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Application Note 106

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Reducing Motor Drive Line Noise

Introduction

Motor drives are often the main contributor to line noise in an industrial cabinet. This application note discusses techniques to reduce line conducted emissions from drives.

This application note covers:

- Drive line noise with and without a commercial line filter
- Choosing and wiring a commercial line filter
- Line filter assembled from separate components
- Using a cable balun to reduce line noise within a cabinet
- Optimum configuration for reducing line noise
- Understanding the source of drive line noise and filter saturation

Noise concerns

There are two levels of concern with line noise:

- Regulatory requirements, such as CE, on line noise conducted from the cabinet to the line
- Noise coupling to other equipment within a cabinet

Regulatory requirements

To meet regulatory line emission requirements, such as CE[1], a two-stage LC filter is needed to reduce the line noise from a typical unfiltered drive to CE levels. Compared to FCC requirements CE requires a physically larger filter, because CE specs extend down to 150 kHz vs 450 kHz for the FCC. CE requirements are very stringent. CE spec levels of 66 dbμV to 79 dbμV translate to about 2 to 10 mv of high frequency noise (150 kHz to 30 MHz) riding on the line voltage.

The easiest approach to meeting CE conducted line emissions is to insert a commercial line filter between the drive and the line. The correctly-chosen line filter is quite effective at attenuating drive line noise. Regulatory requirements on conducted line noise can be met with a single line filter at the line input to a cabinet.

1 CE Mark is required for sale of equipment in the European Community countries after January 1, 1996.

Drive Line Noise with and without a Line Filter

Figure 1a shows the line noise produced by a single drive that does not have an internal balun. This noise has a broadband character and is more than 30 to 40 db above CE specs.

Figure 1b shows the dramatic effect of adding a correctly chosen commercial line filter between the drive and the line. Above about 150 Khz, the lowest CE frequency, the commercial line filter reduces the wideband noise of the drive close to the baseline noise of the test setup (shown in Figure 9). Tests at an approved CE test lab show that this particular drive and line filter combination (tested with a 10 ft cable) did meet CE specs for the full range of line conducted emissions from 150 kHz to 30 MHz.

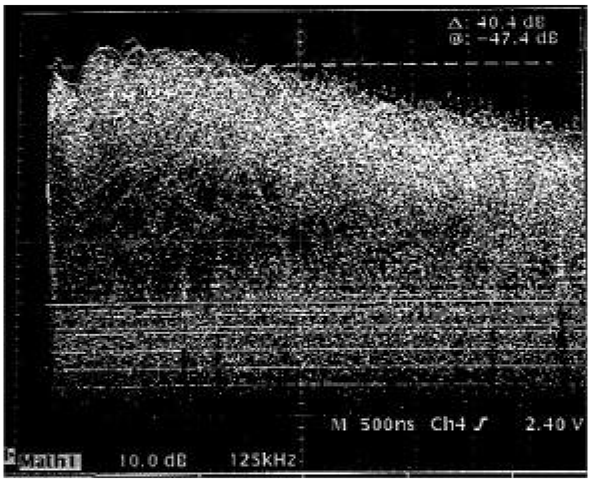


Figure 1a - SC902 with No Line Filter

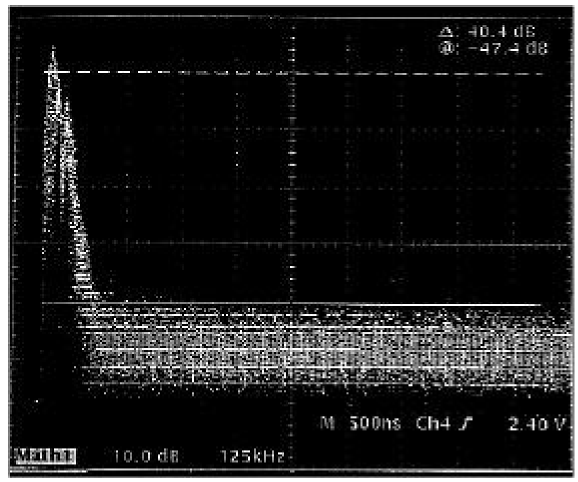


Figure 1b - SC902 with 50 db L/G @ 150 kHz Line Filter (3F15D)

