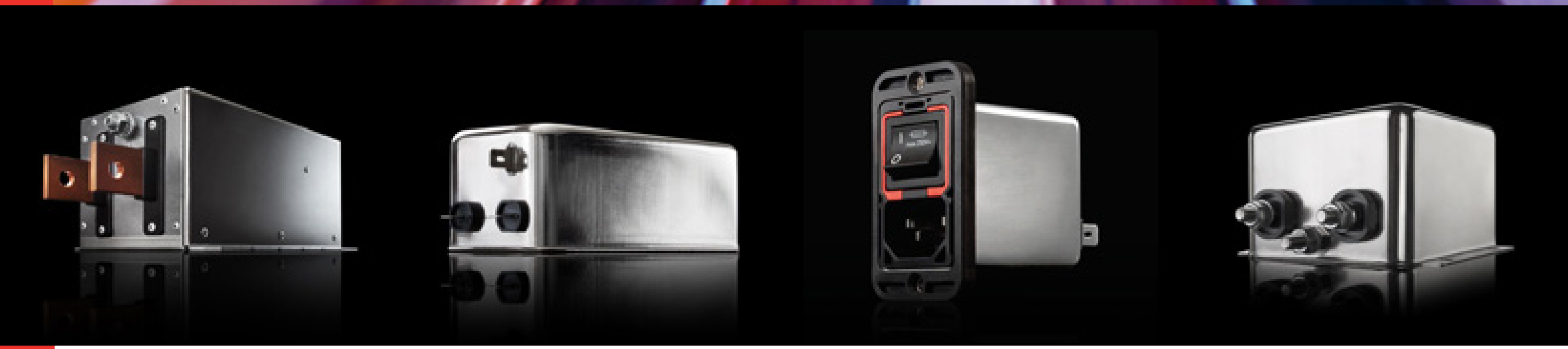


A Design Process in Selecting an AC Powerline Filter

www.schaffnerusa.com

schaffner
shaping electrical power

TABLE OF CONTENTS

INTRODUCTION

Generally, when the designer "designs" an AC line filter, they select a capacitor or inductor that has proven successful on a past project, then modify the value or values to achieve the desired loss. Some designers will just grab a core and start winding to make an inductor or others will spend days with a network analyzer measuring source and load impedances! The result can be a rather time-consuming process. This article attempts to provide a quick and easy process, but still produce an effective filter design.

Why Do We Need EMI Filters?

One reason is that regulatory agency requirements dictate that conducted and radiated emissions be constrained below specified limits, but the unit must also pass immunity/transient requirements. Designers often forget that an EMI filter can assist in meeting immunity and fast transient requirements and radiated emissions as well. Essentially, an AC power or mains EMI filter is a low pass filter that blocks the flow of "noise" while passing the desired input which can be DC or 50/60/400 Hertz power frequency. An ideal EMI filter will reduce the amplitude of all frequency signals greater than the filter cut-off frequency. The cut-off frequency is the frequency between the signal's passband and the reject bands at 3 dB attenuation below the acceptance line. The measure of a filter's ability to reduce a given signal level is insertion loss or attenuation. A power line or mains EMI filter is placed at the power entry point of the equipment that it is being installed into to prevent noise from exiting or entering the equipment and be "transparent" to the AC power line.

SERIES VS. SHUNT ATTENUATION

An EMI filter is made up of two basic types of components–capacitors and inductors. Generally, to reduce noise currents, we want to place a high impedance between the source and load (i.e. series attenuation) or a low impedance in parallel between the source and load to divert the noise current to a return conductor (i.e. shunt attenuation).

SOURCE VS. LOAD IMPEDANCE MISMATCH MATRIX

There is a simple "rule of thumb" approach that can be used to assist the engineer in selecting which filter component(s) to use. The first filter element nearest the source of the noise should be selected to provide the highest possible mismatch at EMI frequencies. Typically, this means that if the source or load impedance is low (<100 Ohms), then the first filter element should be an inductive component. Conversely, if the source or load impedance is high (>100 Ohms), the first filter element should be capacitive. This provides the designer an extremely efficient design with the least number of stages or components. Refer to *Figure 1* as a quick, handy guide.

