voltage withstand capability is directly related to insulation thickness. Thicker insulation is better. The relatively high frequency associated with VFD-related shaft voltage makes the capacitance another important consideration. Given the same insulation thickness, smaller surface area results in lower capacitance.

For a given bearing size, the inner race is approximately one-third the surface area of the outer race, so one-third the capacitance. However, the insulation coating of a coated inner race is 1½ to 2 times the thickness of a coated outer race.

Surpassing both is the hybrid bearing; the insulation thickness is the diameter of the rolling element, and the capacitance is based on the very small contact surface between the balls and the races.

The VFD-fed motor has a capacitance between the stator and rotor, so insulating just one bearing does not provide sufficient protection. At a minimum, insulate the non-drive end and install a shaft grounding device on the drive end. Insulating both bearings, and adding a shaft grounding device to one end, is recommended.

An alternative is to insulate the bearing housing(s), but care must be taken to ensure that the bearing cap does not bridge the insulated housing, rendering it ineffective.

There are several competing solutions for the "shaft current mitigation" issue. The comparison of these devices is beyond the scope of this paper.

INDUSTRY STANDARDS

ANSI/IEEE Std. 841 [20] contains a list of items to consider when applying ASDs to AC motors, as shown below. Note that most of them in some way deal with the effects of the nonlinear voltage waveform.

MOTOR/DRIVE APPLICATION CONSIDERATIONS

- Motor current exceeding the continuous non-sinusoidal nameplate data due to excessive voltage harmonics, improper volts/hertz levels, or increased loading.
- Motor temperatures too high for the rated class of insulation at any operating speed or load dictated by the application. Insufficient cooling, excessive torque levels for the given frame size, reduced motor efficiencies, increased horsepower requirements, or intermittent motor overloads can all cause excessive temperatures.
- Insufficient motor starting torque due to reduced volts/hertz levels, deficiencies in the momentary current capacity of the drive or incorrect application details.
- Motor noise levels exceeding acceptable limits due to increased fan noise, excitation of mechanical resonant points, or magnetic noise caused by ASD waveforms.
- Mechanical failure of the motor or associated coupling components due to torque pulsations, mechanical critical frequencies, rpm levels in excess of design maximums, reduced bearing lubrication at the extreme ends of the speed range.
- Winding damage or premature failure due to repetitive high-transient voltages, fast rate of voltage rise, or excessive switching rates. Voltage "ringing" is caused by impedance mismatch, usually related to cable length.
- Damage to the motor and drive due to improper installation or application of power factor correction capacitors.
- Loss of third-party listing, such as UL or CSA, for hazardous location operation due to usage or non-sinusoidal waveforms.
- Induced shaft voltages, which can cause circulating currents harmful to the bearings.

IEEE Std. 519: *Recommended Practices and Requirements for Harmonic Control in Electric Power Systems* [21] also addresses the effects of the voltage waveform reflected back to the line and passed on to the motor from the drive. This standard limits line distortion to 5%. Regarding the effects of harmonics, the standard states: "Even in the case of the least susceptible equipment, harmonics can be harmful . . . they can cause dielectric, thermal or voltage stress, which causes premature aging of electrical insulation."

NEMA Stds. MG 1, Part 30, "Application Considerations for Constant Speed Motors Used on a Sinusoidal Bus with Harmonic Content and General Purpose Motors Used with Variable-Voltage or Variable-Frequency Controls or Both," [12] establishes limitations for general purpose NEMA Design A and B induction motors. These can be summarized as follows:

- Derating curve based upon harmonic content of line voltage.
- Maximum safe operating speed.
- Reduced torque capability curves for operating speeds due to reduced cooling.
- Reduced torque capability curves for operating speeds above 60 Hz.
- Maximum voltage stress levels:
  - Motors rated 600 volts or less:
  - V peak $\leq$ 1 kV; rise time $\geq$ 2 μ sec
  - Motors rated greater than 600 volts:
  - V peak $\leq$ 2.5 pu; rise time $\geq$ 1 μ sec

NEMA Stds. MG 1, Part 31 [12] specifies limitations for "Definite Purpose Inverter-Fed Motors." These can be summarized as follows:

- Definition of rating basis, including speed/torque ranges, as well as recommended horsepower and speed rating.
- Temperature rise limits.
- Starting, operating and breakdown torque consideration.
- Leakage currents and shaft voltages.
- Voltage spikes and pulsed voltage rise time requirements for motors rated 600 volts or less to be compatible with PWM inverter drives.
- Maximum voltage stress levels:
  - Motors rated 600 volts or less:
  - V peak $\leq$ 1.6 kV; rise time $\geq$ .1 μ sec
  - Motors rated over 600 volts:
  - V peak $\leq$ 2.5 pu; rise time $\geq$ .1 μ sec
- where: 1 pu = $\sqrt{2}$ VLL/$\sqrt{3}$

CONCLUSIONS

Much of the existing confusion about successful application of ASDs is due to the fact that the impact of ASDs on motors has been evaluated amid a rapidly changing technology. For instance, early studies of the effect of drives on bearing currents were conducted in an environment of low dv/dt's and low carrier frequencies. The same can be said of studies that focused on the impact of long cable runs and noise/vibration levels.

Another major variable is the wide variety of power transistors and circuitry employed in generating the motor voltage waveform. Motor insulation systems also vary widely, as do the ways in which they respond to the various waveforms that can be applied.

Hence, future studies of the impact of ASDs and motors on a system should be done on equipment that uses state-of-the-art technology. Some technical publications on the subject do not even make clear which hardware was employed in the evaluation.

In conclusion, this paper is not intended to discourage the use of PWM drives. Instead, the goal is to assure proper application of the drive and motor to achieve the desired performance and life expectations. With proper application, the rewards and benefits of using ASDs and motors for speed control and energy conservation far exceed the risks. As with all new technologies, however, knowledge is the key to success. Because ASD technology is changing rapidly, it is important to recognize that the old "rules of thumb" or application standards may no longer apply.