Separate Component Filter Tests

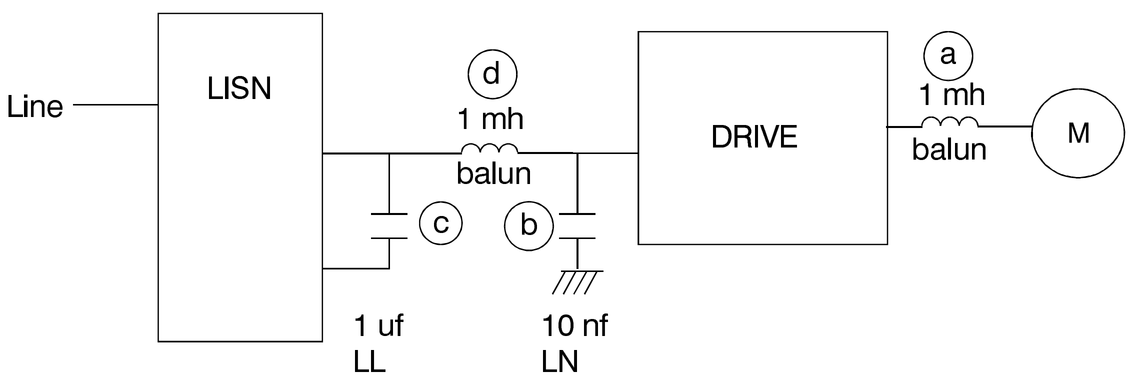
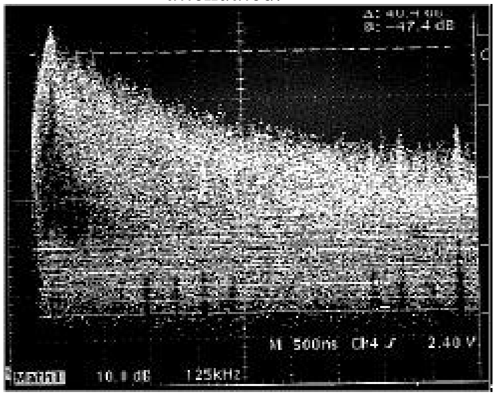


Figure 2 - Constructed line filter

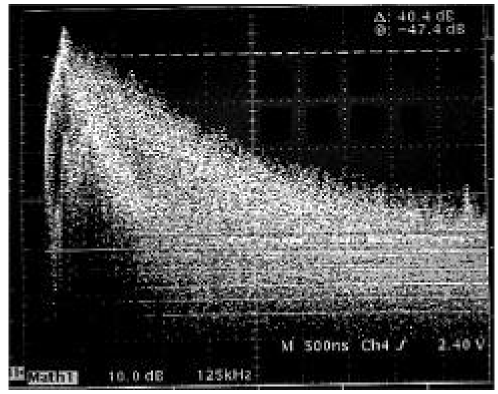
Figure 2 shows a line filter constructed of separate components. These components are:

- a - 1 mh balun @ motor cable
- b - 10 nf caps L/N @ drive input
- c - 1 µf caps LL @ line
- d - 1 mh balun @ line (between caps b and c)

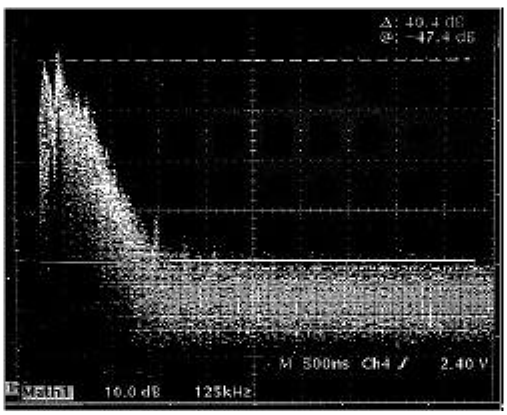
Beginning with the unfiltered drive shown in Figure 1a, the pictures below show the attenuation as each component is added. It is not until all four components are in place, forming a two stage LC filter, that the performance approaches a good commercial line filter and is 150 kHz noise strongly attenuated.



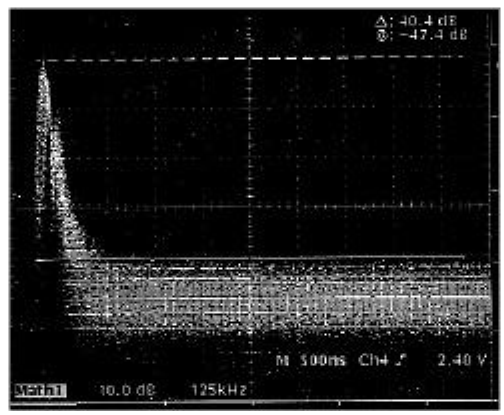
a (Motor Cable Balun)



a + b



a + b + c



a + b + c + d

Looking at the figures above, it can be seen that a motor cable balun, when used with no other filtering, comes nowhere near meeting CE requirements. Yet in the field, adding a motor cable balun is known to be a very effective technique to prevent the drive from affecting nearby equipment.

