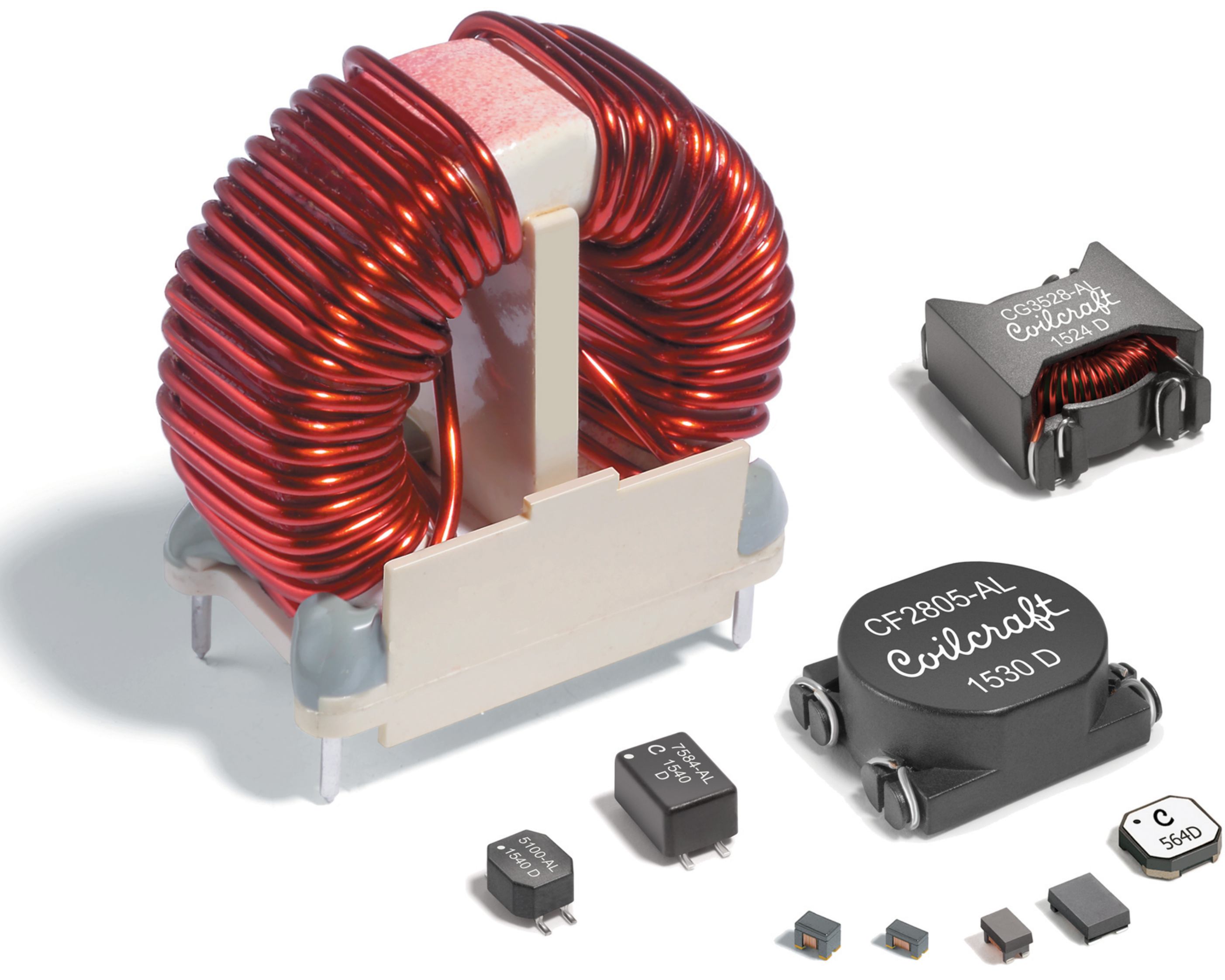

Reducing EMI Noise with Common Mode and Passive LC Filters

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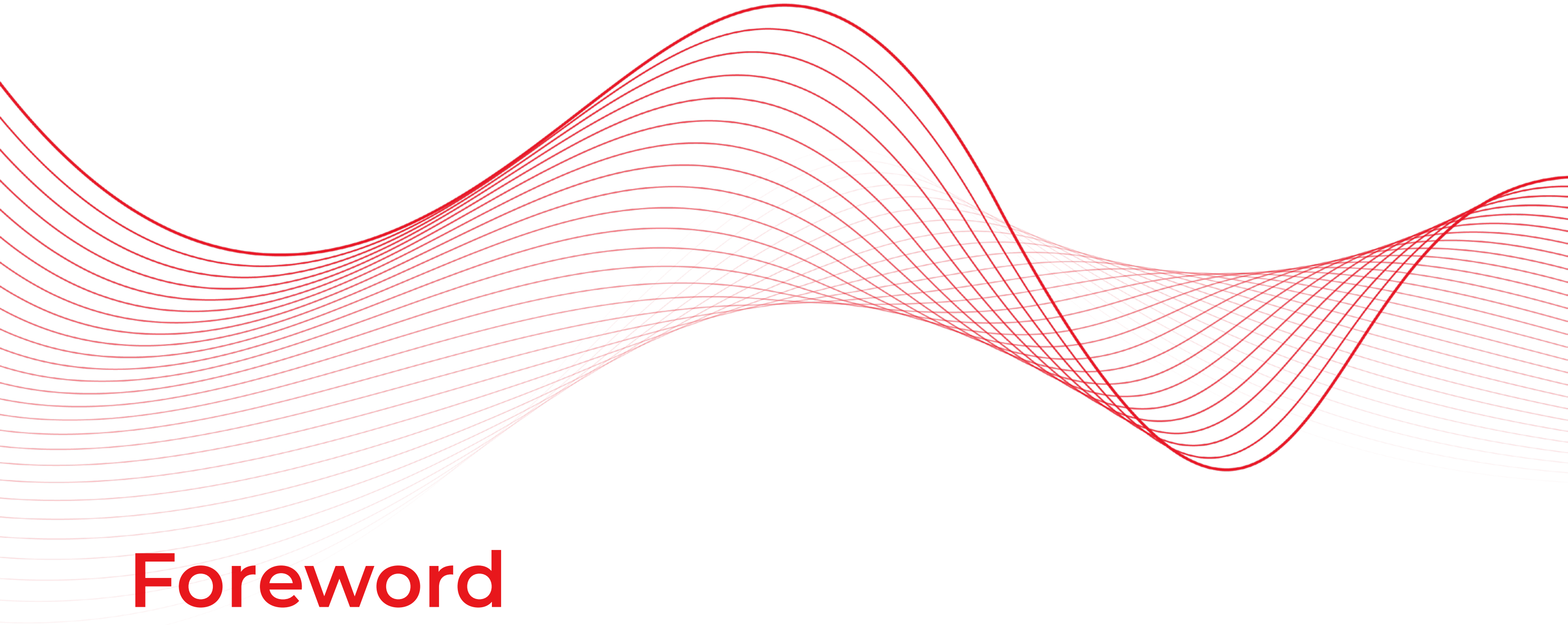
Contents



Foreword

The world is increasingly relying on the use of electronics and electrical devices at home, at work, and in every aspect of daily life. This increased use of devices — such as televisions, cell phones, notebook computers, and IoT devices — combined with technology such as appliance motors, lights, fans, and HVAC units running in the background has led to an environment full of competing signals and noise sources of various frequencies. This can lead to increased field interactions, current loops, ground loops, crosstalk, and other potential sources of electromagnetic interference (EMI), or undesired electrical disturbance (noise) that interferes with other devices.