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Long cable runs with IGBT inverters, load reactors and passive filters

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As technology and competitiveness grow within industry, so does the use of variable-frequency drives (VFDs). VFDs offer many benefits, including:

- Increased productivity
- Energy savings
- Decreased maintenance
- Tension control
- Process control
- Improved accuracy.

While potential benefits are significant, important application considerations are often neglected, ignored or, in many cases, unknown by the user and equipment provider. This article addresses problems associated with one such consideration: the distance between the motor and control. It also examines the effectiveness of remedies for such problems, including load reactors and passive filters.

Heightened awareness of motor-to-control distances is very important now that insulated gate bipolar transistors (IGBTs) are being used in many pulse-width modulated (PWM) controls. These controls are popular because they are compact, efficient, quiet and relatively inexpensive. Unfortunately, they also can adversely affect motor life when used on cable runs of more than 50 feet (15 meters).

THE PHENOMENON

IGBT transistors turn *on* and turn *off* much more quickly than the earlier bipolar or GTO transistors, allowing voltage to rise much faster. The diode bridge front-end converts the AC RMS voltage into DC voltage at a rate of 1.41 times the AC input. A 460-volt AC control therefore would have a 648-volt DC bus (460 x 1.41) and pulse 648 volts to the motor. The faster switching rate of IGBT devices also causes the voltage to *rise* more quickly.

This faster voltage rise in combination with increased cable length affects the ultimate voltage transient at the motor. In basic terms, long cable runs cause impedance mismatches between the cable and the motor and between the cable and the control. As a result, some portion of the waveform's high-frequency leading edge will be reflected back in the direction it came from. When the reflected leading edges encounter the leading edges of other waveforms, the voltages add, producing voltage "overshoots" or ring-ups.

If the waveform were symmetrical, it might be possible to "tune" the cable to nullify the additive voltages. The pulse width varies, however, so no predictable null point exists.

THE RESULT

The high-voltage transient eventually will damage the motor winding, typically in one of two ways:

- The first 1 to 3 turns will be burnt; or
- There will be pinhole insulation failures typically in the endcoils of the first couple of turns.

Motor damage may not occur for six months to a year, or it may happen in as little as 20 to 30 minutes. Generally, failure will occur more quickly with the addition of each of these factors:

- The higher the voltage
- The less the phase insulation
- The higher the carrier frequency
- The smaller the motor (and wire size of the winding).

SOLUTIONS

Ways to increase motor life when using VFDs include:

- Keep cable lengths as short as possible.
- Make sure motors are phase insulated.
- Keep the operating temperature of the motor below that specified for its insulation class.
- Consult the motor supplier concerning new types of magnet wire that are designed to withstand voltage transients better.
- If the cable length cannot be shortened, consider using load reactors for the output of the PWM control.
- If load reactors do not provide enough protection, or the application is critical, consider using output filters.

LOAD REACTORS AND PASSIVE FILTERS

The effectiveness of load reactors and passive filters for protecting motors from harmful voltage transients has been widely discussed in recent months. To see the effective increase in protection afforded by each technology, study the oscilloscope traces that begin on Page 5-45.

The traces were made on a 10 horsepower, 4-pole, 215TC energy-efficient Baldor inverter motor; a Series 15H 460-volt AC inverter; 10/4 power cable; a 3 millihenry load reactor (when applied); and a KLC8BE low-pass filter (when applied).

SUMMARY

Adding a line reactor to a long cable run decreases the voltage ring-up, which in turn increases the life of the motor. With the addition of a filter, the voltage ring-up is close to that of a short cable run.

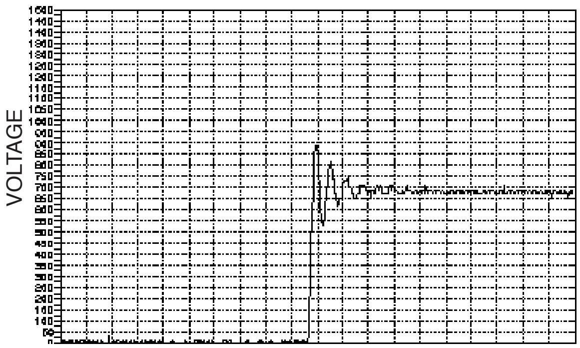
So, when considering an application with longer motor cable runs [50 feet (15 meters) or more], higher voltage input (460-volt AC or more), and IGBT transistors, consider filtering the output.

Note: This originally appeared in *EASA Currents* (June 1996). It was reviewed and updated as necessary in October 2020.

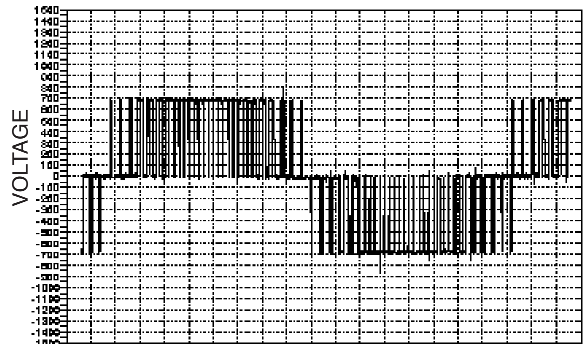
LOAD REACTORS AND PASSIVE FILTERS

Editor's Note: The oscilloscope traces on the following pages are from a study by Baldor Electric Co. (now ABB Motors & Mechanical) on the effectiveness of load reactors and passive filters in protecting control-driven motors from harmful voltage transients. The traces on the left show the rate of voltage rise at the motor terminals. The traces on the right show the frequency of higher pulses AND general waveform at the motor terminals.

