Selection Criteria for Facility-Type EMI/EMC Filters

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BACKGROUND

EMI/EMC filters are used to attenuate EMI noise in a variety of applications, including shielded enclosures, anechoic chambers, computer racks, MRI enclosures, and as part of a manufacturer's OEM equipment. These filters are passive devices whose role in the overall effectiveness of the system is frequently overlooked. Often, it is only when a system is powered up, or a fire alarm goes off in error, for example, that the filter is identified as a critical component of the total EMI/EMC system. What happens in these scenarios? Usually, after much "hair pulling," the problem is determined to be the result of the incorrect filter being selected for the application. This article will present the most important criteria for filter selection for a given application.

Proper attention to filter selection can save the designer time and money.

A brief review of basic filter theory will provide a better understanding of the relative complexity of these innocuous devices. A filter, being reactive in nature, must either pass energy through itself or reflect energy back to the source. Passive low-pass filters are generally manufactured using three basic elements: inductors, capacitors, and resistors (Figure 1). Inductors (L) create high series impedance for high frequency signals while capacitors (C) shunt high frequencies to ground. This creates the voltage drop termed insertion loss. At a given frequency, the insertion loss of a filter connected into a given transmission system is defined as the ratio of voltages appearing across the line immediately beyond the point of insertion, before and after insertion. Most industry specifications reference MIL-STD-220A for the description of the test setup used to measure insertion loss (Figure 2).

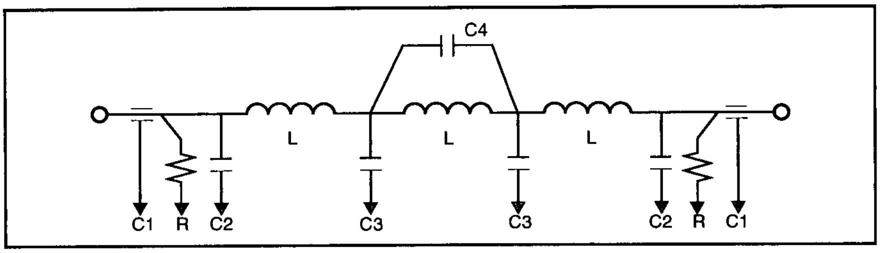

Figure 1. *Filter Schematic.*

$$\text{Insertion loss} = 20 \log \frac{E_1}{E_2}$$

where
E_1 = Output voltage appearing across the load with the component in the circuit and
E_2 = Output voltage appearing across the load without the component in the circuit

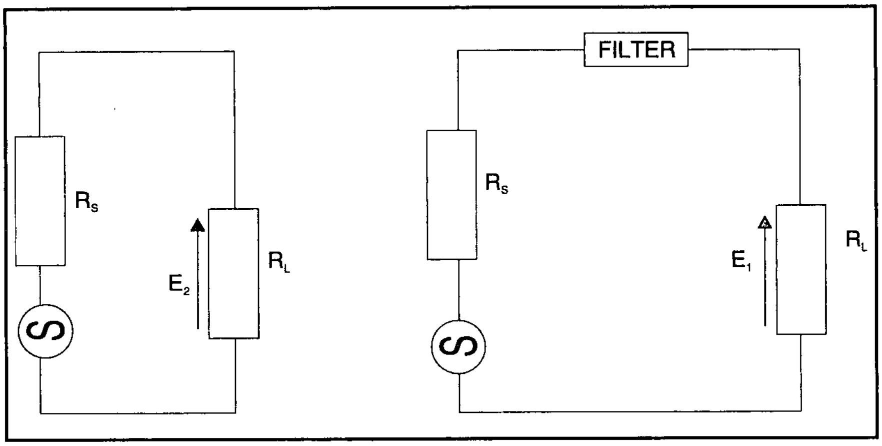

Figure 2. *Insertion Loss.*

Bleeder resistors (R) allow energy stored in the capacitors to discharge when power to the filter is removed. This is a safety feature mandated by UL, the National Electrical Code, and many other specifications for facility-type power-line filters.

Quality power-line filters utilize stable inductors (linear through their operating range) and overrated capacitors for longer life expectancy. Worst case total harmonic distortion should be low, such as 0.5% at full-rated load current. The in-

*See Advertisement on Page 3.

sertion loss level should be unaffected by load current over the entire range from zero to full-rated load current.

Given this basic understanding of EMI/EMC filter design, the selection criteria for power-line filters and for signal, data and control-line filters can be reviewed. Each filter type has its own distinct selection criteria. This is often overlooked when selecting signal, data, and control-line filters especially. Non-technical personnel, such as facility managers, often are tasked with selecting filters, and this can add to the difficulties.