In conclusion, although it is possible to construct a CE type line filter with individual components, it is a lot easier to buy a commercial line filter that packages a 2 stage LC filter in a sealed can with terminals.

Control Supply Noise Tests

Figure 3a shows the line noise of the drive control supply. This is the noise seen when the drive is disabled. It is mostly carrier harmonics of the switching control supply of the drive. These levels are 10db to 20 db above CE requirements.

If the control supply is powered separately from the inverter, also filter the control supply line. Figure 3b shows the attenuation obtained with a small, commercial, single phase line filter. As can be seen, the filter tested did not fully suppress the fundamental and second carrier harmonic because it was slightly undersized. The single phase filters listed in this application note are a little larger than the model tested.

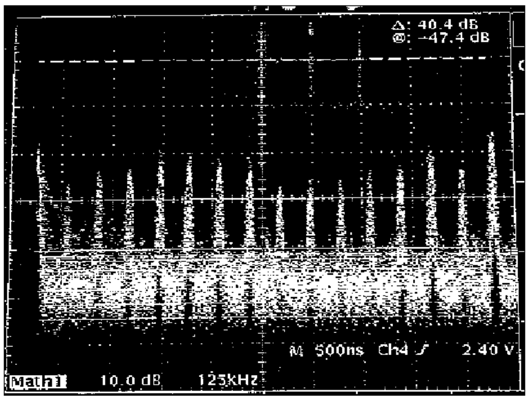


Figure 3a

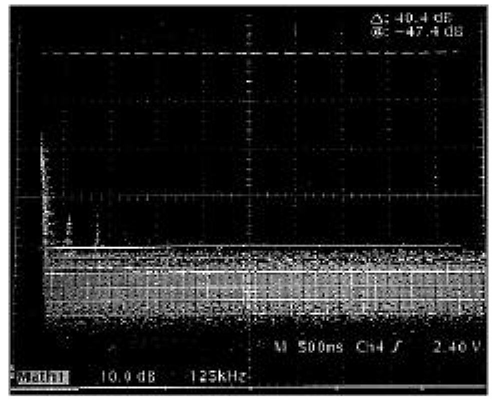


Figure 3b

Commercial Line Filters for Drives

Sizing the Filter

Filters are sized on continuous RMS line current. The filter current rating must exceed the actual continuous RMS line current of the application. In most servo applications continuous RMS line current is much less than the rated, continuous line 'Input Current' shown on a drive data sheet.

If line currents are not known, use the following guideline: Add together the rated continuous RMS line currents of all drives, then multiply by the following factor:

Light Duty Application — 0.33

Heavy Duty Application — 0.66

Add to the derated drive current the estimated line current of other loads to get the minimum current rating of the filter.

It is always better to oversize than undersize the filter. The only real penalty for oversizing the filter is physical size, since filters are relatively inexpensive and the filter performance of a given filter family is the same for all sizes.

If control power is separate from bus power, it should have its own (one phase) filter to meet CE. Control current on Pacific Scientific servocontrollers is 0.5 A_{RMS} (max).

Filter Attenuation

Filter selection depends strongly on the required attenuation at lower frequencies. The most difficult frequency to meet the CE line conducted emissions spec is 150 kHz. Danaher Motion tested a single drive with a Filter Concepts 3F series filter and passed the CE conducted emission spec (Class A). The 3F15 filter is a two stage LC filter (from Load to Line): balun, LG caps + LL caps, balun, LL caps. The 3F15 specified attenuation at 150 kHz, measured Load to Line with Line loaded with 50 ohms, is listed below:

L/L at150 kHz	50 db
L/G at 150 kHz	50 db

The table below shows the physical size of the Filter Concepts 3F series three phase, delta line filters vs current rating:

Manuf and Model	**I Rating**	**Phases**	**Size (in)**
Filter Concepts 3F7D	7.5 A	3	3 x 3 x 6.25
Filter Concepts 3F15D	15 A	3	4 x 4 x 8.6
Filter Concepts 3F30D	30 A	3	5 x 4.75 x 10
Filter Concepts 3F45D	45 A	3	5 x 4.75 x 13
Filter Concepts 3F60D	60 A	3	6.5 x 4.75 x 14

Three phase filters with 10 db more L/G attenuation at 150 kHz than the Filter Concepts 3F series are Filter Concepts 3X series and Tri-Mag SF series. These are both specified at L/L 65 db, L/G 60 db. These filters provide extra attenuation to handle multiple drives.