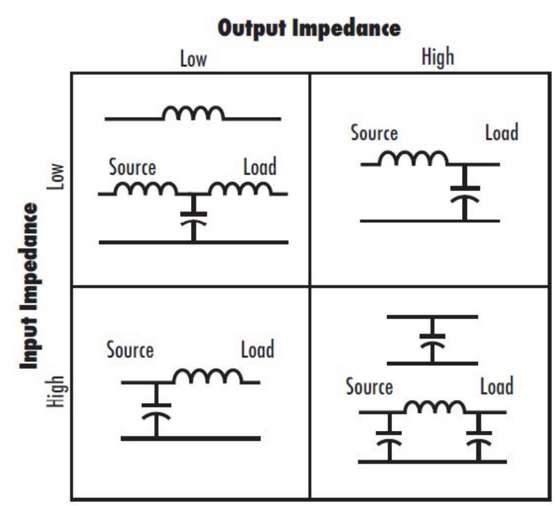


Figure 1. Handy Reference Chart for Impedance Mismatch

ESTIMATING SOURCE AND LOAD IMPEDANCES

The actual real-life impedance of the mains power lines can and will vary quite a bit. This, of course, will lead to a variation in the filter's performance. However, most typical conducted emissions standards utilize a Line Impedance Stabilization Network (LISN) to connect the test device to the mains input power source. The impedance of an LISN is around 50 ohms for each input power line to earth ground. So, for differential mode, the impedance can be estimated to be 100 ohms and for common mode it can be estimated as 25 ohms.

For estimating the power supply input impedance, use the impedance value as calculated by dividing the lowest input voltage required by the power supply by the highest input current of the power supply. Use this value for both the differential and common mode impedance. To be a little more accurate, if it is possible, measure the capacitance from the input leads of the power supply to chassis and use this value as the common mode impedance. CAUTION: Be careful to verify that one does this measurement with the power supply turned off and all capacitors are fully discharged!!

TWO TYPES OF NOISE

In all circuits both common-mode (CM) and differential-mode (DM) currents are present (see *Figure 2*). There is a significant difference between the two. Given a pair of transmission lines and a return path, one or the other mode will exist, usually both. Differential-mode signals carry data or a signal of interest (information). Common-mode is an undesired side effect from differential-mode transmission and is most troublesome for EMC.

Common-mode current is the component of RF energy that is present on both signal and return paths, often in common phase to each other. The measured RF field due to common-mode currents will be the sum of the currents that exist in both the signal and return trace. This summation could be substantial. Common-mode currents are generated by any imbalance in the circuit. Radiated emissions are the result of such imbalance.

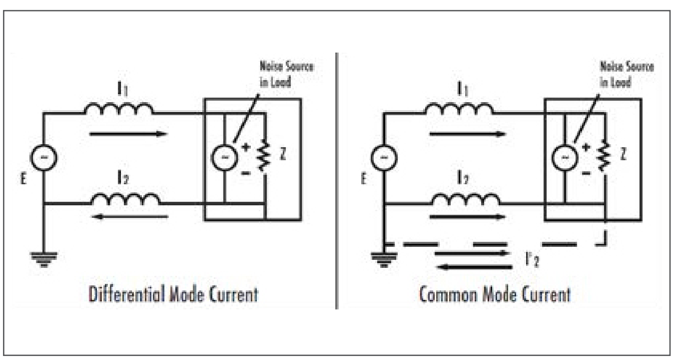


Figure 2. Common Mode and Differential Mode Current Flow

Gathering Data for Filter Selection Criteria's

LABORATORY TESTING TECHNIQUE

In determining the filter component values, there are a couple of approaches. Step 1 is to use a test laboratory facility and test setup to scan results without any powerline filter inserted into your device under test. This scan result becomes the baseline for the filter design. CAUTION: In performing this measurement, verify that a transient limiter device is inserted to the input of the receiver device and sufficient external attenuation is in series to protect the receiver from overload.

ATTENUATION DESIGN GOALS

Step 2 is to estimate the amount of attenuation required by the AC mains line filter by calculating the level of the noise just measured without any filter to the desired specification limit plus some for margin (usually an additional 4-6 dB), and then Step 3 is to determine whether the noise is common mode or differential mode. Since there are two different noise current modes of propagation, it is important to determine which type of noise current exists so that proper filtering can be implemented for maximum efficiency and minimize component costs. For common mode noise, a common mode inductor and/or Y-capacitors to chassis ground is used while for differential mode noise, line-to-line X-capacitors are used.