POWER-LINE FILTER SELECTION CRITERIA

Power-line filters are specified most commonly for electrical power distribution and lighting, test equipment, etc., i.e., applications where high current (above 5 A) is required. When selecting a power-line filter, the following performance characteristics should be considered:

- Current rating
- Voltage (line-to-line, line-to-ground)
- Operating frequency (dc, 50/60 Hz, 400 Hz)
- Insertion loss, stopband*
- Configuration (single or multi-circuit)
- Power factor correction inductors (for 400-Hz filters only)
- Type of system (3- or single-phase, wye, delta)
- Temperature rise
- Voltage drop
- Operating temperature range
- Harmonic distortion
- Maximum size and weight

POWER-LINE FILTER PERFORMANCE CHARACTERISTICS

INSERTION LOSS

When specifying the insertion loss, the level that is really needed in the impedance of the system must be considered. Typically, the insertion loss specification has the greatest cost and size impact on the filter design. Over-specifying insertion loss can result in an unnecessarily large and expensive filter. For example, a 150 kHz filter at 100 dB costs 20 to 30% less than a 14 kHz filter at 100 dB.

VOLTAGE DROP

Voltage drop is usually specified for a load with a unity power factor. Variations in the level of the

*The interference in electrical systems may appear in two modes, known as common (or asymmetric) and differential (symmetric) (Figure 3). If the noise appears between the lines, it is termed differential-mode interference. Noise appearing between a line and ground is termed common mode interference, meaning that the interference (or noise) is identical on both lines. The construction and application of facility-type power-line filters typically yields equal effectiveness for both interference modes.

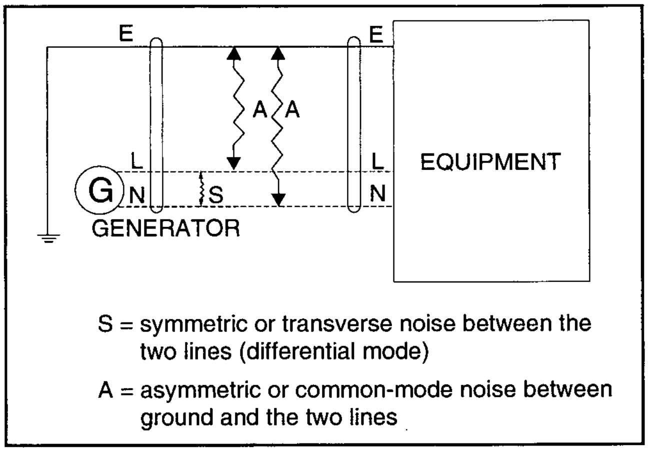

Figure 3. *Interference in Two-line Systems.*

load and the type of load associated will cause the voltage drop to increase or decrease. Largely inductive loads, for example, result in a larger voltage drop than that measured for a unity power factor. This is typically a concern for power filters used with electrical motors, such as those in air conditioning systems, and for power supplies. No-load or light-load conditions can lead to a voltage rise. This is most apparent in higher power frequency applications, such as 400 Hz.

INDUCTIVE INPUT DESIGN

Rather than the common capacitive input design, an inductive input design may be warranted for EMP applications or other instances where occasional high power surges may be expected. The first inductor in an inductive input filter helps dissipate the energy from a power surge, thereby protecting the filter capacitors from potential damage. Surge arrestors, or MOVS, can also supplement the surge protection provided by inductive input filters.

CAPACITANCE

Inherent in high-performance filter designs are large values of line-to-case (ground/neutral) capacitance. Under no-load conditions, these filters will draw capacitive reactive current (commonly referred to in this context by the misnomer "leakage current") which is directly proportional to the capacitance values and the voltage and frequency of the source. If the level of reactive current is important in the application, this should be specified when selecting a filter. Leakage current is of concern especially with MRI applications.

POWER FACTOR CORRECTION INDUCTORS

When power-line filters are used in a 400-Hz application, reactive current may be of particular concern because of the higher power frequency. This will result in proportionally higher shunt current for the same capacitance values when compared to a 60-Hz application. The power source will see a load which is a combination of both the load current and the filter's capacitive reactive current. The net reactive current can be greatly reduced or eliminated by shunting the power-line filter capacitance with a suitable power factor correction inductor (Figure 4). Ideally, the inductive reactance should equal the capacitance reactance. However, under this condition the filter and inductor are in resonance at the power-line frequency and this must also be taken into consideration. Power factor correction inductors are commonly used on single-phase or 3-phase systems. The inductor is not typically required for the neutral line in a 3-phase, four-wire wye power system.