Filters for the control supply from the Filter Concepts SF series:

Manuf and Model	**I Rating**	**Phases**	**Size (in)**
Filter Concepts SF3	3.0 A	1	3.2 x 2.0 x 1.25
Filter Concepts SF10	10 A	1	4.0 x 2.2 x 1.8

Commercial Line Filter Suppliers:

Filter Concepts
2624 S. Rousselle St.
Santa Ana, CA 92707
714-545-7003
714-545-4607 (fax)

Tri-Mag Inc.
1601 N.Clancy Ct.
Visalia, CA 93291
209-651-2222
209-651-0188 (fax)

Wiring the Filter

Figure 4 shows a commercial line filter (WYE filter shown, delta filter preferred) wired to a LISN for regulatory testing. Some three phase line filters have five terminals (WYE filters) and some have four (delta filters). The difference is that WYE filters have four windings on their internal baluns (three hot + 'N') plus a ground terminal. The delta filters are missing the "N" terminal and have only three windings on their internal baluns (three hot) plus a ground terminal.

A delta line filter is preferred with drives. A WYE filter is also used with drives if the N terminals are left open. Connecting the N terminals to earth ground in a WYE filter weakens the filtering because a path for circulating cable and motor capacitive current is created.

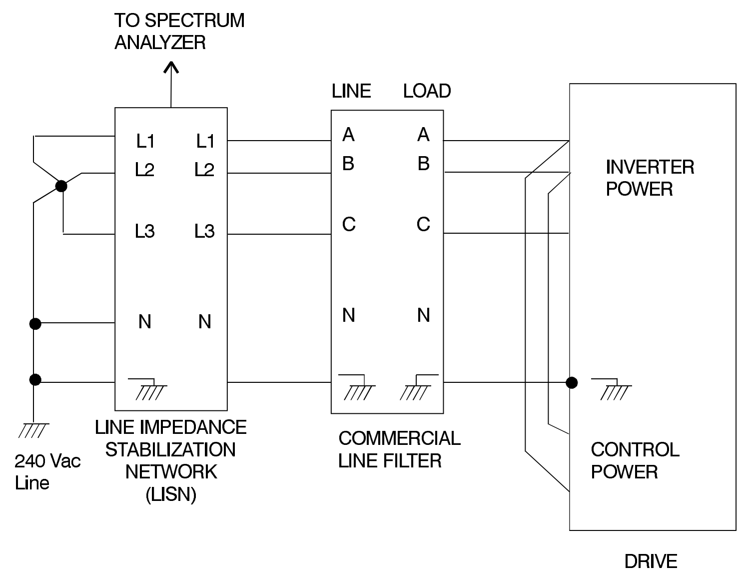


Figure 4 - Wiring a commercial line filter

Line Filter Mounting and Radiated Emissions

Line filters are also effective at reducing cabinet radiated emissions. Line wiring can radiate in the 30 MHz to 80 MHz region. Drives have a broadband switching noise in this region that can leak out of the line connectors onto the line wiring. The same line filter that attenuates conducted line noise can keep most of this high frequency noise from getting onto the line wiring IF the line filter is mounted properly.

For the line filter to attenuate drive noise at 30 MHz to 80 MHz, it is important the filter case be RF grounded to the drive chassis. This is accomplished by mounting the filter near to the drive on the same mounting plate or common metal surface. It is important the line wiring between the drives and the line filter be routed along the common metal surface and away from the motor cables so it does not radiate.

The preferred mounting position for the filter is near the outside wall of the cabinet and adjacent to the drives. The line cord should enter the cabinet wall near the filter and be routed along the common metal surface and away from the motor cables.

- Keep the wiring between the line filter and the drives short. Route it along the common metal surface and away from the motor cables.
- RF ground the line filter case to the drive's chassis by mounting the filter and the drives on a common metal surface.

Cable Balun to Reduce Line Noise within a Cabinet

Danaher Motion field experience has shown that adding a balun to a motor cable is a very effective technique to prevent a drive from interfering with other equipment within a cabinet.

A motor cable balun is easily constructed by winding the hot wires of a motor cable a dozen turns or so through a large ferrite toroid. Figure 5 shows how to add a balun to a motor cable. Baluns are also available commercially from filter manufacturers. Tri-Mag has a line of baluns with terminals designed for insertion between drives and motors (Delta RF Reactors TPDR Series).