CABLE RUN OF 9 FEET (2.7 METERS): 2.5 KHZ PWM FREQUENCY (NO RING-UP EFFECT)

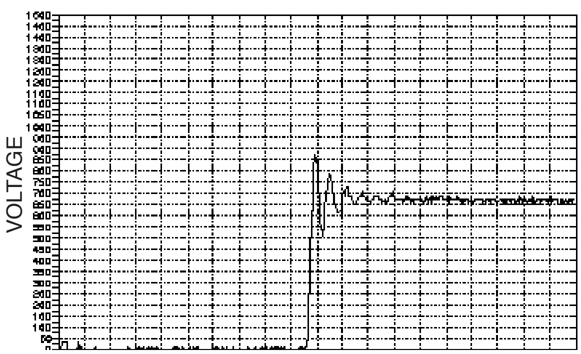


TIME BASE (micro seconds from trigger)

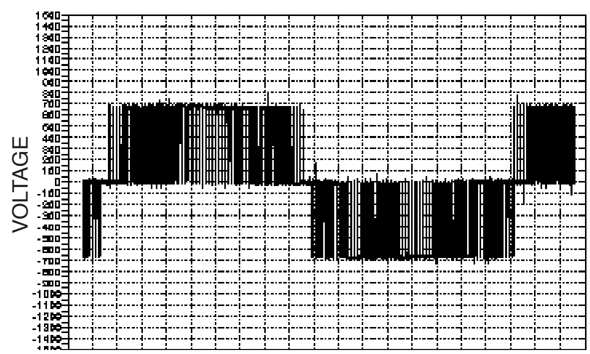


TIME BASE (micro seconds from trigger)

CABLE RUN OF 9 FEET (2.7 METERS): 8.0 KHZ PWM FREQUENCY (NO RING-UP EFFECT)



TIME BASE (micro seconds from trigger)

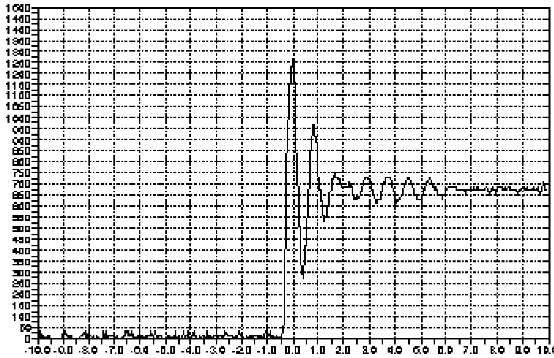


TIME BASE (micro seconds from trigger)

CABLE RUN OF 70 FEET (21 METERS): 2.5 KHZ PWM FREQUENCY

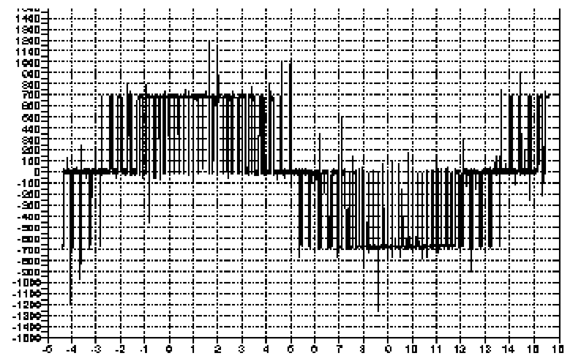
NO REACTOR OR FILTER

VOLTAGE



TIME BASE (micro seconds from trigger)

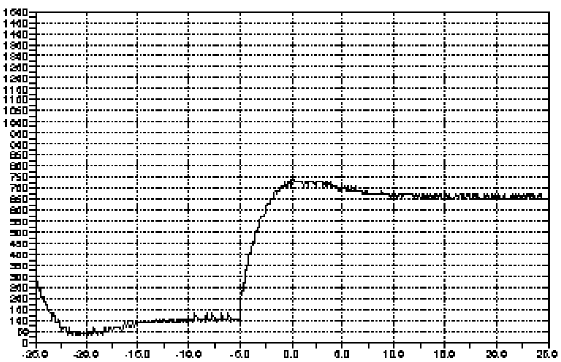
VOLTAGE



TIME BASE (milliseconds from trigger)

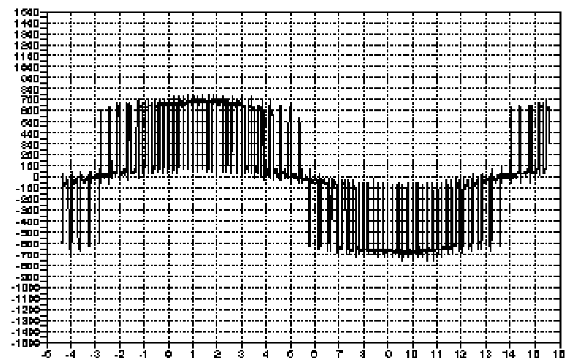
WITH KLC8BE FILTER

VOLTAGE



TIME BASE (micro seconds from trigger)

VOLTAGE

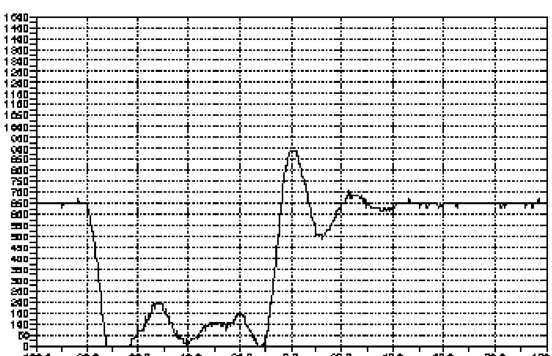


TIME BASE (milliseconds from trigger)

Note: Waveforms taken at 60 Hz output frequency.

