Specifying an EMI Filter: A Foolproof Checklist

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INTRODUCTION

Electromagnetic interference (EMI) filters are very important elements of nearly all electrical/electronic products. Their proper selection and installation into the end-product ensure timely compliance with mandatory regulatory standards. EMI filter misapplication, incorrect installation, and incorrect selection not only result in frustration, but result in equipment re-design, late product shipments, and unhappy stakeholders.

EMI filters work by subduing undesirable radio frequency (RF) energy in two very elementary ways: they either form a low-impedance path for RF currents to return to the local source of energy, and/or they provide a high-impedance path to prevent RF currents from flowing on a cable, printed circuit board (PCB) trace or some other type of noisy wire, signal trace or circuit element. Their importance to robust product design and development cannot be emphasized enough.

Regulations across the globe specify how much RF energy products can emit via radiated and conducted emissions standards, and in some regions, how much RF energy they must tolerate without upset, damage or malfunction via radiated and conducted immunity (commercial) or susceptibility (military) standards.

Regulatory electromagnetic compatibility (EMC) tests, which confirm that products will operate smoothly without EMC issues or damage, are typically performed at the end of the product development cycle, usually because complete and production-intent final versions of the product are not available until near the end of the development cycle. This is an unfortunate situation for many when they find that the EMI filter they had painstakingly specified does not adequately suppress RF energy as expected, the product is non-compliant to mandatory EMC standards, and it's not legal to ship it. It is much better to correctly determine the filtering requirements at the beginning of the development cycle for each unique product design and to correctly match filter characteristics to meet EMI requirements at this time. Filter redesign options at late stages of the product development process are much fewer than what is available early on in the product development cycle.

The intent of this paper is to address the critical factors to consider when specifying an EMI filter, so they are designed and implemented correctly from the start. It will show that EMI filter design is not guesswork, and that if EMI filter design is done correctly, production release will occur on-time, on-budget, and on-schedule.

Note: This article will not cover poles and zeros, nor anything at that level of detail. It will describe the most important factors that must be taken into account so that EMI filters designed using textbooks or circuit simulators, or chosen from catalogs, have the greatest chances of performing as required.

FILTER APPLICATIONS

In general, EMI filters used for EMC compliance are usually configured as passive low-pass filters. Conceptually, these types of filters are easy to understand. A low-pass filter is one in which the frequencies below a certain significant frequency are let through easily (also known as passband frequencies), and those above this frequency are heavily attenuated (also known as stopband frequencies). These low-pass devices are used in applications such as the front end of power supplies, AC-DC converters, DC-DC converters, variable-frequency drives, and similar types of fast-switching, RF noisy types of devices.

Filters are also used in high-speed applications where they are required to slow down clock edges and in the filtering of reset lines of microprocessors to prevent false resets caused by transient EMI events. They are often used for filtering in communication and data lines, as well as for transient voltage and surge protection for products which must pass electrical fast transient, electrostatic discharge, surge immunity, and other similar types of EMC compliance tests.

They can be purchased as off-the-shelf items packed in metal boxes or built from discrete components and installed directly onto PCBs.

Their incorrect use and installation can make a product's EMC emissions or immunity worse than if they had not been used at all.

HOW EMI FILTERS WORK

As noted above, EMI filters perform their intended function by either blocking or diverting unwanted signals, or a combination of both. Blocking is performed by high series impedance (Z) using resistors, inductors, or ferrites. Diverting is performed by low shunt impedance (Z) using capacitors.

The simplest filters are single-element filters, such as a capacitor placed in shunt across the circuit to be filtered or an inductor placed in the circuit in series. These simple one-element filters provide filtering at a rate of 6 dB/octave or 20 dB/decade. If this amount of filtering is not adequate, including more passive elements in the filter design will result in higher rates of attenuation.

FILTER TYPES

There are three basic types or "shapes" of EMI filters, named for how they look schematically. These are the L, T, and π-type filters.

L-type filter: The most basic type of low-pass filter type is the inverted L-type filter where the series element is comprised of either a resistor (R), inductor (L), or ferrite (F), and the shunt element is a capacitor (C). Because this filter includes two elements, it provides filtering at a rate of 12 dB/octave or 40 dB/decade.