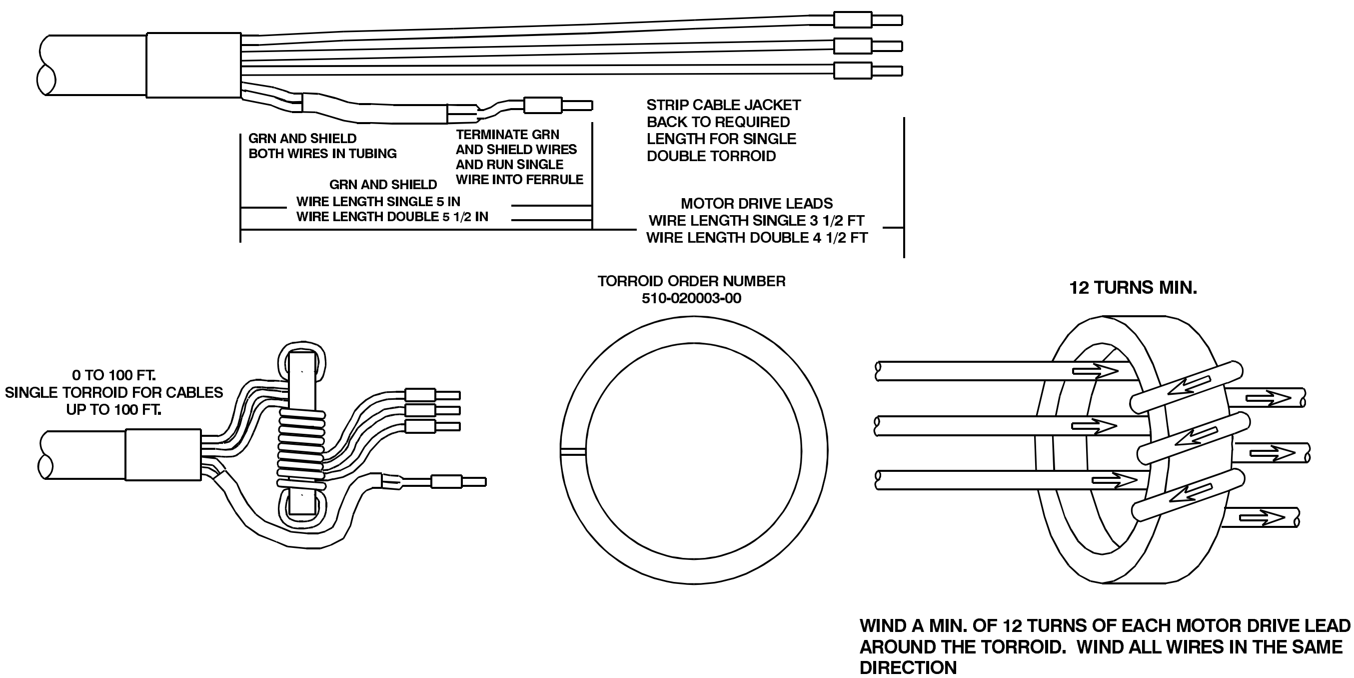


Figure 5 - Adding a Balun to the Motor Cable

A motor cable balun has no effect on motor performance because motor torque current is differential and produces no net flux change in the balun. A motor cable balun works by absorbing (and slowly releasing) the high frequency common mode energy from the inverter. This slows and reduces the amplitude of the current charging the cable capacitance and motor capacitance and so attenuates the noise conducted back to the power line.

Cores for Baluns

Cores for motor cables less than 20 ft are ungapped toroids. For motor cables more than 20 ft the core is a custom gapped toroid to avoid saturation.

Core	Size (Weight) in	Inductance (Energy) µh for 12 Turns	Maximum Cable Length
Magnetics Inc F-47313-TC	2.9 O D x .5 H (177 gms)	702 (680 µ)	20 ft
Magnetics Inc F-44932-TC	1.9 O D x 1.25 H(150 gms)	1,019 (576 µj)	20 ft
Pacific Scientific #510-020003-00	2.9 O D x .5 H (177 gms)	125 (3,600µj)	100 -150 ft

X and Y Rated Line Capacitors

An important consideration in the choice of capacitors is that they be rated for line operation. Capacitors to be used from the line to earth ground should be of the Y class. Capacitors to be used from the line to line should be of the X class. X and Y are European rating for line operation. Capacitors from the line to earth ground add to machine 'leakage current'. A generally accepted international threshold for leakage current is 3.5 mA. To stay below this threshold the capacitance on each phase of a 240 VAC line should be no more than 10 nf.