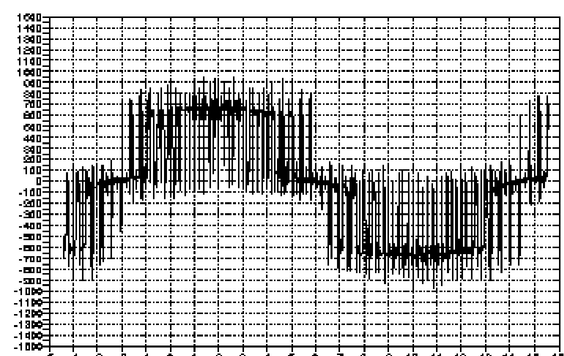
WITH LINE REACTOR

VOLTAGE



TIME BASE (micro seconds from trigger)

VOLTAGE

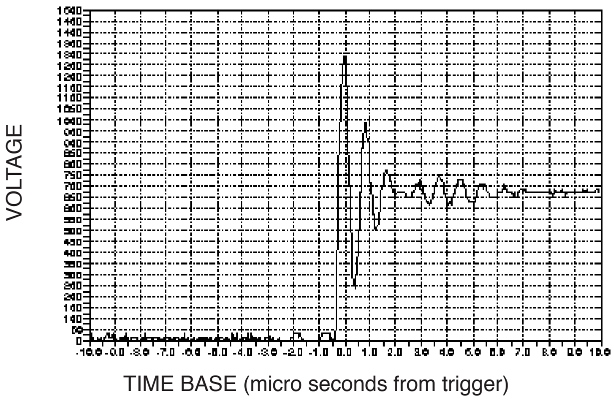


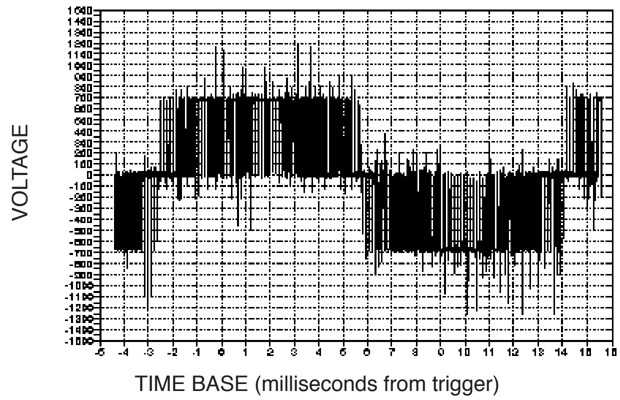
TIME BASE (milliseconds from trigger)

Note: Waveforms taken at 60 Hz output frequency.

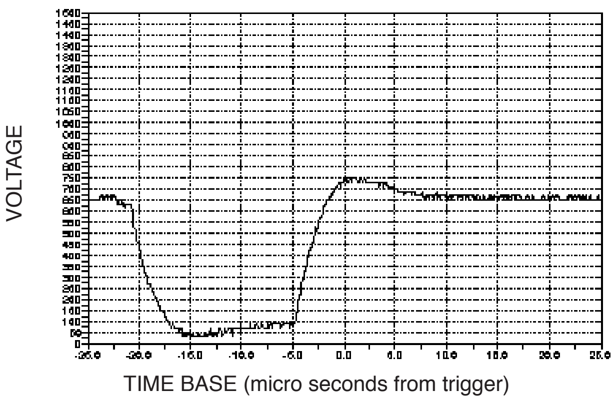
CABLE RUN OF 70 FEET (21 METERS): 8.0 KHZ PWM FREQUENCY

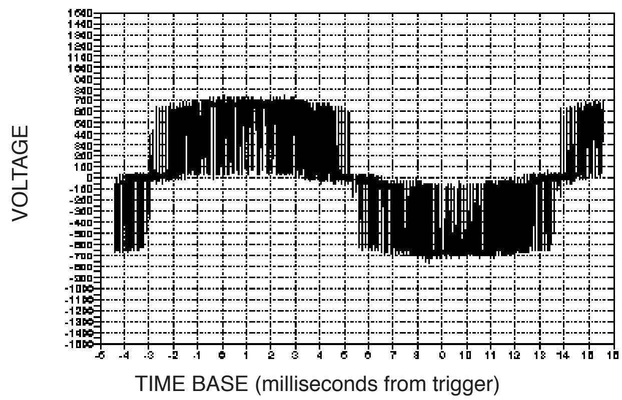
NO REACTOR OR FILTER





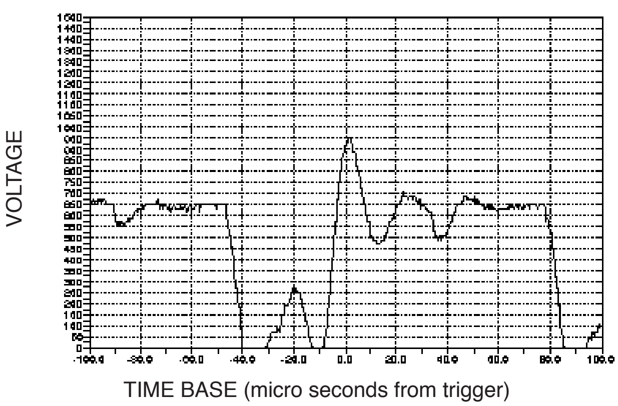
WITH KLC8BE FILTER

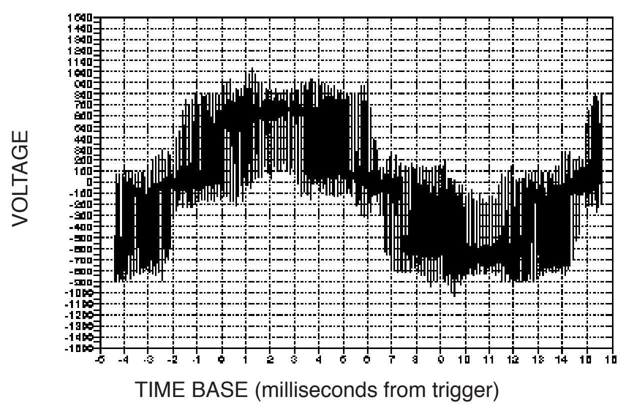




Note: Waveforms taken at 60 Hz output frequency.