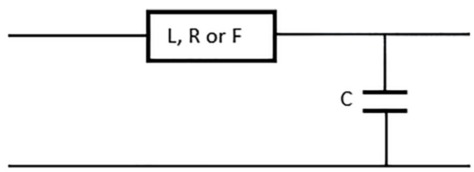


Figure 1 – L Filter

T-type filter: This type of filter has in-circuit series elements comprised of a resistor (R), inductor (L), or ferrite (F) that is installed on the filtered line, and a capacitor (C) installed line to return. Additionally, there is another in-circuit series element comprised of either a resistor (R), inductor (L), or ferrite (F), installed on the other side of the filtered line. Because this filter includes three separate elements, it provides filtering at a rate of 18 dB/octave or 60 dB/decade.

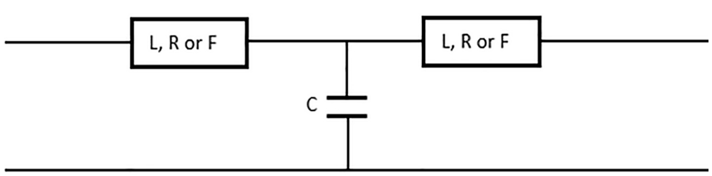


Figure 2 – T Filter

π-type filter: Named for the Greek letter π (pi), this filter has a capacitor from the filtered line to the return, an in-circuit series element comprised of either a resistor (R), inductor (L) or ferrite (F), and an additional capacitor (C) placed on the filtered line to return. Because this filter includes three separate elements, it provides filtering at a rate of 18 dB/octave or 60 dB/decade.

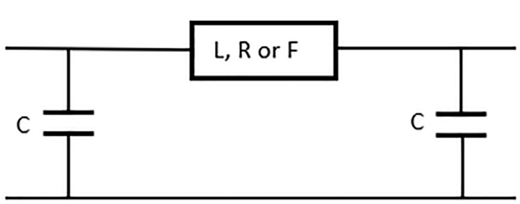


Figure 3 – π Filter

INSERTION LOSS

EMI filters purchased off-the-shelf as complete packages are specified by their insertion loss (IL) or attenuation, usually expressed in dB. In the recent past, these types of filters have been tested and specified in accordance with MIL-STD-220. IL is the magnitude of the attenuation provided to the circuit expected due to the addition of the filter, characterized with attenuation versus frequency curves.

A major issue associated with the MIL-STD test method is that an EMI filter's ability to attenuate unwanted noise is not controlled like it is in the test method. It is highly dependent on both the source and load impedances presented to it by the actual circuit/device its installed in. The measuring instruments, source and load impedances, input attenuator, and other components of the MIL-STD-220 test method are specified as having ideal 50Ω characteristic impedances, a rare occurrence in a real-life circuit. Real circuits usually do not contain ideal 50Ω source or load impedances, so an EMI filter's actual in-circuit performance could be much worse (or better) than specified in its datasheet.

Also, the input attenuator used in the test method has a series impedance that can dampen out any resonances when the filter tested. This input attenuator is not present in the end-product, further leading to inadequate filter performance when installed in the end-product. Figure 4 is an example of typical low-pass filter response curve.

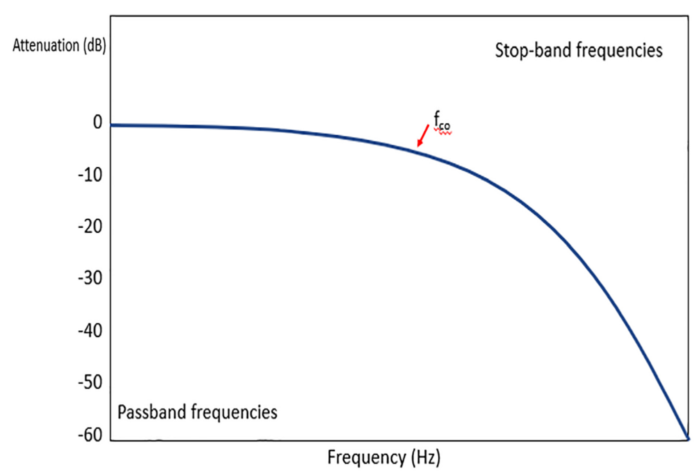
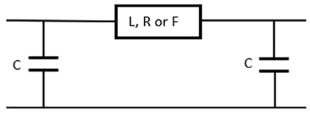
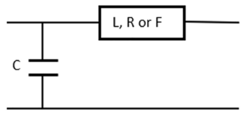
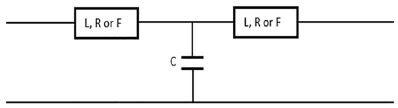
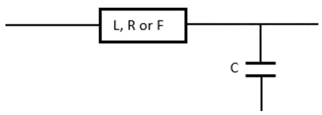