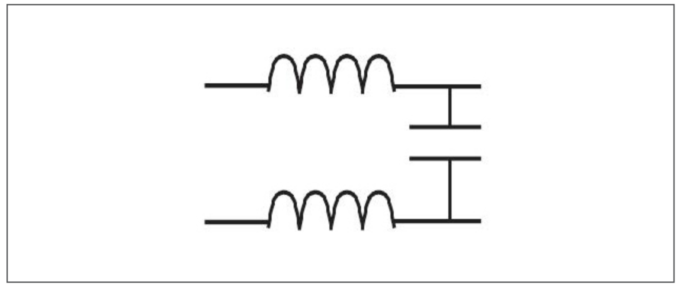


Figure 3. Differential Mode Filtering

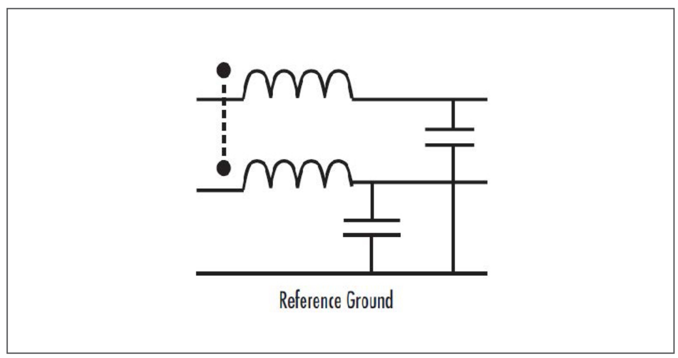


Figure 4. Common Mode Filtering

MEASURING THE LEVEL OF COMMON MODE AND DIFFERENTIAL MODE NOISE

The coupling mode will be determined experimentally with a current probe, (*Figure 5*). A current probe is a loosely coupled transformer that has the primary windings of a transformer's coil connected to a coaxial connector. The time-variant magnetic field present on the wire (Faraday's law) is coupled to the primary winding (Lentz's law). Current probes are available in a wide variety of configurations, frequencies ranges and power levels.

For EMI analysis, a probe should be chosen that exceeds the frequency range of interest. To use a clamp-on current probe insert one of the input-power wires and secure shut. If current flow is measured it can be either common-mode or differential-mode. Now insert the second input power wire together with the first wire. If current is still present, we have common-mode current. However, if there is no current flowing at this time differential-mode propagation exists since we now have "equal and opposite" currents flowing through the aperture of the current probe. Ask Schaffner for assistance in determining how to obtain this data.

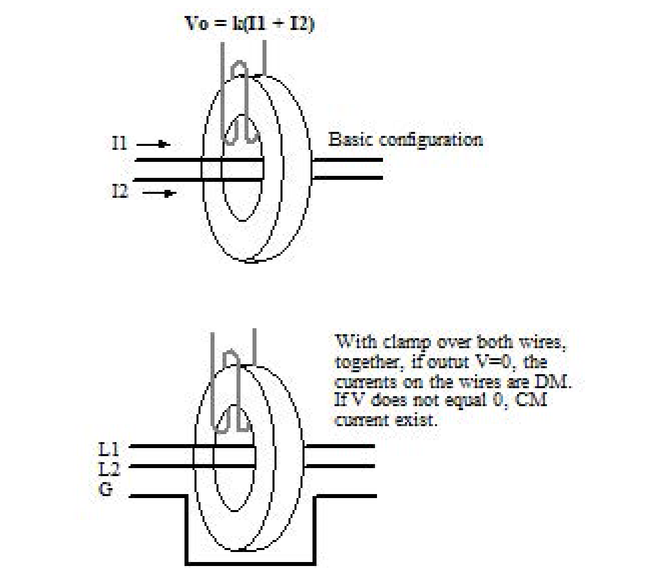


Figure 5. Using a current probe to determine if noise is common mode or differential mode

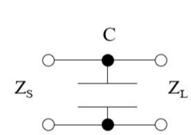
From this gathered data of Steps 1, 2, and 3 (amount of source noise, type of noise, and necessary attenuation) along with knowing the source and load, the desired filter can now be selected.

CASCADING FILTER COMPONENTS

When filter components are cascaded together, the filter may still fail to work as intended. What occurs is that the filter components "detune" each other or create "parasitic resonance effects" especially if the filter component has a circuit Q of 2 or higher. The higher Q increases the chance of an oscillation to occur. Typically, this oscilla¬tion moves the cut-off frequency into the bandpass region reducing the input voltage to where the equipment being powered may not function. Also, the increased cascaded to¬tal capacitance could cause higher line and harmonic cur¬rents possibly adding heat to the filter.