WITH LINE REACTOR

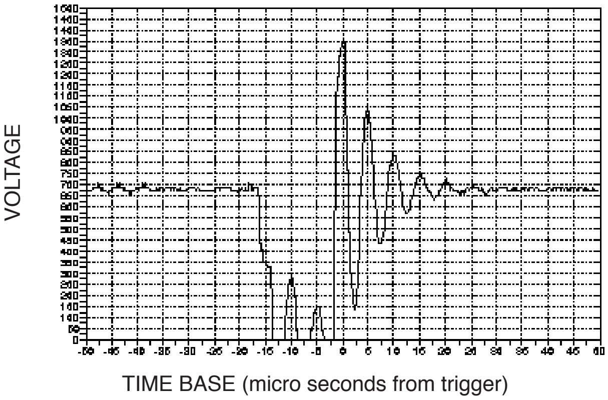


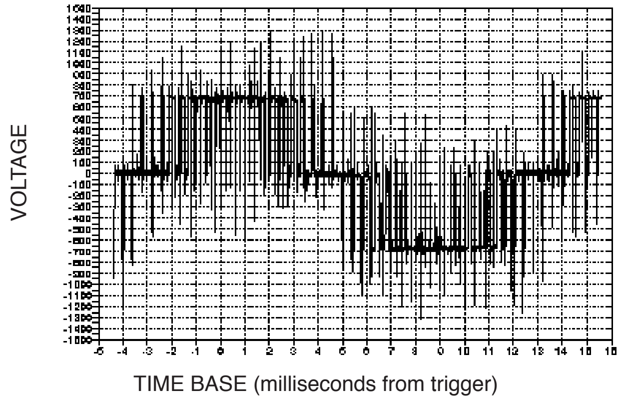


Note: Waveforms taken at 60 Hz output frequency.

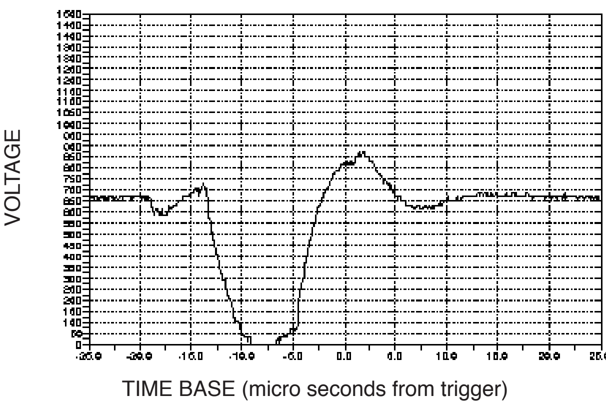
CABLE RUN OF 500 FEET (152 METERS): 2.5 KHZ PWM FREQUENCY

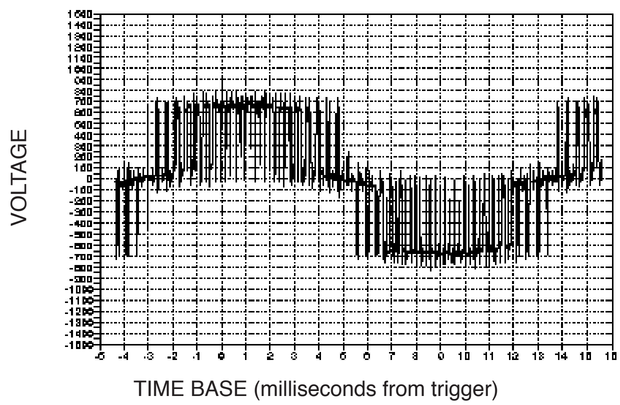
NO REACTOR OR FILTER





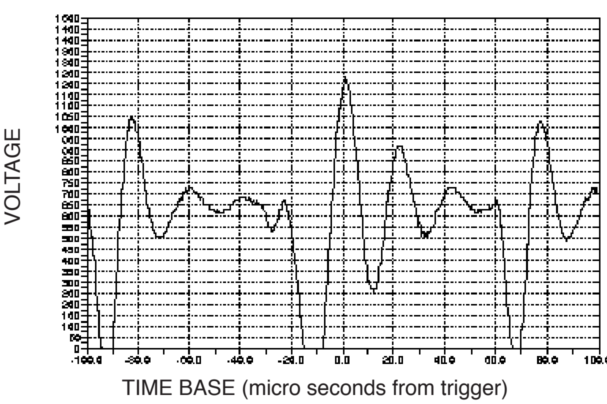
WITH KLC8BE FILTER

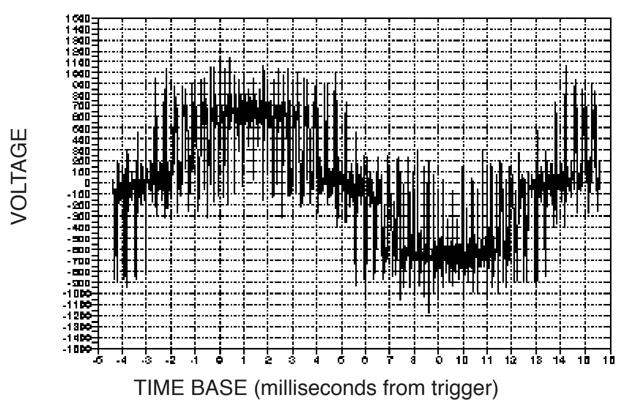




Note: Waveforms taken at 60 Hz output frequency.