Electronic devices and gadgets are also smaller, lighter, and faster today than ever before, while also providing the benefits and convenience of longer battery life and continuously improving processing ability. Although these smaller devices have the advantage of reducing some types of EMI, with a compact design comes smaller spacing between parts, which can also contribute to other potential sources of EMI. Understanding how fields interact to create intentional and unintended transmitters and receivers and applying EMI mitigation strategies can help devices meet electromagnetic compliance for electromagnetic compatibility (EMC), or the ability of electronic equipment to function properly without interference from noise sources (immunity/susceptibility) and without causing disturbances to other electronic equipment (emissions).

We will discuss several EMI solutions in this eBook. These include designing common-mode filters to prevent excessive noise by calculating specific filter alignments by manipulating the transfer function coefficients (component values) of a filter to achieve a specific damping factor. Another solution involves designing the right passive LC filter to block noise through modeling and analysis utilizing free design programs and models available online. Further, using a communication standard allows you to select the optimal common mode filter choke within the signal frequency that will not adversely attenuate, so that you can maintain high-speed communications free of EMI.

TECHNICAL ARTICLE

Fundamentals of Electromagnetic Compliance

Introduction

Everyone enjoys the advantages of electronic devices and gadgets becoming smaller, lighter, and faster while providing longer battery life and ever-improving processing ability. Smaller devices require smaller electronic components - an advantage in reducing electromagnetic interference (EMI). However, a compact design also means smaller spacing between components, circuit traces, and enclosures, which can lead to increased field interactions, current loops, ground loops, crosstalk, and other potential sources of EMI.

We benefit from the convenience of televisions, cell phones, digital tablets, notebook computers, and IoT devices, all operating at the same time, while appliance motors, lights, fans, and HVAC units are operating in the background to keep us comfortable. With multiple electrical and wireless electronic devices operating at the same time, signals must remain reliable in electromagnetically noisy environments.

The rapid growth of the electric vehicle (EV) and hybrid electric vehicle (HEV) market raises new electromagnetic compatibility (EMC) concerns as high-voltage batteries and chargers see increased use. High-voltage and high-frequency automotive electronics, if not properly designed, can lead to EMC compliance headaches. Focusing on design techniques that mitigate EMI will help ensure a low-emissions outcome.

High levels of electromagnetic (EM) noise lead to EMI, which is any undesired electrical disturbance (noise) that interferes with other circuits. Electromagnetic emissions occur when electrical or electronic equipment radiates or conducts EM noise that interferes with other devices. Electromagnetic compatibility is the ability of electronic equipment to function properly without interference from noise sources (immunity/susceptibility) and without causing disturbances to other electronic equipment (emissions).

EMC is verified by testing industry standards developed by regulating agencies described later in this discussion. These standards define specific test conditions and limits of noise emissions that may vary by location, application, and operating environment.

Noise Sources

Noise might be of a transient or discontinuous nature, or it might be generated continuously. Potential sources of transient or discontinuous conducted emissions include automatic switches, temperature controllers, appliance controllers, and other automatic controllers, motor controllers, and any other non-constant or event-driven on/off switching of voltage. Potential sources of continuously conducted emissions include electric motors, unshielded or poorly shielded data lines, switch-mode power converters, and any other constant, steady-state switching of voltage. Improperly designed PCBs with power and signal areas too close together or having insufficient filtering can result in transient or steady state conducted emissions.

Modes of Electrical Noise Propagation

Noise is generally discussed as being either radiated or conducted. The solution to any noise problem requires identifying and understanding the nature of the noise. This can be complicated by the interaction between radiating and conducting modes. After all, any conducted electricity has the potential to generate radiating fields, and likewise, fields can cause electrical signals.

Designing and testing for EMC involves understanding how electric fields (E-fields) and magnetic fields (B-fields) propagate and interact. A fundamental understanding of antenna theory provides insights into how the size and design of electronic components, PCB traces, pads, and grounds relate to various frequencies and their associated wavelengths. Understanding the modes of electrical noise propagation and the methods of testing for EMC leads to design solutions that greatly improve the probability of passing EMC compliance tests in the earliest stages. Failing to design for EMC often results in expensive redesigns and PCB re-spins.

Conducted Emissions

Electrical noise can be transferred to “victim” equipment by field-coupling from source “aggressor” equipment through conducting input lines, cables, connectors, or traces to the equipment circuits. This mode of noise propagation and its effects on power quality are referred to as conducted emissions. Conducted emissions can be conducted directly into the circuit

on the input lines, or they can be near-field energy that is capacitively coupled (E-field) or magnetically-coupled (B-field) to a circuit unintentionally. Because conducted emissions may involve capacitively- or magnetically coupled fields, they are essentially reactive (non-radiative) near-field effects that can, generally, be modeled using lumped resistive, inductive, and capacitive (RLC) elements. Conducted emissions are typically measured in the 150 kHz to 30 MHz frequency range.

Differential and Common Mode Noise

Conducted emissions consist of differential mode (DM) currents and common mode (CM) currents. The dominant mode depends on the source of the noise. Differential mode noise currents are superimposed on the intended current that powers the circuit, traveling in a loop from the power source, through the circuit, and returning to the ground or the intended source return node for non-grounded circuits.

DM currents include the typically lower-frequency desired fundamental signal and any higher-frequency harmonics. In some circuits, the fundamental frequency plus harmonics make up the desired waveform (AC), such as sine waves, square waves, or triangular waves. In others, the main current is DC, and the AC portion is noise to be filtered out. The cutoff frequency of a low-pass filter inductor, choke, or LC filter must be designed to filter out the high-frequency noise without significantly attenuating the intended signal.

CM currents travel in the same direction through one or more conductors toward a common return point that closes the current loop (e.g., ground). When the return path is not intentional, the CM current may be the result of energy capacitively or magnetically coupled to the common point. Common-mode chokes are designed to create a high impedance to such CM noise (**Figure 1**) while presenting low impedance to the desired differential signal.

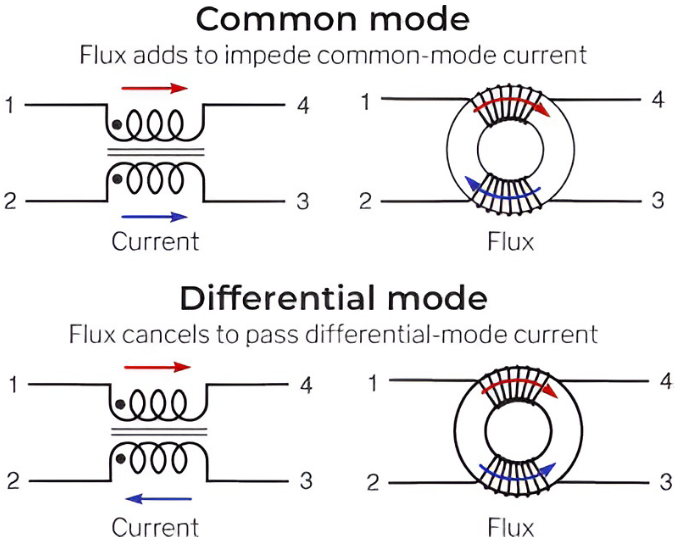


Figure 1. Differential and common mode noise.
Source: Coilcraft

Radiated Emissions

Near-field and far-field are terms associated with antennas. Why mention antennas in an EMC discussion? Unintentional transmitters are circuit elements that unintentionally radiate or scatter radiation. These are in effect “antennas” that were not intentionally designed to transmit energy. Unintentional transmitters cause radiated emissions, that is, electromagnetic noise propagated through the air that is received by other parts of the circuit or other devices.