Y Type Capacitors for 250 VAC Line to Ground operation:

Sprague	440L family	440LD47	4.7 nf
		440LS10	10 nf

X Type Capacitors for Across the 250 VAC Line operation:

Panasonic	ECQ-UP series	ECQU2A105MP	1.0 µf

Optimum Configuration

The optimum configuration to reduce machine line noise is to have a balun in each motor cable and single line filter at the line input to the machine. Many Pacific Scientific drives have a motor cable balun built into the drive. With these drives, it is rarely necessary to add a motor cable balun external to the drive. For additional information about built-in baluns, please consult the factory.

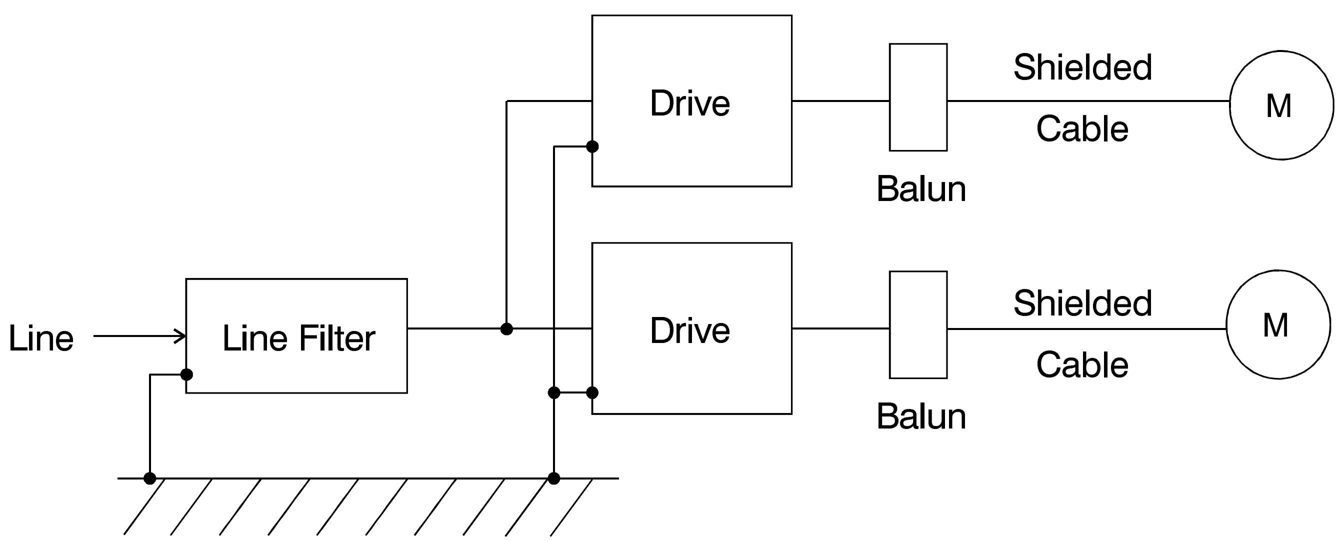


Figure 6 - Optimum Configuration for Reducing Line Noise

Modeling Drive Line Noise

PWM Modulation

During drive operation, PWM action causes motor winding-to-case capacitance and motor cable wire-to-shield capacitance to be charged and discharged the full bus voltage at each edge of the PWM carrier. Figure 7 illustrates how if the drive is unfiltered, capacitive load current can also flow in the line. Common mode motor and cable capacitive current is the dominant source of line noise.