WITH LINE REACTOR

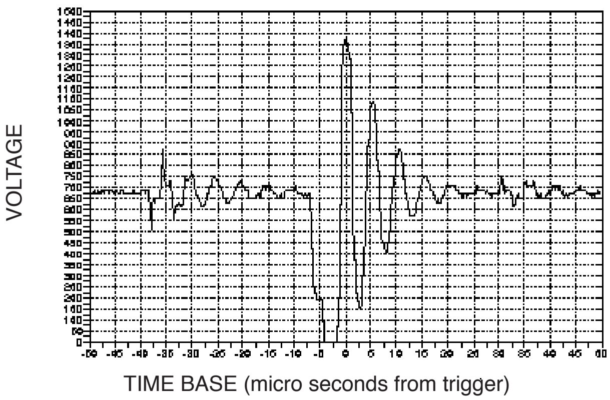


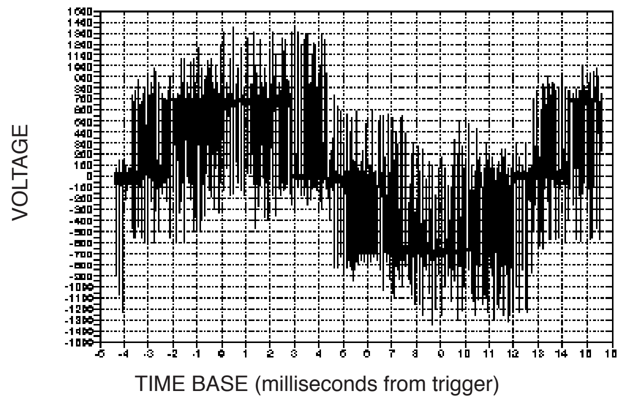


Note: Waveforms taken at 60 Hz output frequency.

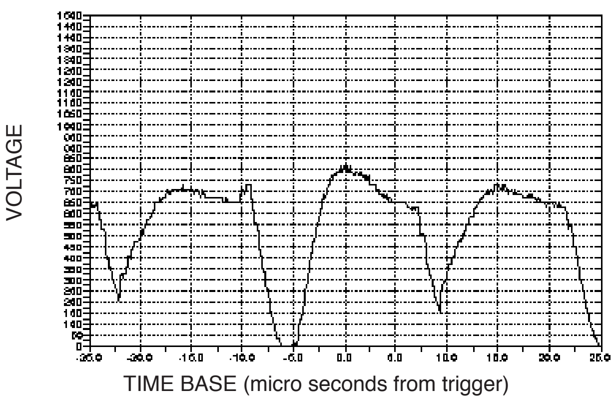
CABLE RUN OF 500 FEET (152 METERS): 8.0 KHZ PWM FREQUENCY

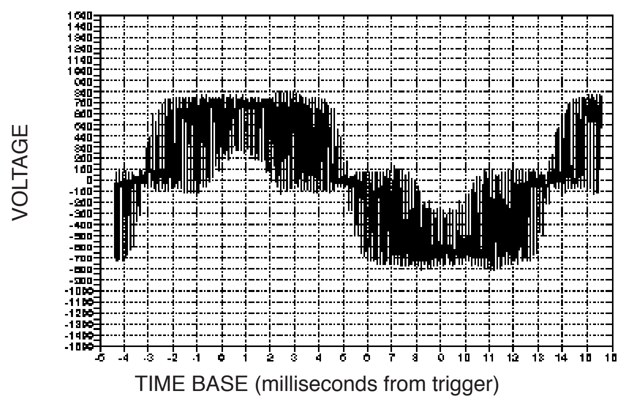
NO REACTOR OR FILTER





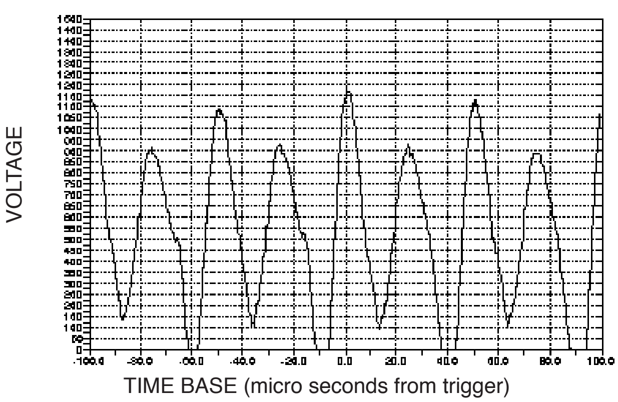
WITH KLC8BE FILTER

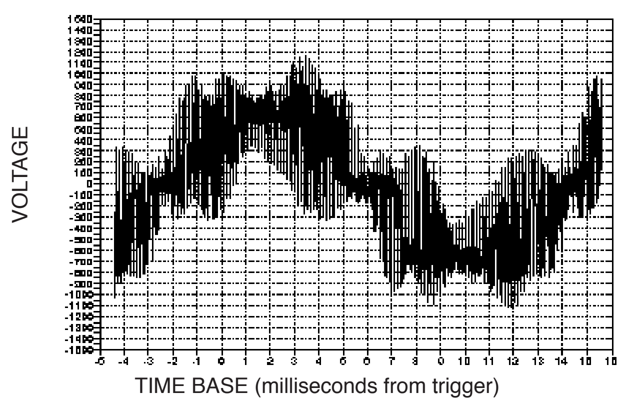




Note: Waveforms taken at 60 Hz output frequency.

WITH LINE REACTOR





Note: Waveforms taken at 60 Hz output frequency.