Radiated emissions are essentially far-field at approximately two or more wavelengths distance from the source. The maximum dimension of an optimized antenna is about 1/4 wavelength of the intended signal being transmitted or received. When the size of an unintentional circuit transmitter, such as a PCB trace cable or slot behaving as an antenna, approaches about 4x the wavelength, the transmitted high-frequency energy can be modeled by distributed (transmission line) elements.

Wavelength and frequency have an inverse relationship; therefore, at higher frequencies in which the corresponding wavelength approaches about 1/4 of the size of the unintended antenna or smaller, radiated emissions can be expected. Consequently, radiated emissions are tested at higher frequencies than conducted emissions, typically in the 30 MHz to 1 GHz range.

Potential sources of radiated emissions include switched wireless devices, IoT devices, radios, switching power supplies, electric motors, digital signal data lines, communications devices, motor drives, and any unshielded or radiating source with ineffective shielding. Some of these are also included as sources of conducted emissions because they can interact with both power cables and data lines, as well as via radiation over the air.

EMC Compliance Agencies and Test Methods

The following is a brief overview of EMC compliance agencies, test setups, methods, and standards. It also includes design hints for mitigating EMI and tips for EMC test troubleshooting.

EMC standards define specific test equipment, test setups, and pass/fail limits. EMC standards generally set limits on both peak (or quasi-peak) and average emissions levels vs. frequency range for the appropriate classification of the measured device. The equipment designed for measuring these levels is defined within the applicable product standard or the referenced basic standard. EMC standards are continually under review due to new product types and applications. Therefore, the latest approved standard should be applied in any EMC test plan.

Figure 2 (next page) shows the test limits for FCC Part 15 (radio frequency devices) Subpart B radiated emissions limits for frequencies greater than 1 GHz for average measured values at 3 m and 10 m distances. **Figure 3** (next page) shows the same for measured quasi-peak values.

Quasi-peak measurements apply a weighting factor based on the repetition frequency of the spectral components of the signal. Even if the emission is over a test limit when measured with peak detection, it can pass if the quasi-peak level is below the limit. For this standard, one must meet the limits for both average and quasi-peak measurements. Quasi-peak measurements require more time than peak measurements. If initial (faster) peak measurements pass, they will pass quasi-peak testing, and the slower quasi-peak test is not needed.

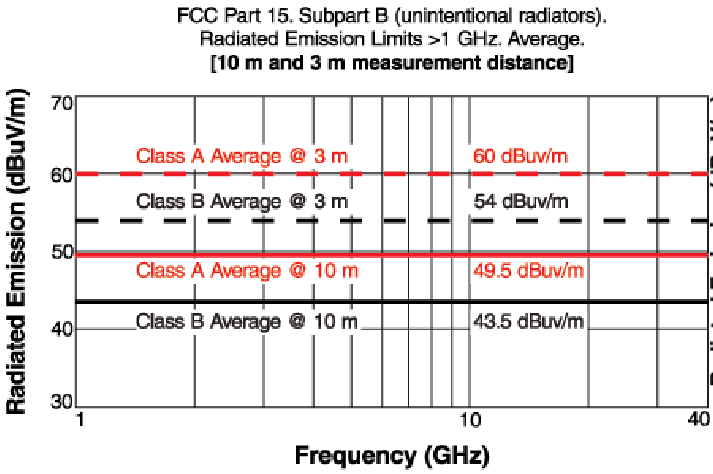


__Figure 2.__ FCC Part 15. Subpart Radiated Emissions Limits> 1GHz - Average

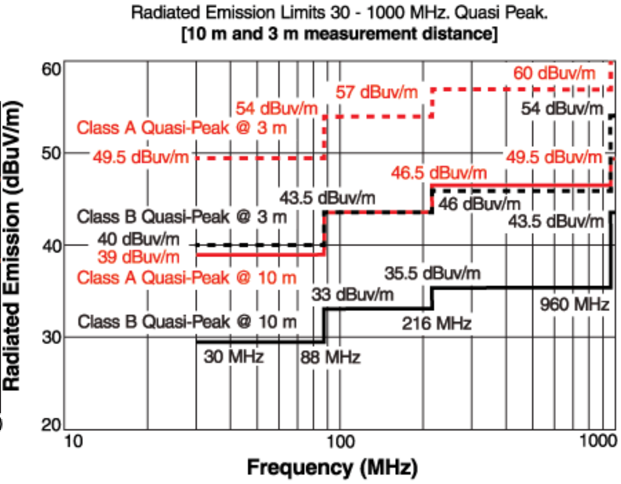


__Figure 3.__ FCC Part 15. Subpart B Radiated Emissions Limits 30 -1000 MHz - Quasi-Peak

Basic EMC publications include definitions of terms and specific test setups and equipment requirements, such as those for line impedance stabilization networks (LISN) that stabilize the impedance of the source and provide isolation of the test equipment and circuit under test. EMC product standards and EMC product family standards refer to specific products and categories of products, while generic EMC standards apply where specific product or family categories do not exist.

Product, product family, and generic EMC standards reference the more fundamental basic EMC standards. Selecting appropriate EMC standards can be confusing, requiring a clear indication of the product category and markets, whether local, international, or both. Consulting an accredited EMC test laboratory can save much time and effort in determining the appropriate test standards and requirements for general or specific products and applications.

The following are the major EMC regulation agencies and examples of some of their basic products, product families, and generic standards currently in effect.

Major US and Global EMC Regulating Agencies

The major regulating agencies that publish EMC standards include:

- FCC - Federal Communications Commission (USA/ North America).
    - Products designed for North American markets are generally tested to the basic compliance limits of the Federal Communications Commission (FCC) Part 15.
- IEC - International Electrotechnical Commission (International).
- CISPR - Comité International Special des Perturbations Radiolecétriques (International)
    - CISPR is part of the IEC.

Basic EMC Standards

The major basic EMC standards cover a wide range of devices and include:

- FCC Title 47 Part 15 - Radio Frequency Devices is a basic standard in the USA. Under this standard:
  - Class A digital devices are generally marketed for use in commercial, industrial, or business environments.
  - Class B digital devices are generally marketed for residential use but can include commercial, industrial, or business environments. Class B requirements are more stringent; therefore, Class B devices can be used in Class A environments.
- IEC 61000 Series Parts 1, 2, 4, 5, 6, and 9 define basic terminology, test and measurement methods, and installation and EMI mitigation guidelines.
- IEC 61000-3 European (international) Standard for all electrical and electronic equipment that is connected to the public mains up to and including 16 A max.
- CISPR 16 - Defines measuring apparatus and methods for radio disturbance and immunity testing from 9 kHz to 1 GHz.

Product EMC Standards

Product EMC standards apply to specific products, such as electric vehicle conductive charging systems, power electronic converter systems, cables and connectors, or medical electrical equipment. Examples of product-specific EMC standards include:

- IEC 61851-21- Electric vehicle conductive charging system - Part 21: Electric vehicle requirements for conductive connection to an a.c./d.c. supply.
- IEC 62477-1- Safety requirements for power electronic converter systems and equipment - Part 1: General.
- IEC 61726 - Cable assemblies, cables, connectors, and passive microwave components - Screening attenuation measurement by the reverberation chamber method.
- IEC 60601-1-2 - Medical electrical equipment - Part 1-2: General requirements for basic safety and essential performance – Collateral standard: Electromagnetic compatibility - Requirements and tests.

Product Family EMC Standards

Product family EMC standards apply to wider general product categories, such as vehicles, information technology equipment, industrial, scientific, and medical equipment. Examples of product CISPR EMC standards include:

- CISPR 25 - Vehicles, boats, and internal combustion engines – Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers. This is the go-to standard for automotive applications.
- CISPR 22 - Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement - High frequency conducted emissions standard.
- CISPR 11 - Industrial, scientific, and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement – High frequency conducted emissions standard.
- CISPR 15 - Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment.