Figure 4 – Filter Response

IMPEDANCE MISMATCHING

The actual source and load impedances of the circuit to be filtered must be carefully considered in selecting the proper EMI filter configuration (L, π, or T). The reason for this is because in order to perform their function correctly, the passive components comprising EMI filters must see impedance mismatches to successfully provide the necessary attenuation.

Source Z	Filter Configuration	Load Z	Analysis
High (>100Ω)		High (>100Ω)	Use shunt capacitive element or π filter for greater roll-off.
High (>100Ω)		Low (<100Ω)	Shunt element faces High Z source and series element faces the Low Z load.
Low (<100Ω)		Low (<100Ω)	Use inductive series element or T filter for greater roll-off.
Low (<100Ω)		High (>100Ω)	Shunt element faces High Z load and series element faces the Low Z source.

If installing a low-pass filter into a circuit does not result in the suppression of unwanted emissions as expected, check that an impedance mismatch exists. A high-impedance series component should face a low-impedance (i.e. capacitor) and vice versa. Not always but overall, impedances of less than 100Ω are considered low Z and impedances greater than about 100Ω are considered high Z.

The MIL-STD test method utilizes 50W source and load termination impedances that do not represent actual circuit source and load impedances and the attenuation curves cannot be relied upon to predict actual filter performance once installed in the end product.

For a more accurate prediction, the CISPR 17 method can be used. Rather than the 50Ω impedance setup, CISPR 17's alternative system uses 0.1Ω and 100Ω impedances.

As defined by the CISPR 17 standard, EMI filters must be tested in impedance systems with 0.1Ω/100Ω terminating impedances, and vice versa. When checked against the measurements of real EMI filters, this CISPR 17 method results in attenuation curves that correspond greatly to the real filter performance, with maximal differences more or less in the range 2 dB.

DIFFERENT TYPES OF NOISE

The attenuation provided by EMI filters depends on the type of noise it's intended to suppress. There are two different types of noise. The first is called differential-mode (DM) noise. The second is called common-mode (CM) noise.

DM noise is associated with the actual intended signals of the circuit, where one line is the outgoing signal and the other line is the incoming or return signal. These types of signals are out of phase and provide useful information. The prediction of DM mode currents is well documented and easy to determine in advance of having actual prototype test samples available for test. DM filtering involves suppression of DM noise by placing capacitors across the outgoing and return lines and/or placing an inductor in series with either outgoing or return lines. Be careful because an EMI filter's attenuation specification may only refer to its capability to suppress DM noise. If this is the case and installing a DM filter does not solve the noise problem, then the source of emissions is most likely CM noise.

CM noise is unintended, in-phase signals that do not tend to cancel but add up, creating a mountain of work for professional EMC engineers. CM noise current flows equally on all lines, including the ground path. CM noise results from stray capacitances and unintended current paths around a particular circuit. CM noise coupling paths are not identified on any schematic but include line-to-ground paths. The prediction of CM mode currents is not well documented and not easy to determine in advance of having actual prototype test samples available for test. Determination of CM currents is best accomplished by measuring working test samples.

An EMI filter specified to provide CM noise suppression should include capacitors placed across each signal line to ground reference. An additional CM choke placed in the normal outgoing and returns lines of the circuit will also help suppression unwanted CM noise in these paths but will not suppress any intentional DM signals.