5.5 HARMONICS

Harmonics: Answers to common questions

By Bill Colton
ABB Motors & Mechanical, Inc. (formerly Baldor Electric Co.)
Commerce, CA

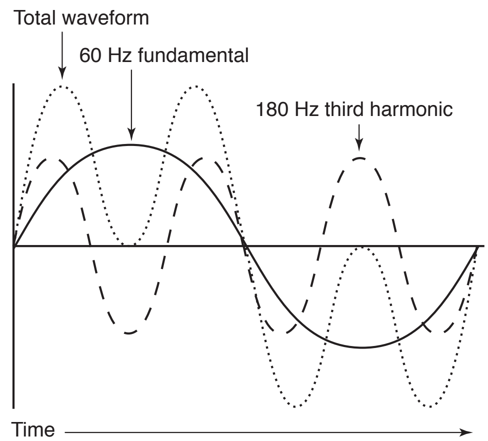
What are harmonics?

Harmonics are wave forms superimposed over the main, or fundamental, sine wave (see Figure 5-68). The fundamental sine wave (in the U.S. at 60 Hertz) does the primary work of rotating motors.

Harmonics ride on top of the fundamental sine wave and may be harmful. Products powered by fundamental sine wave must filter these harmonics; the general result is additional heating.

Interestingly, even-numbered (2, 4, 6, 8) harmonics cancel themselves out (as one goes up, another goes down), so they do not cause problems. The odd-numbered (1, 3, 5, 7) harmonics are the culprits. It is not uncommon to see high 3rd (3 x 60 = 180 Hz), 5th and 7th harmonics (300 and 420 Hz), and sometimes the 11th and 13th.

FIGURE 5-68



Harmonics are wave forms superimposed over the main, or fundamental, sine wave.

What harmonics may do to your customer

High total harmonic distortion (THD) may cause a number of problems in industrial plants, such as:

- Blowing fuses on power factor correction capacitors;
- Tripping circuit breakers;
- Overheating wires (including neutrals);
- Overheating transformers and motors;
- Causing electronic control malfunctions (including machine controls, computers, display quality on PCs and nuisance tripping on drives).

What causes harmonics?

Harmonics are typically caused by devices that draw current in uneven (non-sinusoidal) amounts. As the current is pulled through the transformer in quick, uneven amounts, it reacts by changing the voltage. This change of voltage rides on top of the fundamental sine wave as harmonics.

What devices create these harmonics?

Among the devices that create harmonics are AC and DC drives, uninterruptible power supplies (UPS systems), arc welders, arc furnaces, computers, copiers and electronic ballasts.

Can you measure harmonics?

You can measure harmonics at the point of common coupling where the drive connects to the power system, such as the breaker panel. Dedicated harmonic meters are available in the marketplace.

What can be done to eliminate harmonics?

Several things can be done to reduce harmonics. First, select an appropriate low-reactance transformer. Second, utilize proper drive technology. Another help is the addition of line reactors, isolation transformers, tuned filter traps, active filter traps and line capacitors.

What is a line reactor?

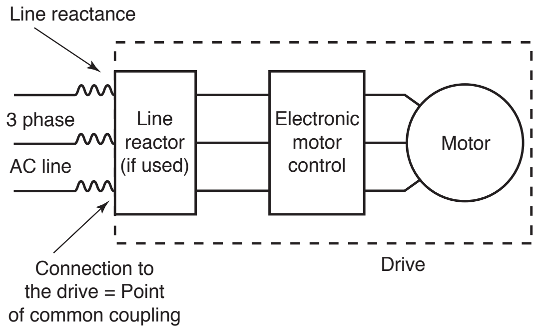
A line reactor is an iron-laminated core with copper strips wound around the pole pieces and insulation between the copper strips. In a three-phase line reactor, there are three poles and six terminals, with one input terminal and one output terminal per phase.

What is the purpose of a line reactor?

Line reactors are added to the input to the drive to smooth the current disturbances (harmonics) and voltage harmonics back to the point of common coupling (see Figure 5-69 on Page 5-51). For example, a 200 horsepower, 480 volt, AC diode bridge front-end control powered by a transformer with 1% line reactance may experience 83% total harmonic distortion voltage. Adding a 3% line reactor (a standard selection) reduces the voltage total harmonic distortion (thd) to approximately 38%. This is a significant reduction. Further reductions would require other devices, such as tuned filter traps, active filter traps, or special-design line capacitor traps.

Another advantage of adding a line reactor to a control input is to slow down a current spike that is "walking" down the line to the control. Slowing this current spike increases the time for the control to sense the rise of voltage and turn off the transistors before damage occurs to the transistors and motor. This is a very inexpensive form of insurance. Because

FIGURE 5-69



Line reactors are added at the input of the drive to help smooth current disturbances (harmonics) and voltage harmonics back to the point of common coupling.

line reactors in front of a control always help to protect the control from bad power and reduce harmonics without any reduction in performance, it makes good sense to consider them for every drive specification.

Line reactors are also used on the output of the control (mounted near the control, not the motor). The output of a pulse-width modulated (PWM) control is not a perfect sine wave. When the pulses of voltage sent through the wire reach the motor and the impedance of the motor does not match the impedance of the line (and it probably never will), then some of the voltage is reflected back. This effect accumulates and sends large transient voltage pulses to the motor. It is not uncommon to see 1500- to 2500-volt spikes on a 480-volt system.

When these high-order pulses hit the motor, they tend to ionize the insulation on the first couple of winding turns, resulting in line-to-line shorts. A 3% line reactor would reduce these pulses to 700-800 volts, substantially increasing the life of the motor. Note that the effects of this "voltage ring up" increase with smaller motors, with higher voltage controls (460 volts), and with the length of the cable between the control and the motor.

Is a line reactor an isolation transformer?

No. An isolation transformer has two sets of windings and operates from the induction of voltage from one set of windings to the second set of windings. This adds a great deal of short-circuit protection–and cost.

Are there other names for line reactors?

Yes. Line reactors are also called chokes or inductors.

Can we conquer harmonics?

There are several ways to conquer harmonics. These solutions vary in degrees of suppression, the harmonic they suppress and, of course, price. Of one thing you can be sure: If more suppression is required than a line reactor can handle, you are starting to look at serious money.

Are there any standards for harmonics?