Generic EMC Standards

Generic EMC standards are grouped as either residential, commercial and light industrial, or as industrial. Industrial includes higher-power industrial, and scientific and medical equipment. When a specific EMC standard does not exist for new products, a simplified generic EMC standard may be invoked. As with other product standards, they may refer to basic EMC standards for specific test methods.

Generic EMC standards examples include:

- IEC 61000-6-3 - Emission standard for equipment in residential Environments.
- IEC 61000-6-4 - Emission standard for industrial environment.
- IEC 61000-6-8 - Emission standard for professional equipment in commercial and light-industrial locations.

Designing to Mitigate EMI

Because higher-frequency harmonics are considered noise in conducted emissions testing, low-pass filters are purposely designed into electronic equipment to reduce this high-frequency noise to below the defined limits of the conducted emissions test. Series inductors and capacitors between line and neutral lines, such as X-caps between the power and neutral lines, are employed to reduce the high-frequency DM currents. Common mode chokes and Y-caps between the lines and chassis ground are used to reduce the CM noise.

When the source includes significant conducted noise, as with switching power supplies, additional elements may be needed to create higher-order LC filters that further reduce the DM and CM noise. Some good news is that the use of small surface mount (leadless) components reduces connection inductance and the length of traces that may contribute to higher EMI.

Design Hints for Passing EMC Pre-compliance and Compliance Tests

These design hints for passing EMC pre-compliance and compliance testing do not comprise an exhaustive list. However, following these guidelines will help ensure minimal generation of EMI.

1. Minimize the length of circuit traces to avoid making unintentional emitters/ antennas. This is listed as #1 because it is most critical in preventing EMI. Minimizing trace length decreases the total stored reactive energy of the trace and reduces ringing due to parasitic inductance. This is especially critical in switched power converters.

2. Consider EMC in the earliest stages of the design process. It can save considerable time and help prevent time-consuming PCB redesigns.

3. Use simulation programs to design and simulate noise filters, and use real measurements to verify them. Even accurate models may not fully capture some important parasitic interactions.

4. Use magneticallyshielded inductors to minimize B field coupling, unless your design requires purposeful interaction with the inductor field (e.g., NFMI or RFID). Magnetic shielding is created by surrounding the inductor with a high-permeability, low-reluctance material (e.g., ferrite), creating a “closed” magnetic path. The purpose of magnetic shielding is to reduce the amount of magnetic flux generated outside the inductor, in turn reducing the likelihood of radiating energy to nearby components or circuit board traces, causing electro-magnetic interference (EMI).

5. Avoid electrically conducting (metal) materials directly above, next to, or below inductors or high-frequency switches (e.g., switched power converters). When this can’t be avoided, use raised inductors to increase the distance between the inductor and conductors below.

6. Place the start winding of the inductors closest to the high dv/dt side of the switches.
7. Maintain spacing between components, generally 1.5x the largest x-y dimension.
8. Avoid or slow down sharp rising-edge and falling-edge waveforms (slew rate control). This can lead to reduced efficiency, so there are tradeoffs, and a balance must be struck.
9. Route clock lines and other high-speed traces away from power sources.
10. Avoid running high-speed lines across gaps in return lines.
11. Consider ground loops or return paths of reference planes as potential EMI sources.
12. Avoid discontinuous signal return paths, e.g., gaps in ground planes.
13. Utilize filtering or shielding to block coupling paths from energy sources.
14. Engage filter reference designs with proven performance and save design time.
15. A single-pole (Lor C) filter provides -20 dB/decade of frequency filtering. A two-pole (LC) filter has a more rapid attenuation rate of -40 dB/decade. A three-pole filter (e.g., LCL) gives -60 dB/decade attenuation. Therefore, a sharp cutoff frequency requires a high-order filter.
16. Consider spread-spectrum control methods to spread noise energy to lower levels over a range of frequencies.
17. Slope compensation requires a certain level of ripple current to maintain stability. If the ripple is too high, it can cause EMI. When using slope compensation, check that the ripple current is not a source of EMI.

EMC Filter Simulations

Computer programs for designing noise filters speed up the design and analysis phase of electronic product development. Free programs are useful for designing and verifying the performance of LC filters. Physics based three-dimensional EM (3D EM) simulation programs that use more advanced computational solver methods, such as FEM, FDTD, and MoM are higher-priced and require more advanced knowledge, however, these advanced solver programs provide more geometry- and materials-related insights when attempting to understand EM field interactions.

Cost-free Passive Component Filter Simulation Programs

These no-cost programs help engineers design and simulate lumped element filters and their effects on circuit behavior. It typically takes much less time to model and simulate a proposed circuit than to build and test the physical circuit, especially when performing “What-if?” analyses that involve many iterations. Thus, SPICE-based and other circuit design and synthesis simulation programs provide fast insights while saving time in the initial stages of design and analysis.

Analog Devices

- LTspice
- LTpowerCAD (Includes EMI Filter Design Module).

Coilcraft

- Coilcraft LC Filter Designer Software: Create elliptic low-pass filters using actual Coilcraft inductor values, not just ideal components.
- Coilcraft LC Filter Reference Designs

WA4DSY.NET

- Design LC Filters: Filter design calculations for designing multi-pole filters

3D Electromagnetic Simulations

The major advanced 3-dimensional electromagnetic (3D EM) programs for simulating printed circuit boards (PCBs), electronic components, and circuits include Ansys - HFSS, AWR Axiem / Analyst, CST Studio Simulia, and Cadence Clarity. These programs use physical models that include materials and geometry details, and advanced computational techniques for a better understanding of the effects of materials and spacings at various operating conditions.

Pre-Compliance Testing

Even the best design simulations can miss unanticipated field or wave interactions. Intertek Testing Services NA, Inc., an accredited EMC test lab, has found that about 50% of EMC tests fail on the first try (note 5). Some failures may be unavoidable, but many are due to preventable design oversights, such as failure to apply EMC principles or to simulate predictable interactions between circuit components. Pre-compliance testing allows engineers to pre-verify EMC standard compliance so that no such surprises delay the release of a product due to necessary re-designs. When un-predicted EM noise is made visible by pre-compliance testing, there are methods that can be employed to identify the source and remediate the problem.

Tips for EMC Test Troubleshooting

1. Use E-field and B-field probes to locate sources of EMI on a PCB.
2. If inductors or capacitors are suspected, rotate inductors by 180 degrees, and place nearby inductors and capacitors 90 degrees to each other. If available, replace inductors having side terminations with bottom-terminated inductors.
3. Use a spectrum analyzer to determine the frequency range and amplitude of noise sources.
4. Set the resolution bandwidth of the spectrum analyzer to that specified in the applicable emission standard.
5. Slower voltage rise times create higher-order harmonics of lower magnitude and faster rise times lead to higher-magnitude, higher-order harmonics.
6. Lower duty cycle leads to lower-magnitude, higher-order harmonics and higher duty cycle leads to higher-magnitude, higher-order harmonics.
7. Determine whether the noise is DM or CM. If the noise is suspected to be CM, select a CM choke for the offending frequencies. If the noise is reduced, the noise was CM (unless the choke is a combination choke). If the noise is not reduced, it is more likely to be DM noise.
8. If changing EMI filter components does not change the EMC test results, this points to a possible PCB layout issue.
9. A combination of too many circuit elements can lead to resonances that amplify unwanted harmonics. In such cases, removing a component, such as a capacitor, may improve EMC test results. This may seem counterintuitive; however, sometimes more is not better.