NON-IDEAL COMPONENT BEHAVIOR

The non-ideal behavior of passive filter elements is often overlooked by product designed. As frequencies increase, parasitic elements of components detrimentally impact their ability to function as intended. At a certain resonant frequency, the stray inductance in the leads of a capacitor will cause it to stop

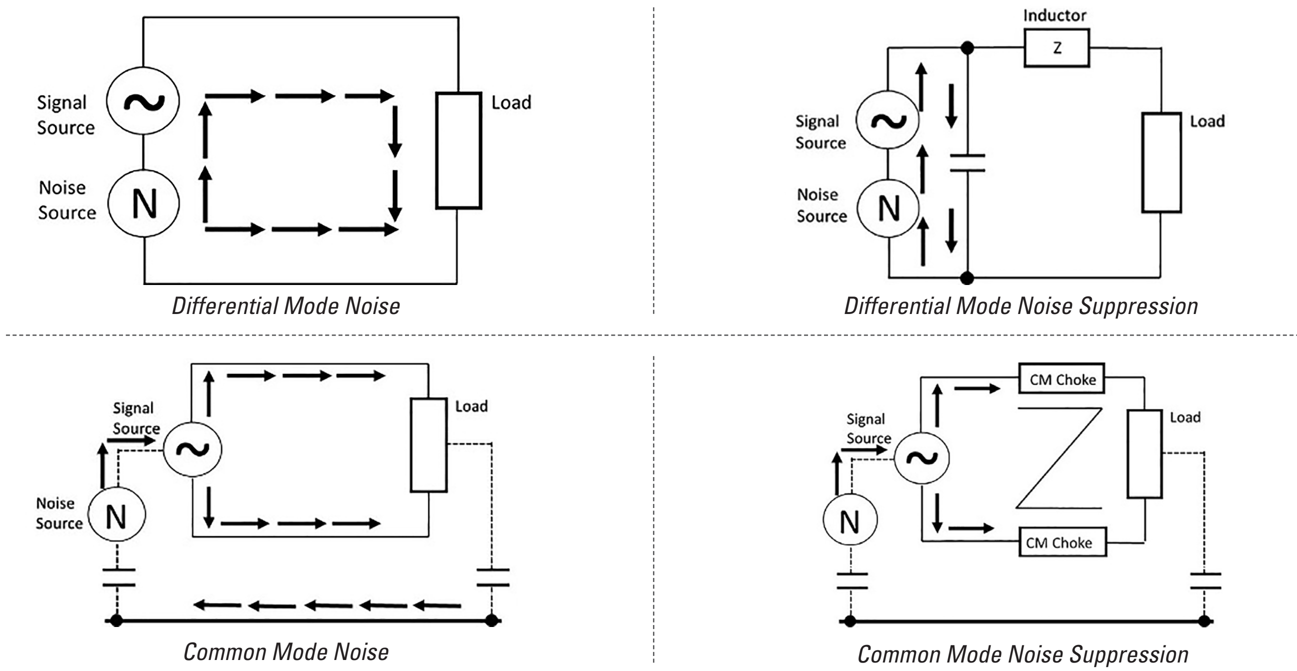


Figure 5 – Types of Noise and Suppression Techniques

performing as capacitor and start behaving like and inductor. The same problem is encountered with inductors. At a certain resonant frequency, the stray inter-winding capacitance between the turns of wire in an inductor will cause it to stop performing as an inductor and start behaving as a capacitor.

These non-ideal behaviors of components will greatly impact the performance of the EMI filter. An EMI filter affected by parasitics will not suppress unwanted emissions as intended but may even amplify them. This somewhat mysterious non-ideal behavior of components is another reason why EMI filter design is considered a "dark art."

OTHER IMPORTANT EMI FILTER DESIGN CONSIDERATIONS

Cut-off Frequency: The cutoff frequency (f_{co}) of an EMI filter occurs at resonance, where the capacitive reactance (X_c) equals the resistance (R) or inductive reactance (X_L) – Note: To calculate f_{co} with X_C, use R if a series resistor is used as a filter element, or X_L if an inductor is used as a filter element where:

$$X_C = 1/2\pi f C$$

$$X_L = 2\pi f L$$

$$f_{co} = \frac{1}{2\pi\sqrt{LC}}$$

Adding a filter's impedance to a circuit should not create a signal integrity problem by attenuating wanted signals. Avoid any issues from occurring by maintaining at least the 5th harmonic of the intended signal in the passband. Maintaining at least the 10th harmonic in the passband is ideal.