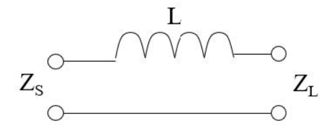
SIMULATION/ANALYTICAL TECHNIQUE

If available, one can also use a SPICE or MathCad or any similar circuit modeling program as an alternative approach. With the analysis tool, one will be able to take the circuit expression and numerically solve the expression yielding an insertion loss or attenuation plot and ultimately the filter component values. Below are a few of the most common filter circuits and calculation of the filter components as examples:



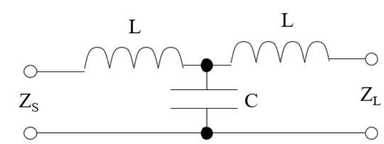
$$IL_{dB} = 10 \log [1 + 4(\pi f C)^2 (Z_S Z_L \,/\, (Z_S + Z_L))^2]$$

Figure 6. Capacitor Filter



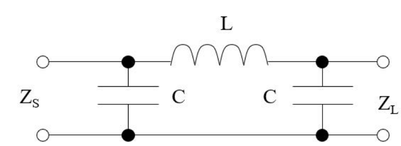
$$IL_{dB} = 10 \log [1 + 4(\pi f L \,/\, (Z_S + Z_L))^2]$$

Figure 7. Inductive Filter



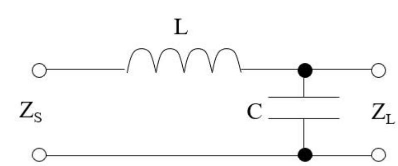
$$IL_{dB} = 20 \log [\ 1 + (j\omega)^2 LC + ((j\omega C Z_S Z_L) + (2j\omega L) + (j\omega)^3 L^2 C) \,/\, (Z_S + Z_L)]$$

Figure 8. "T" Filter



$$IL_{dB} = 20 \log [1 + (j\omega)^2 LC + (2j\omega C Z_S Z_L + j\omega L + (j\omega)^3 L C^2 Z_S Z_L) \,/\, (Z_S + Z_L)]$$

Figure 9. "Pi" Filter



$$IL_{dB} = 20 \log [1 + (j\omega L + j\omega C Z_S Z_L + (j\omega)^2 LCZ_L) \,/\, (Z_S + Z_L)]$$

Figure 10. "L-section" Filter

BREADBOARDING

At this point, having a PC board ready for soldering components and a selection of X-capacitors such as 10nF, 47nF, 150nF, 470nF values rated 275VAC and a good number of Y-capacitors of 680pF, 1nF, and 2.2nF values plus several common mode inductors with 700uH, 1mH, 3.3mH, 6.8mH, 10mH, and 20mH values can be an additional time saver by building up the filter circuit and performing a scan. In theory, the common mode inductors are transparent to the DM signals but, because of leakage inductance, it will offer some filtering with the X capacitor(s) for differential mode signals.

CAUTION: Be very careful in this process as one will have exposed AC connections in doing this!!! Another approach is to ask Schaffner for their assistance in recommending a filter or filters that will meet your requirements.

Design Concerns – Stability and Resonance

There are times when a filter can act as a resonant circuit across any power converter terminals and can affect the stabil¬ity of the converter if the filter is under damped and the filter's resonant frequency is inside or close to the control loop bandwidth. It can appear deceptively easy to design filters. Unfortunately, many other factors must be consid¬ered such as peak load cur¬rent, saturation of inductors, elevated temperatures and output impedance. The output impedance of the filter can be a critical item when incorporated within switching pow¬er supplies. The negative input impedance of a switching power supply can oscillate in conjunction with the output impedance of the line filter. A design-criteria known as the Middlebrook criteria must be considered. This Middle¬brook criteria states that the output impedance of the fil¬ter must be less than the reflected load impedance of the switching power supply.

Summary

Another time saver before going to the test lab, is to procure different filter configurations from a commercial filter company to have on hand during testing. If the original one doesn't pass, then change over to an alternate one. Having them on hand will shorten the development time and save on test lab cost due to multiple revisits.

Schaffner not only can provide off the shelf EMC filter solu¬-tions but also support manufacturers with their EMC lay¬out from the early stages of new product ideas or designs, they also can offer custom made solutions to help manufacturers meet any unique electrical, mechanical or EMC challenge. Schaffner has complete laboratory and simulation capabilities to perform all the steps mentioned in this article to reduce time in selecting the proper filter for your device. Contact your nearest Schaffner represen¬tative for assistance.

For more information on selecting an emi filter, refer to Schaffner's publication "***A Step-By-Step Process for Selecting an EMI Filter***"

References

- **Reference 1** – The Engineer's Guide to Designing Your EMI Filter by Schaffner USA
- **Reference 2** – Testing for EMC Compliance, Mark I. Montrose and Edward M. Nakauchi, John Wiley & Sons, Inc. 2004.
- **Reference 3 –** A Step-By-Step Process for Selecting an EMI Filter by Schaffner USA

shaping electrical power

SCHAFFNER EMC INC.
52 Mayfield Avenue
Edison, New Jersey 08837
+1 800 367 5566
+1 732 225 4789
usasales@schaffner.com
www.schaffnerusa.com

Product Types
- Ecosine active
- EMC/EMI
- Power quality

Responsible For
- USA
- Brazil
- Canada
- Mexico