10. Is the ringing in your switched-mode power supply switching edges causing EMI? Use a simulation program to design an RC snubber circuit to reduce the ringing. Higher resistance dampens the ringing but can affect efficiency, so use simulation to optimize the trade-offs.
11. If the source issue is a strong E-field, a metal “Faraday cage” shield connected to ground provides a closed field path that shunts noise to ground.
12. Wrap thin copper completely around a noisy transformer and connect the copper to ground to create a Faraday cage shield.
13. Use copper tape in closed loops to create prototype shielding. Test with and without the shielding to determine whether it is needed.
14. Review the design hints above for additional insights into possible solutions.

Conclusion

The continual increased use of electronics and electrical products has led to an environment filled with many signal and noise sources over a wide range of frequencies. Understanding how fields interact to create intentional and unintended transmitters and receivers, and applying EMI mitigation techniques when designing and testing, can lead to positive outcomes in electromagnetic compliance testing.

Definitions

CISPR - Comité International Special des Perturbations Radiolecétriques

Common mode current (noise) involves currents flowing in the same direction to circuit ground at higher frequencies. It is also called asymmetrical or longitudinal current.

Conducted emissions are unintentionally conducted, capacitively coupled (E-field), or magnetically coupled (B-field), to the circuit. They are typically measured in the 150 kHz to 30 MHz frequency range.

Crosstalk occurs when a high-frequency (e.g. clock) signal couples into nearby analog circuits.

Differential mode (normal) noise involves currents flowing in opposite directions at lower frequencies, also called symmetrical or transverse currents.

Electromagnetic (EM) field - A field of force that consists of both electric and magnetic components, resulting from the motion of an electric charge and containing a definite amount of electromagnetic energy.

Electromagnetic (EM) noise, also called electrical noise, is any unwanted electrical disturbance, not necessarily in the audible frequency range (audible noise).

EM Emissions occur when equipment radiates or conducts electromagnetic noise.

EM Immunity is the ability of the equipment to withstand outside sources of EM noise without adversely affecting functionality.

EM Susceptibility is the sensitivity of equipment to function within an environment of EM noise.

> An **aggressor** is equipment that emits EM noise. Aggressors conduct or radiate EM emissions.
>
> A **victim** is equipment that is adversely affected by EM noise. Victims are susceptible to EM emissions.

EMC is electromagnetic compatibility. EMC is verified by testing to industry global and local standards.

EMI is electromagnetic interference. If EMI exists at a level that exceeds the applicable EMC testing standards, the equipment is not EMC-compliant.

Far-field - Involving a distance from the source at which the distributed element models are needed for high-accuracy far-field simulations. The transition from near-field to far-field exists at about 1/6 the wavelength of the signal (or noise).

FCC - Federal Communications Commission (USA)

FCC Title 47 Part 15 - Radio Frequency Devices is a basic EMC standard in the USA applicable to electromagnetic energy at any frequency in the radio frequency (RF) spectrum between 9 kHz and 3 GHz.

FDTD - Finite Difference Time Domain - A powerful method of solving Maxwell's equations directly without requiring physical approximations.

FEM - Finite Element Method - An advanced method of numerically solving differential equations that, for example, define physical relationships over a geometric space.

IEC - International Electrotechnical Commission

Intentional transmitters (antennas) purposely transmit EM waves for wireless charging and communications.

LISN - Line Impedance Stabilization Network - Pi filter networks that stabilize the impedance of the test source and provide isolation of the test equipment and circuit under test.

MoM - Method of Moments - Efficient full-wave numerical technique for solving open-boundary electromagnetic problems.

Near-field - Involving capacitively coupled E fields or magnetically coupled B fields. Lumped element models can be sufficient for near-field simulations.

Radiated emissions are the result of unintentional current loop paths that radiate EM noise from the circuit. They are typically measured in the 30 MHz to 1 GHz frequency range.

SMPS - Switched Mode Power Supply (switching converter).

Unintentional radiator - A device that intentionally generates radio frequency energy for use within the device, or that sends radio frequency signals by conduction to associated equipment via connecting wiring, but which is not intended to emit RF energy by radiation or induction.

Unintentional transmitters unintentionally transmit EM waves as noise. The FCC defines this as an "incidental radiator" - A device that generates radio frequency energy during the course of its operation, although the device is not intentionally designed to generate or emit radio frequency energy.

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TECHNICAL ARTICLE

Common Mode Filter Design Guide

Introduction

The selection of component values for common mode filters need not be a difficult and confusing process. The use of standard filter alignments can be utilized to achieve a relatively simple and straightforward design process, though such alignments may readily be modified to utilize predefined component values.

General

Line filters prevent excessive noise from being conducted between electronic equipment and the AC line; generally, the emphasis is on protecting the AC line. **Figure 4** shows the use of a common mode filter between the AC line (via impedance matching circuitry) and a (noisy) power converter. The direction of common mode noise (noise on both lines occurring simultaneously, referred to as earth ground) is from the load and into the filter, where the noise common to both lines becomes sufficiently attenuated. The resulting common-mode output of the filter onto the AC line (via impedance-matching circuitry) is then negligible.

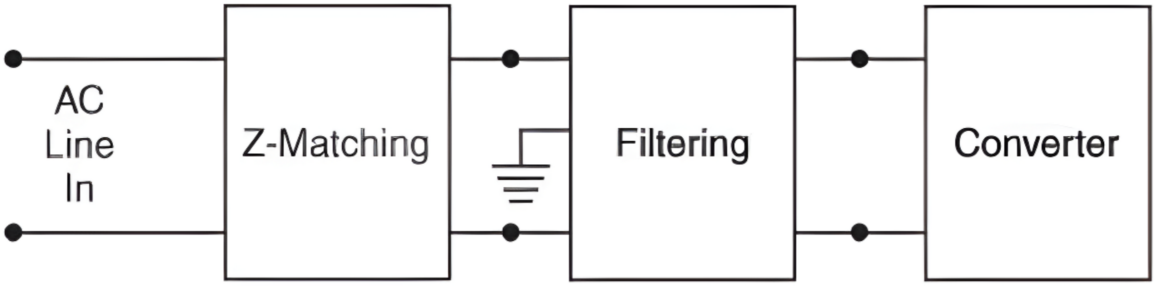


Figure 4. Generalized line filtering

The design of a common-mode filter is essentially the design of two identical differential filters, one for each of the two polarity lines, with the inductors of each side coupled by a single core, as shown in **Figure 5** (next page).

For a differential input current (A) to (B) through L1 and (B) to (A) through L2, the net magnetic flux that is coupled between the two inductors is zero. Any inductance encountered by the differential signal is then the result of imperfect coupling of the two chokes; they perform as independent components with their leakage inductances responding to the differential signal: the leakage inductances attenuate the differential signal. When the inductors, L1 and L2, encounter an identical signal of the same polarity referred to as ground (common mode signal), they each contribute a net, non-zero flux in the shared core; the inductors thus perform as independent components with their mutual inductance responding to the common signal: the mutual inductance then attenuates this common signal.

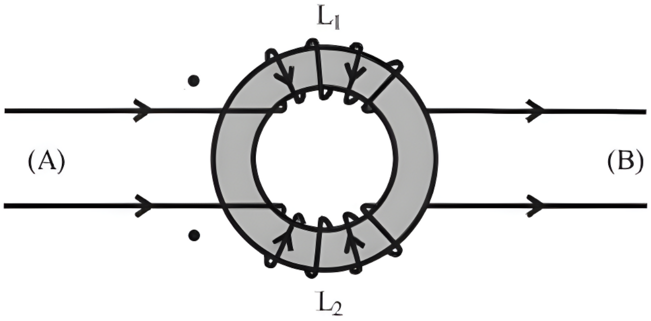


Figure 5. *The common mode inductor.*

The First Order Filter

The simplest and least expensive filter to design is a first-order filter; this type of filter uses a single reactive component to store certain bands of spectral energy without passing this energy to the load. In the case of a low-pass common mode filter, a common mode choke is the reactive element employed.