Layout and Placement: Proper layout and placement is critical in EMI filter design. Unnecessarily long trace lengths add extra parasitic inductance and impedance which compromise the effectiveness of the filter as described above. To avoid this problem, keep connections short and place filter components close to the filtered circuit.

Don't neglect length of the return trace or rely on ground as being the ultimate zero-ohm impedance path and sink for noise. It is far better to understand the path of current flow and to keep loop areas small, in addition to maintaining a low Z ground connection.

Be intentional with filter trace or wire routing paths to avoid creating too much capacitive and inductive coupling (crosstalk) to other nearby noisy signal or traces. To prevent crosstalk from occurring, place filter components right at the entry connector of input/output (I/O) and power inputs. An EMI filter placed a considerable distance from the entry point gives the noise currents a greater chance of circumventing around the filter.

Remember to mount the filter as close to the noise source as possible and make sure the surface is a conductive, paint free surface. To ensure safety and EMC, always properly ground the filter.

Use of Ferrites: Some circuits cannot tolerate too much of a voltage drop across a series resistance to function properly. In these instances, a device such as a ferrite must be used instead of a resistor. A ferrite acts as a high-frequency resistor with minimal voltage drop. Because the ferrite presents the circuit with high AC impedance while not affecting signal quality, ferrites are most optimal for filtering at frequencies greater than about 30 MHz. One downside to the use of ferrites is that they easily saturate, and too much DC or low-frequency current present in the circuit renders them ineffective. Ferrites are often used as CM chokes for cables where they provide about 10-dB of noise suppression.

Current/Power Handling Capability: If building an EMI filter from discrete passive components, first verify the current and power handling capability of the components selected. Filter components must be able to withstand worst case expected operating environment. Proper derating is advised.

If specifying an off-the-shelf EMI filter, note that MIL-STD-220 doesn't require current to flow in the filter during testing. The value of inductance in the filter may be different if DC current is flowing. Just like a ferrite, a choke can saturate when used outside of its specified current range, leaving it unable to supply its intended impedance.

Use of Shields: Shielding of filter components can alleviate many of the crosstalk problems addressed previously, including the elimination of the coupling of noise from sources like switching power supplies or fast rise-time digital logic circuits. If mounting filter components on a PCB, include provisions for installation of an EMI shield over the filter components in the preliminary design. The mounting provisions can be removed in the final design if they are deemed not required to pass EMC compliance testing.

A common problem that occurs is when I/O power lines to the filter are run too close together. Unwanted crosstalk between these lines reduces the filter's attenuation capabilities considerably. These problems are mitigated in power line filters by shielding and mounting them on the equipment enclosure wall, with the input power connector mounted to the filter enclosure. Keeping I/O connections to the filter separated far apart from one another also helps alleviate this problem. The I/O connections can be actual wires or traces located on a PCB.

Filter Testing & Troubleshooting: Because of the many issues involved in EMI filter design (identified previously in this article), it's a good idea to include enough time early in the project plan to perform some iterative testing and EMI filter debugging using actual hardware. The initial hardware should allow some flexibility so that different filter topologies can be tested should the initial EMI filter design not perform as expected.

A perfect filter testing situation is one that does not necessarily follow the standard MIL-STD-220 method. To be effective, it is one tailored for the specific EMI test supply impedance and utilizes the actual circuit (i.e. switching power supply planned for the product, etc.), operated at the expected current draw. A filter's insertion loss or attenuation characteristics should also be established at no load and full load current levels to provide the best results and information to filter designers.

SUMMARY

There are three basic filters types used for EMI filter topologies. These types are the L, T, and π-type filters based on their layout shapes. Filters purchased off-the-shelf do not perform as specified in their datasheets. This is because this information is based on an ideal test configuration, that is not often present when the filter is installed in real circuits. The issues encountered when specifying or designing an EMI filter can also be avoided by proper section of its cut-off frequency, careful layout and placement, use of ferrites when appropriate, choosing components with the proper current handling capability, using shields when needed, and thoughtful filter test planning and debugging.

See the follow-up article to this one, titled "How an EMI Filter Affects Your Product's Performance," which addresses additional issues concerning temperature effects, overload, distortion, harmonics and safety.

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