Another important consideration for 400-Hz applications is a voltage rise at the output terminal of the filter when a light- or no-load condition exists. This can be approximately a 10 to 20% voltage rise on a 400-Hz system with no load connected. Three pi filter circuits typically result in a lower voltage rise than two pi circuits for the same performance specification. Other methods may also be used to reduce this effect.

SIGNAL, DATA AND CONTROL-LINE FILTER SELECTION CRITERIA

Signal, data and control-line filters are specified most commonly for communications and security applications, i.e., where the current rating is typically less than 5 A. When selecting a signal, data or control-line filter, the following performance characteristics must be considered:

- Analog or digital signal
- Amperage, peak or switching
- Voltage (line-to-line, line-to-ground)
- Insertion loss, stopband*
- Configuration (single or multi circuit)
- Impedance (line-to-line, line-to-ground)
- Passband frequency range** (cut-off frequency***) or baud rate (on data-line filters primarily)
- Passband ripple and phase linearity
- ESR (equivalent series resistance)
- Maximum capacitance (line-to-ground/line-to-line)
- Maximum size
- Maximum weight

*The stopband of a filter is the frequency range for which the filter is intended to prevent noise or data transmission from passing through the system. A minimum level of attenuation or insertion loss desired is usually specified for the stopband.

**The passband of the low-pass filter is the frequency range from dc to the cut-off frequency. This is the frequency range for which a low-pass filter is intended to pass data.

***Cut-off frequency is the frequency at which the output power is attenuated by 50%. In other words, the signal is attenuated by 3 dB.

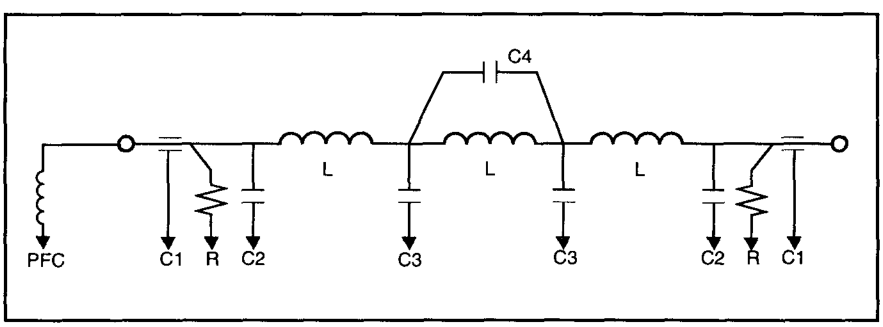

Figure 4. *400-Hz Schematic Diagram with Power Factor Correction Inductor.*

PERFORMANCE SPECIFICATIONS

The most important performance specifications for these types of filters are the passband impedance and the frequency range. These issues are important, as mismatching the filter and the application can result in various annoying and needless scenarios, including fire alarms going off unexpectedly, computers which cannot communicate outside the shielded environment, too high or too low temperatures within a shielded enclosure due to improperly operating thermostats, dysfunctional CCTVs, etc.

Passband impedance is specified in ohms and is represented by the Greek symbol Ω. The passband impedance is the characteristic impedance of the transmission line for which the filter is designed to be used. It should not be confused with the dc resistance of the line or the filter. It is critical that the filter passband impedance match the impedance of the system in which it is being used. An impedance mismatch will result in unwanted passband ripples and signal reflections that distort the original signal. Depending upon the system, this may or may not be a major problem. Some systems can tolerate minor amounts of distortion while others cannot. In an analog system (commonly voice), distortion of the signal may only result in inferior sound quality. In a digital system, however, distortion may prevent the signal from being properly interpreted by the receiving equipment. Phase non-linearity is also a minor cause of digital waveform distortion.

It is also necessary to know the nature of the signal, i.e., whether analog or digital, so that the proper filter may be selected. The necessary passband frequency range is generally specified by the cut-off frequency for an analog filter and by baud rate for a digital filter.

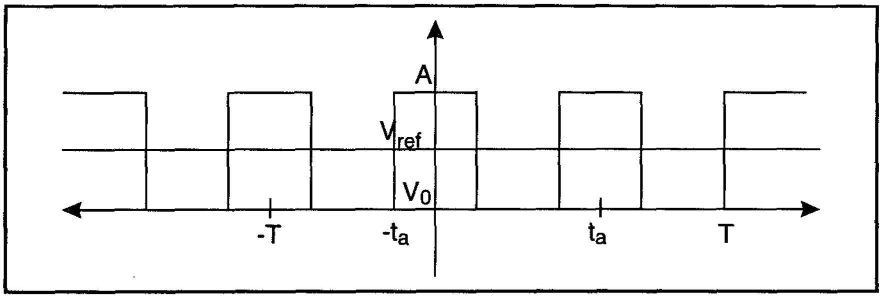

Figure 5. *Data Transmission Square Wave.*

While the signal frequency and passband frequency of the filter have a direct correlation, the passband must be calculated if the baud rate is specified. The frequency can usually be calculated from the following formula:

$$f = 2.5 \times bps$$

where
f = passband frequency
bps = baud rate (bits per second)

The frequency of the stopband should begin at no less than 3 x f to allow practical filter designs and sizes to be utilized.