The value of inductance required of the choke is simply the load in Ohms divided by the radian frequency at and above which the signal is to be attenuated. For example, attenuation at and above 4000 Hz into a 50 Ω load would require a 1.99 mH (50 / (2π x 4000)) inductor. The resulting common mode filter configuration would be as follows in **Figure 6**:

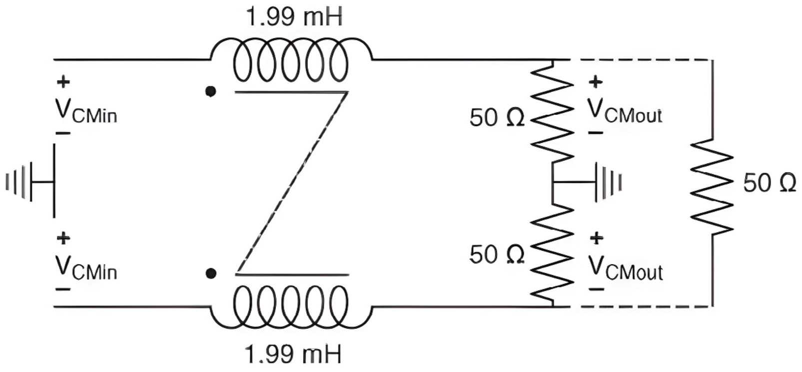


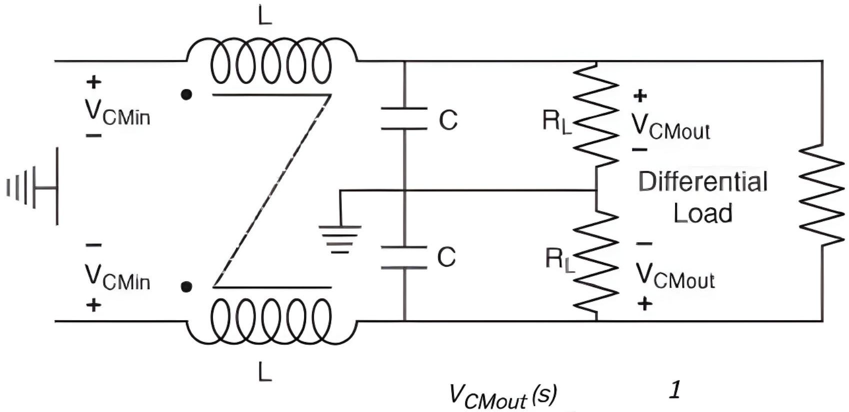
Figure 6. *A first order (single-pole) common-mode filter.*

The attenuation at 4000 Hz would be 3 dB, increasing at 6 dB per octave. Because of the predominant inductor dependence of a first-order filter, the variations of actual choke inductance must be considered. For example, a ±20% variation of rated inductance means that the nominal 3 dB frequency of 4000 Hz could be anywhere in the range from 3332 Hz to 4999 Hz. It is typical for the inductance value of a common-mode choke to be specified as a minimum requirement, thus ensuring that the crossover frequency is not shifted too high. However, some care should be observed in choosing a choke for a first-order low-pass filter because a much higher than typical or minimum value of inductance may limit the choke's useful band of attenuation.

Second Order Filters

A second-order filter uses two reactive components and has two advantages over the first-order filter: 1) Ideally, a second-order filter provides 12 dB per octave attenuation (four times that of a first-order filter) after the cutoff point, and 2) it provides greater attenuation at frequencies above inductor self-resonance (See **Figure 7**).

The design of a second-order filter requires more care and analysis than a first-order filter to obtain a suitable response near the cutoff point, but there is less concern needed at higher frequencies, as previously mentioned.



$$\frac{V_{CMout}(s)}{V_{CMin}(s)} = \frac{1}{1 + (L/R_L)s + LCs^2}$$

$$= \frac{1}{1 - LC\omega^2 + j\omega(L/R_L)}$$

$$= \frac{1}{1 + j2\zeta(\omega/\omega_n) - (\omega/\omega_n)^2}$$

ω = radian frequency

R_L = the noise load resistance

$\omega_n = \frac{1}{\sqrt{LC}}$ $\quad \zeta = \frac{L}{2R_L\sqrt{LC}}$

Figure 7. *Analysis of a second order (two pole) common mode low pass filter.*

One of the critical factors involved in the operation of higher-order filters is the attenuating character at the corner frequency. Assuming tight coupling of the filter components and reasonable coupling of the choke itself (conditions we would expect to achieve), the gain near the cutoff point may be very large (several dB); moreover, the time response would be slow and oscillatory. On the other hand, the gain at the crossover point may also be less than the presumed -3 dB (3 dB attenuation), providing a good transient response, but frequency response near and below the corner frequency could be less than optimally flat.

In the design of a second-order filter, the damping factor (usually signified by the Greek letter zeta (ζ)) describes both the gain at the corner frequency and the time response of the filter. **Figure 8** shows normalized plots of the gain versus frequency for various values of zeta.

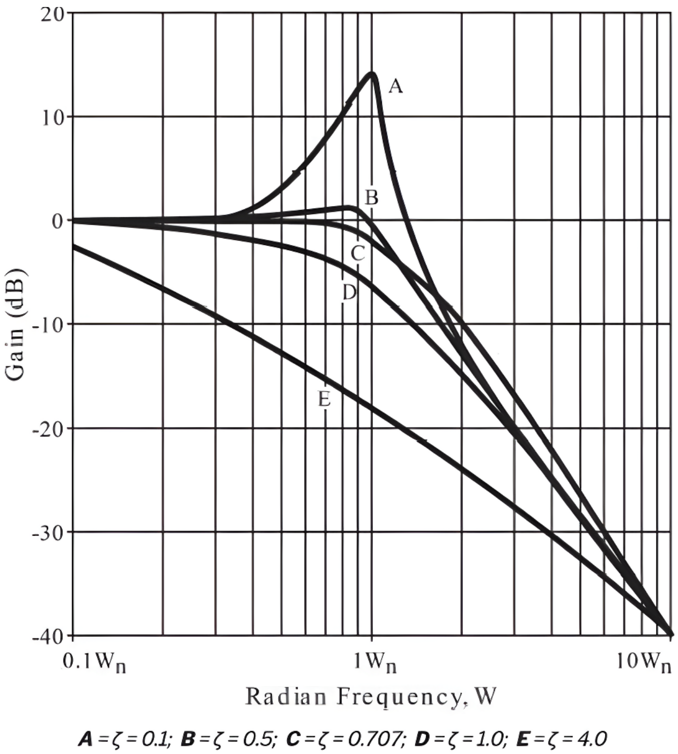


Figure 8. Second-order frequency response for various damping factors (ζ).

As the damping factor becomes smaller, the gain at the corner frequency becomes larger; the ideal limit for zero damping would be infinite gain. The inherent parasitic effects of real components reduce the gain expected from ideal components, but tailoring the frequency response within a few octaves of the critical cutoff point is still effectively a function of ideal filter parameters (i.e., frequency, capacitance, inductance, resistance).

For some types of filters, the design and damping characteristics may need to be maintained to meet specific performance requirements. For many actual line filters, however, a damping factor of approximately 1 or greater and a cutoff frequency within about an octave of the calculated ideal should provide suitable filtering.