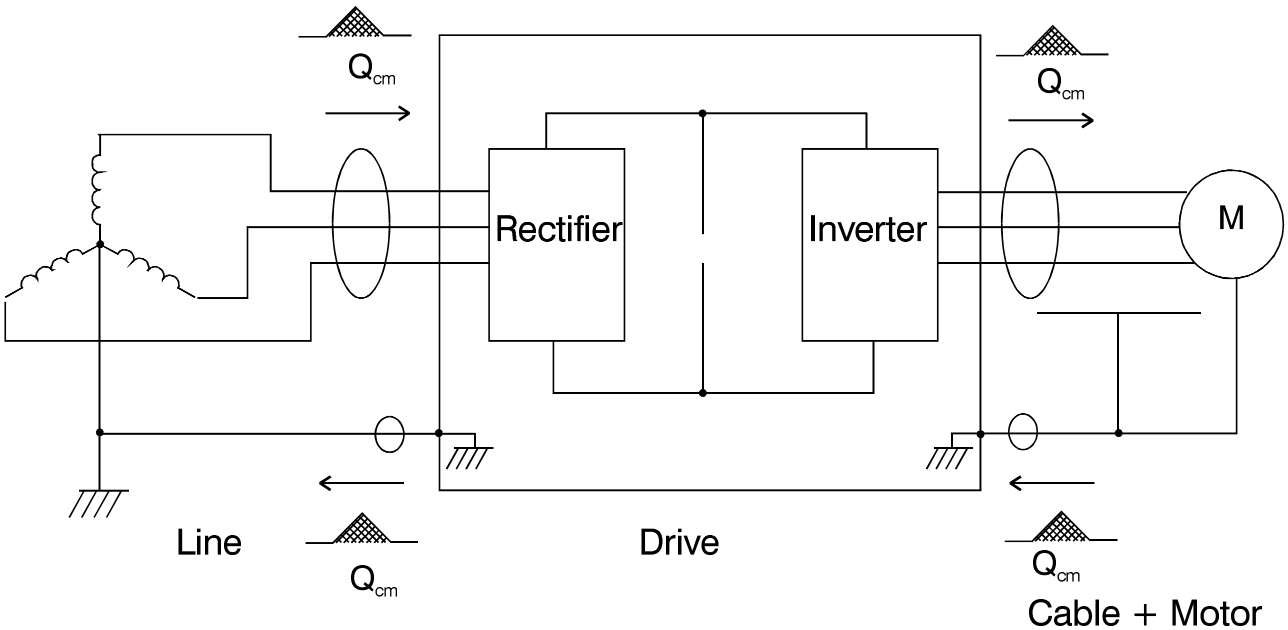


Figure 7

Modeling the CM Noise of a Drive

From a common mode (CM) viewpoint, the inverter can be modeled as a squarewave generator, switching at the PWM frequency, with an amplitude of the bus voltage as shown in Figure 8. The PWM generator drives the line through a high pass filter, where C is the sum of the motor winding-to-case and cable wire-to-shield capacitance, and parallel RL is the model of the line impedance.

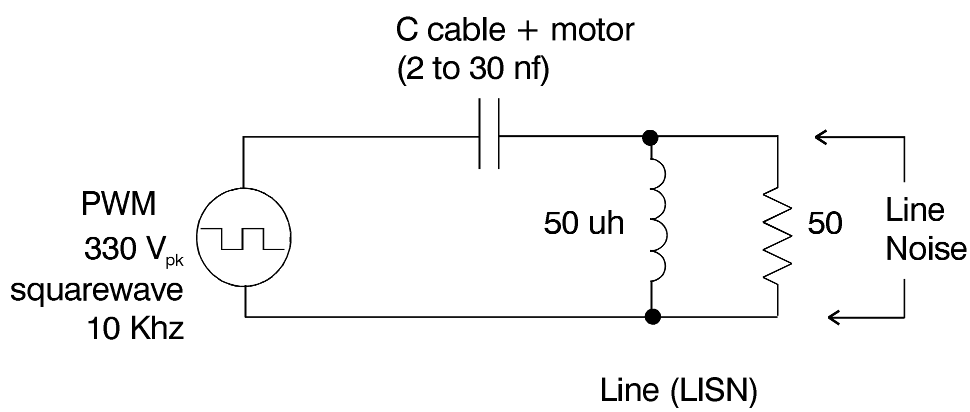


Figure 8 - Common Mode Circuit Model

Cable and Motor Capacitance

Most Pacific Scientific motors (up to 4 inch) have a winding capacitance of 1 to 2 nf. Our standard #18 AWG cable, when measured (R+S+T) to (Gnd+shield) has .0225 nf/ft, so when cables are longer than 10 ft the cable capacitance dominates over the motor capacitance.

A 20 ft, #18AWG shielded motor cable typically has 4.5 nf [at 0.225 pf/ft (R +S+T) to (Gnd+Shield)]. A R43 motor has 1.8 nf winding to case. The resulting high pass time constant is 0.32 µs. Thus, an unfiltered drive can couple a pulse onto the line that has a half period about of 1 µs with an amplitude (in the limit) of 330 V peak and a current of about 6 amps.

Test Cycle

Drive line noise varies little with torque or rotation. Thus a simple machine cycle for regulatory testing is the motors powered and holding position. The spectrums in this paper were taken with the motor running at a constant 500 rpm with no shaft load.