Yes. The standard most people in the U.S. look to is:

- IEEE Std. 519: *Recommended Practices & Requirements for Harmonic Control in Electric Power Systems*.

Europe has three specifications:

- IEC 61000-3-2: *Limits for Harmonic Current Emissions (Equipment Input Current ≤16A per Phase)*.
- EREC G5/4: *Planning Levels for Harmonic Voltage Distortion & the Connection of Non-linear Equipment to Transmission Systems & Distribution Networks in the United Kingdom*.

Prior to 1992, IEEE Std. 519 was fairly easy to meet, because it only addressed voltage distortion. Now, however, IEEE Std. 519 includes current distortion, which means you need to do more than just add a line reactor.

What devices are used to suppress harmonics?

Line reactors resist rapid changes of current and help quite a bit as the first line of defense against harmonics. These devices have a large effect without a large investment. As noted earlier, without a line reactor, a 200 horsepower, 460-volt diode bridge front-end inverter (or vector drive) powered through a 1% reactance transformer results in approximately 83% current harmonics distortion. Adding a 3% line reactor decreases the total harmonic distortion current to 38%. This is quite an improvement, yet IEEE Std. 519 says we need to be at 15% with a 1% transformer.

If we were looking at a 200 horsepower, 480 volt SCR front end–whether it be a current source inverter or DC drive, etc.–we would measure the total demand distortion (TDD) at rated load. So at 50% speed, our distortion would be approximately 137% with a 1% transformer. Adding a 3% line reactor would then drop the distortion to 83%. Once again, this is a good improvement, but it's a far cry from IEEE Std. 519 at 15% distortion.

Isolation transformers will suppress approximately the same amount of harmonics as line reactors and also provide short circuit protection. This is extremely helpful in ungrounded power distribution systems. Isolation transformers, however, are also quite a bit more expensive than line reactors.

Tuned filter traps are an I - C (inductive and capacitive) network designed to suppress certain harmonics. Diode bridge front-end controls typically increase the 5th and 7th harmonic. Often we can add a line reactor and a 5th and 7th trap to meet specifications. In our 200 horsepower, 480 volt example, just the 1% line reactance transformer lets us induce 83% TDD at rated load. Adding a 3% line reactor reduces TDD current to 38%. Then, adding a 5th harmonics filter reduces TDD current to 13%. When we add the 7th harmonic filter to the 5th harmonic filter and the 3% line reactor, harmonic distortion is reduced to 9%. This certainly surpasses the specification of 15%.

Active filters measure the distortion and counter it with an equal wave in the direction that cancels out the harmonic. The advantage of this technology is that it works on many different harmonics at the same time, whereas the tuned filters only work on the harmonic for which they are designed. The disadvantage, of course, is cost.

PWM front-end (line regenerative) controls are new on the market. Their advantage is that they draw current in smaller chunks so as not to disturb the line nearly as much as the diode or SCR.

Additionally, when we are fighting gravity (such as an elevator or hoist), holding back (such as an unwind stand or dynamometer), or just slowing down or stopping often, PWM front-end controls turn the kinetic energy into electrical energy. This puts electrical energy back on the line, which effectively turns the power meter backwards.

There are three disadvantages to this type of control. First, it is more expensive than an SCR or diode bridge front end. Second, it is larger physically than the other types. And third, it tends to produce high-frequency harmonics.

Some manufacturers sell the PWM front-end inverter (and vector drive) with a 12% line reactor and high-frequency traps. On the previous 200 horsepower example, this package would meet IEEE Std. 519 at 9% TDD current with a 2.5 kilohertz carrier, and at 5% with an 8 kilohertz carrier.

Note: This was originally published as a series of three articles in *EASA Currents* (November 1995, December 1995 and January 1996). It was reviewed and updated as necessary in October 2020.

5.6 REFERENCED STANDARDS

The following standards are referenced in this section of the *EASA Technical Manual*. If there is a newer version of a referenced standard, both are listed here.

NEMA Std. MW 1000-2008: *Magnet Wire.* National Electrical Manufacturers Association. Rosslyn, VA, 2008.

ANSI/NEMA Std. MW 1000-2018: *Magnet Wire.* National Electrical Manufacturers Association. Rosslyn, VA, 2018.

EREC G5/4: *Planning Levels for Harmonic Voltage Distortion & the Connection of Non-linear Equipment to Transmission Systems & Distribution Networks in the United Kingdom*. Energy Network Association, Ltd. London, England, 2005.

EREC G5/5: *Planning Levels for Harmonic Voltage Distortion & the Connection of Non-linear Equipment to Transmission Systems & Distribution Networks in the United Kingdom*. Energy Network Association, Ltd. London, England, 2019.

IEC Std. 61000-3-2-2018, Ed. 5.0: *Limits for harmonic current emissions (equipment input current ≤16A per phase)*. International Electrotechnical Commission. Geneva, Switzerland, 2018.

IEC Std. 61000-3-2:2018+AMD1:2020 CSV Consolidated version: *Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16 A per phase).* International Electrotechnical Commission. Geneva, Switzerland, 2020.

IEEE Std. 117-1974/ANSI C50.32-1976: *IEEE Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery.* Institute of Electrical and Electronics Engineers, Inc. New York, NY, 1974.

IEEE Std. 117-2015: *IEEE Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2015.

IEEE Std. 841-2009: *IEEE Standard for Petroleum and Chemical Industry–Premium-Efficiency, Severe-Duty Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors–Up to and Including 370 kW (500 hp)*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2009.

IEEE Std. 519-1992: *Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.* Institute of Electrical and Electronics Engineers, Inc. New York, NY, 1993.

IEEE Std. 519-2014: *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2014.

NEMA Stds. MG 1-2009 (Rev. 1-2010): *Motors and Generators.* National Electrical Manufacturers Association. Rosslyn, VA, 2010.

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

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