The following is an example of a second-order low-pass filter design:

1. **Identify the required cutoff frequency:** For this example, suppose we have a switching power supply (for use in equipment covered by UL478) that is 24 dB noisier at 60 KHz than permissible for the intended application. For a second-order filter (12 dB/octave roll-off), the desired corner frequency would be 15 kHz.

2. **Identify the load resistance at the cutoff frequency:** Assume $R_L = 50\ \Omega$

3. **Choose the desired damping factor:** Choose a minimum of 0.707, which will provide 3 dB attenuation at the corner frequency while providing favorable control over filter ringing.

4. **Calculate required component values:**

$$\omega_n = 2\pi f_n = 94248\ rad/sec$$

$$C = \frac{1}{L\omega_n^2}$$

$$\zeta = 0.707 = \frac{L\omega_n}{2R_L}$$

$$L = 750\mu H$$

5. **Choose available components:** C = 0.05 µF (The largest standard capacitor value that will meet leakage current requirements for UL478/ CSA C22.2 No.1: a 300% decrease from design). L = 2.1 mH (Approx. 300% larger than the design to compensate for reduction or capacitance: Coilcraft standard part #E3493-A)

6. **Calculate actual frequency, damping factor, and attenuation for the components chosen:**

$$\frac{1}{2\pi\sqrt{LC}} = 15532\ Hz\ \text{(very nearly 15 KHz)}$$

$$\zeta = 2.05\ \text{(a damping factor of about 1 or more is acceptible)}$$

$$\text{Attenuation} = (12\ dB/octave) \times 2\ octaves = 24\ dB$$

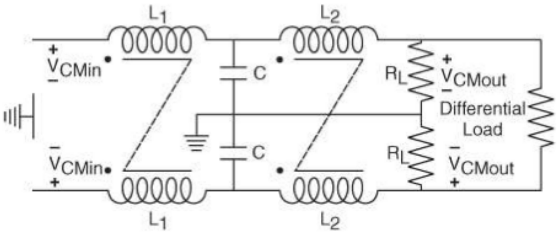
7. **The resulting filter is that of Figure 4 with:** L = 2.1 mH; C = 0.05 µF; RL = 50 Ω

Note: Damping factors much greater than 1 may cause unacceptably high attenuation of lower frequencies, whereas a damping factor much less than 0.707 may cause undesired ringing, and the filter may itself produce noise.

Third Order Filters

A third-order filter ideally yields an attenuation of 18 dB per octave above the cutoff point (or cutoff points if the three corner frequencies are not simultaneous); this is the prominent positive aspect of this higher-order filter. The primary disadvantage is cost, since three reactive components are now required. Higher than third-order filters are generally cost-prohibitive.

The design of a generic filter is readily accomplished by using standard alignments such as the Butterworth ("maximally flat") alignments. **Figure 9** shows the general analysis and component relationships to the Butterworth alignments for a third-order low-pass filter. Butterworth alignments provide an inherent ζ of 0.707 and a -3 dB point at the crossover frequency. The Butterworth alignments for the first three orders of low-pass filters are shown in **Figure 10**.



$$\frac{VCMout(s)}{VCMin(s)} = \left(\frac{R_L}{R_L + L_2 s}\right)\left(\frac{\frac{(R_L + L_2 s)}{sC}}{\frac{(R_L + L_2 s)}{sC} + R_L L_1 s + L_2 L_1 s^2 + \frac{L_1 s}{sC}}\right)$$

$$= \frac{1}{1 + \frac{L_1 + L_2}{R_L} s + L_1 C s^2 + \frac{L_1 L_2 C}{R_L} s^3}$$

$$\text{Butterworth} \rightarrow \frac{1}{1 + \frac{2s}{\omega_{n1}} + \frac{2s^2}{\omega_{n2}} + \frac{s^3}{\omega_{n3}}}$$

$$\frac{(L_1 + L_2)}{R_L} = \frac{2}{\omega_{n1}} \; ; \; \omega_{n1} = \frac{2R_L}{(L_1 + L_2)}$$

$$L_1 C = \frac{2}{\omega_{n2}{}^2} \; ; \; \omega_{n2} = \frac{1414}{\sqrt{(L_1 C)}}$$

$$\frac{L_1 L_2 C}{R_L} = \frac{1}{\omega_{n3}{}^3} \; ; \; \omega_{n3} = \omega_{n2}{}^2 \frac{R_L}{2L_2} = \omega_{n2}{}^2 \omega_{n4}$$

$$\omega_{n4} = \frac{R_L}{2L_2}$$

Figure 9. *Analysis of a third-order (three pole) low-pass filter, where ω 1, ω 2, and ω 4 occur at the same -3dB frequency of ω_o*

The design of a line filter need not obey the Butterworth alignments precisely (although such alignments do provide a good basis for design); moreover, because of leakage current limits placed upon electronic equipment (thus limiting the amount of filter capacitance to ground), adjustments to the alignments are usually required, but they can be executed very simply as follows:

1. First, design a second-order low-pass filter with ζ ≥ 0.5.
2. Add a third pole (which has the desired corner frequency) by cascading a second inductor between the second-order filter and the noise load: $L = R/(2\pi f_c)$, where f_c is the desired corner frequency.

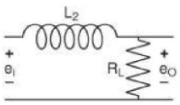
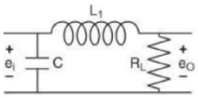
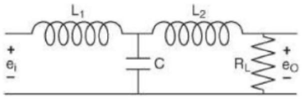
	First Order	Second Order	Third Order
Filter Schematic			
Filter Transfer Function	$\frac{e_0}{e_i} = \frac{1}{(Ls/R_L) + 1}$	$\frac{e_0}{e_i} = \frac{1}{LCs^2 + (Ls/R_L) + 1}$	$\frac{e_0}{e_i} = \frac{1}{(L_1L_2/R_L)s^3 + L_1Cs^2 + ((L_1 + L_2)s/R_L) + 1}$
Butterworth Alignment	$\frac{e_0}{e_i} = \frac{1}{(s/\omega_n) + 1}$	$\frac{e_0}{e_i} = \frac{1}{LCs^2 + (Ls/R_L) + 1}$	$\frac{e_0}{e_i} = \frac{1}{(s^3/\omega_{n3}) + (2s^2/\omega_{n2}) + (2s/\omega_{n1}) + 1}$

__Figure 10.__ The first three order low-pass filters and their Butterworth alignments.

Design Procedure

The following example determines the required component values for a third-order filter (for the same requirements as in the previous second-order design example).

1. **List the desired crossover frequency, load resistance:**

   Choose $f_c = 15000$ Hz

   Choose $R_L = 50\ \Omega$

2. **Design a second-order filter with ζ = 0.5** (see second-order example above)

3. **Design the third pole:**

   $R_L / (2\pi f_c) = L_2$

   $50 / (2\pi 15000) = 0.531$ mH

4. **Choose available components and check the resulting cutoff frequency and attenuation:**

   L_2 = 0.508 mH (Coilcraft #E3506-A)

   $f_n = R / (2\pi L_1) = 15665$ Hz

   Attenuation at 60 kHz: 24 dB (second order filter) + 2.9 octave 6 = 41.4dB

5. **The resulting filter configuration is that of Figure 6 with:**

   L_1=2.1 mH

   L_2=0.508mH

   R_L =50 Ω

Conclusion

Specific filter alignments may be calculated by manipulating the transfer function coefficients (component values) of a filter to achieve a specific damping factor.