Magnetics Saturation

It is important not to use too small a core for a balun, because the CM currents can saturate it. Magnetics saturation is generally not a concern for shielded motor cables up to 20 feet if a large ferrite balun core is used (2 to 3 in OD). For shielded motor cables longer than 20 ft CM capacitive current may get high enough to saturate either an ungapped motor cable balun, or the load side balun inside a commercial filter. If the magnetics saturates, the filter performance will be severely compromised.

Analysis shows that the criteria to avoid saturation is that the energy storage of the magnetics supporting the CM volt-time must exceed the capacitive energy storage in the cable and motor capacitance.

Guidelines to Avoid Saturation

The following guidelines are given for cable balun cores to avoid saturation:

- For shielded cables up to 20 ft, an ungapped ferrite toroid weighing more than 150 gms with moderate to lower mu is recommended. Such a toroid will have an OD of 2 in or more and 0.5 in or more in height. When wound into a motor cable, it can provide about 1 mh of CM inductance.
- For shielded cables of more than 20 ft, a gapped ferrite toroid is recommended. Pacific Scientific has available a custom gapped 2.9 in OD toroid for motor cable baluns. When wound into a motor cable, it can provide about 125 µh of CM inductance. For shielded cables longer than 100 ft, use two gapped toroids wound separately into the cable.

The baluns inside the recommended commercial filters should handle cables up to 20 ft without saturation. For cables longer than 20 ft it may be necessary to reduce the volt-time seen by the load side inductor inside the filter.

Adding a motor cable balun is always a good idea because it cuts down noise at the source, reduces line noise within a cabinet, and reduces the likelihood of magnetics saturation within a commercial line filter, because it supports some of the inverter CM volt-time. Adding LN capacitors at the filter load side (or drive line inputs) further reduces the likelihood of saturation within the filter.

Details of the Line Noise Tests

The line noise spectrums in this application note were obtained with the following equipment:

LISN

CE type Line Impedance Stabilization Network built by Danaher Motion. The LISN lowers high frequency line impedance using a Y of large film capacitors and then inserts in each leg (including N) a known impedance consisting of a 50µh inductor in parallel with a 50 ohm resistor. High pass filters within the LISN couple the voltage across the known impedances to a spectrum analyzer.

Spectrum Analyzer

Tektronix TDS 420A operating in FFT real time mode. Scope setup: 10,000 points in FFT, Black Harris windowing, HiRes mode, and infinite persistence. It took 1 to 3 minutes to get a clean display.

Drive, Motor, Cable

R43G motor running at a constant 500 rpm connect to a SC902 servo drive with a standard Danaher Motion #18 AWG shielded cable of length 20 ft. This cable has a capacitance (three hot wires to gnd/shield) of 4.5 nf. The SC902 drive has no internal line filtering and does not contain a balun for LN fault protection.

Baseline noise (see Figure 9) of this setup was close to CE levels. This setup is useful for design and filter evaluation, but is not quite good enough for a true CE pass/fail test. Danaher Motion has done line noise testing at an approved CE test house on selected filter configurations.

Picture scale

Scale on all pictures in the application note is the same:

Vertical: 10 dbV/cm

Horizontal: 125 kHz/cm

Lower cursor: -47.4 dbV (+72.6 dbµV)

The pictures show the spectrum from 0 Hz to about 1.2 MHz. The lower cursor, which is just above the baseline noise, approximately indicates the CE emission levels, EN55014, Class A (industrial equipment), 150 kHz to 500 kHz. These levels are +79 dbµV (quasi-peak) and +66 dbµV (average).

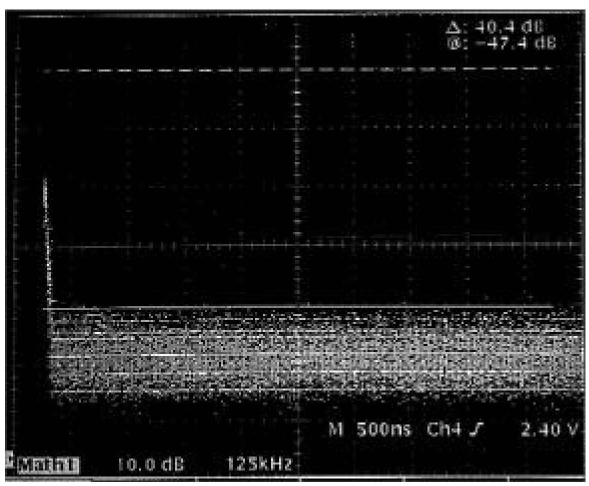


Figure 9 - Baseline Noise - Drive not connected

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