The formula for f is derived using the Exponential Fourier Series Approximation to model the typical square wave being transmitted (Figure 5). For each half cycle of the square wave, the voltage switches from V_0 to A or vice versa and the voltage crosses V_{ref}. Each time the signal crosses V_{ref} represents one bit of data. Therefore, two bits of data can be transmitted for each cycle of the square wave.

The Fourier Series enables the effects of the filter on the signal to be understood by representing the square wave as an infinite sum of complex sinusoids given by:

$$f(t) = \sum_{n=-\infty}^{\infty} C_n e^{jn\omega_0 t}$$

Where:

$$C_n = \frac{A}{n\pi}\sin(n\omega_0 t_a) \quad \text{(for square wave)}$$

$$\omega_0 = \frac{2\pi}{T}$$

$n = 0, \pm1, \pm2, \pm3, \ldots, \pm\infty$
T is the period for one cycle
T_a is 1/2 of the pulse width
A is the peak-to-peak amplitude of the pulse

By inspection it is found that $C_n = 0$ for the square wave when n is an even number and C_0 equals the average value of the signal (dc component). Therefore, the original square wave can be modeled by the sum of a complex sinusoid with the same fundamental frequency of the square wave and an infinite number of its odd harmonics.

The quality of the representation of the square wave is dependent upon the range of the odd harmonics passed through the filter. As the primary concern is with the transition from V_0 to A and vice versa, passing the fundamental frequency and the first five harmoncs gives a fairly good representation of the original signal for this purpose. Since the baud rate is twice the fundamental frequency, 2.5 x baud rate will cover the frequency range required for the passband. However, if the actual shape and time delay of the square wave are critical, a wider passband may be needed.

Fire and smoke alarm systems, as well as many other systems which employ low level signals, can be very sensitive to line-to-line and/or line-to-ground capacitance and resistance. This is especially true for ground fault detectors. Attention should be paid to the capacitance levels of filters for these applications. It is also not uncommon for relay coils to be held energized by the capacitance in a filter. This happens when a low current device is powered by a floating (non-grounded) ac power source and the on-off control is routed through a two-line filter. One solution is to ground the non-switched power lead. The other solution is to use a very low capacitance filter.

It should also be noted that most signal and control line filters do not contain bleeder resistors. The presence of such resistors can lead to the erratic operation of some low-current systems. The absence of bleeder resistors is not a safety concern with these filters, however, as it is with power-line filters, since signal and control-line filters are typically used only on low voltage applications.

Unfortunately, the performance information discussed above is often difficult to obtain from the equipment manufacturer. For example, if the signal is digital and the application is a security alarm, alarm manufacturers are reluctant to divulge performance information about their product as they consider this proprietary. Thus, it can be "hit or miss" when selecting the filter to use with their system. To avoid this situation, filter manufacturers should supply complete performance information on possible filters to the equipment manufacturer directly, so they will feel more comfortable selecting the correct filter from the list supplied. This is an ideal situation which encourages confidence that the correct filter was selected for the actual application.

One last comment on facility-type filters should be made: users should be aware that the misapplication of filters may be a potential problem. For example, a top-of-the-line high performance filter with an insertion loss of 100 dB at 14 kHz to 10 GHz should not be installed on a bottom-of-the-line enclosure with inferior or no shielding effectiveness. Interference can

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bypass the filter if there are alternate paths, which often occur with a "leaky" enclosure. In other words, in this case the filter alone will not be the solution to an interference problem.

SUMMARY

It is a good idea to remember the following steps when considering EMI/EMC facility-type filter requirements:

- Define the applicable specification for the filter
- Ensure technical compatibility with the system
- Allow sufficient lead time for manufacture of the filter

By following the above steps and properly selecting the filter for any given application, costly delays can be avoided when the system is ready to be initiated.

ACKNOWLEDGMENT

The authors wish to acknowledge and thank fellow Lindgren engineers Mike Leone and Dale Svetanoff, Steve Jensen of Steve Jensen Consultants, Inc., Don Weber of ElectroMagnetic Engineering Technology, Dr. Marty Gazourian of Florida Atlantic University, and Ray Adams of TRW for their contributions to this article.

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