A step-by-step design procedure may utilize standard filter alignments, eliminating the need to calculate the damping factor directly for critical filtering. Line filters, with their unique requirements and non-critical characteristics, are easily designed using a minimum allowable damping factor.

Standard filter alignments assume ideal filter components; this does not necessarily hold true, especially at higher frequencies. For a discussion of the non-ideal character of common-mode filter inductors, refer to the application note “Common Mode Filter Inductor Analysis,” available from Coilcraft.

TECHNICAL ARTICLE

Passive LC Filter Design and Analysis

Using measurement-based models for design and analysis

Passive electronic LC filters are used to block noise from circuits and systems. Ideal filters pass the required signal frequencies with no insertion loss or distortion and completely block all signals in the stop-band. Real filters have DC and AC resistances that contribute to insertion loss, requiring careful component selection.

Selecting the exact values of the components required for a particular application may appear to be a daunting task for beginners. Filter categories include low-pass, high-pass, band-pass, band-stop, all-pass, and multiplexers. The simplest to design and implement are the low-pass and high-pass types.

A number of possible filter alignments exist, including Butterworth, Bessel, Chebyshev, and elliptic. Selection of the filter alignment involves trade-offs in the flatness of the frequency behavior versus the sharpness of the cut-off. The very simplest LC filter consists of an inductor and a capacitor. Higher-order filters use more components to give a sharper, more defined roll-off for better attenuation of unwanted noise. See Appendix A for details. The good news is that modern circuit synthesis and analysis programs can quickly perform otherwise tedious and time-consuming calculations. Filter synthesis programs generate the required inductance (L) and capacitance (C) values. Analysis programs simulate the results after the user enters the appropriate values. Once the initial ideal values have been calculated, practical solutions are created using off-the-shelf components.

Modeling Filter Behavior

Ideally, one could simply define the band of frequencies to be passed, and those to be blocked, and a program would generate standard component values resulting in the actual on-board performance.

Free programs for generating basic filter designs are available on the internet, such as Design LC Filters (V 3.0) at wa4dsy.net. Programs like this synthesize a filter design using ideal element values as a starting point. If the design results are not standard values, some compromises in performance may be necessary. Substitute standard part values and run a circuit simulation to determine the effects on the filter performance.

For lower-frequency filter designs, ideal component models may be sufficient for analysis. However, the effects of circuit parasitics of inductors, capacitors, and circuit board traces may require the selection of slightly different component values to tune the performance of higher-frequency filters. In this case, for better prediction of the real filter, accurate inductor models and circuit board trace and pad models should be involved. For many designs, accurate inductance models based on actual component measurements are necessary, but ideal capacitors can be used for the simulation. Simulations of filters approaching the Gigahertz range may require non-ideal capacitor models as well.

Coilcraft offers free, accurate, measurement-based models of many off-the-shelf inductors as seen in **Figure 11**, including detailed instructions for implementing them in popular simulation programs, on our Spice Models / S-parameters page at Coilcraft.com. These inductor models help get your filter design closer to real performance than simpler, ideal inductor models. Finally, a prototype board should be assembled, tested, and tweaked if necessary. Once the design appears to be acceptable, analysis of the effects of component tolerances can be performed.

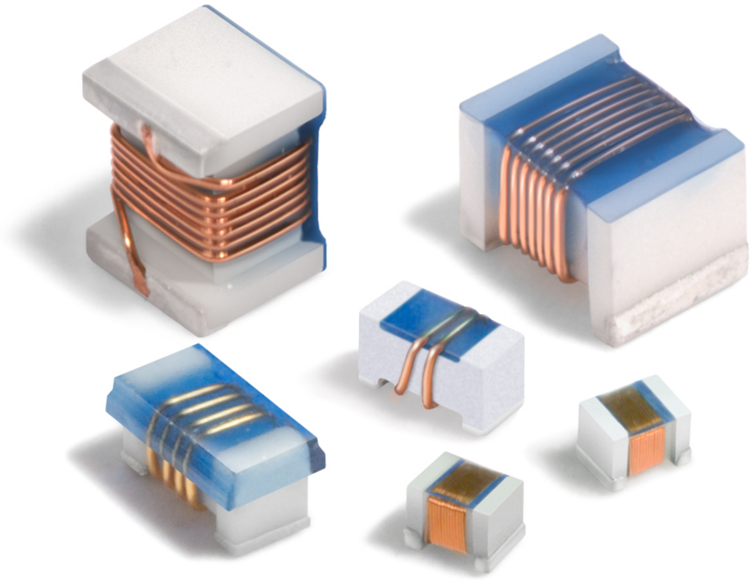


Figure 11. *Coilcraft offers a wide variety of tight-tolerance ceramic chip inductors, SPICE models, and design support.*

Demonstrated Low Pass and High Pass Solutions

To simplify LC filter design, Coilcraft has created LC filter reference designs, including 3rd-order Butterworth lowpass and high-pass, and 7th-order elliptic filters. These designs demonstrate the high performance that can be achieved using Coilcraft inductors and standard capacitors.

References

1. Rhea, Randall W., *HF Filter Design and Computer Simulation* (Noble Publishing Corporation, 1994)
2. Vizmuller, Peter, *RF Design Guide* (Artech House, Inc., 1995)
3. Williams, Arthur B., *Electronic Filter Design Handbook* (McGraw-Hill, 1995)

Appendix A- Filter Alignments and Properties

Butterworth - Maximally flat (more linear) pass-band response, slower roll-off, flat stop-band response. Requires a higher order to achieve a specific stop-band spec. vs. Chebyshev and Elliptic.

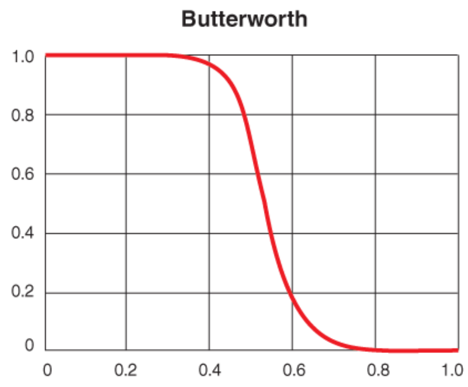
Chebyshev (Type 1) - More pass-band ripple, sharper roll-off, flat stop-band Response

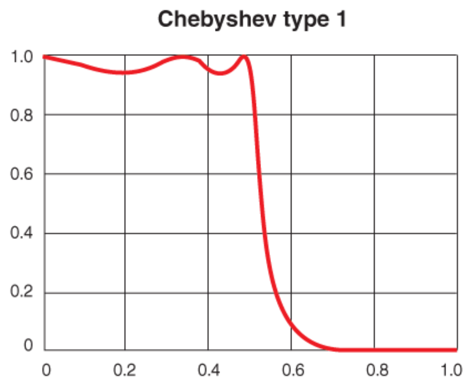
Chebyshev (Type 2) - Flat pass-band response (requires more components), sharper roll-off, more stop-band ripple

Elliptic (Cauer) - Sharpest roll-off, more pass-band ripple and stop-band ripple. Equiripple elliptic filters are maximally insensitive to component variation.

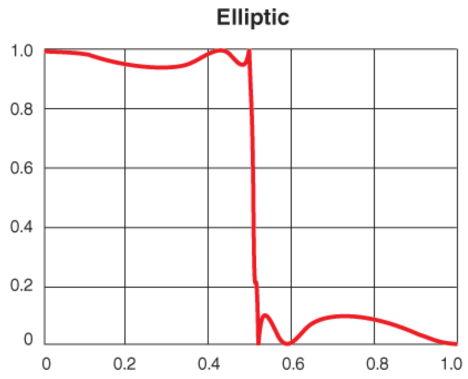
Bessel - Maximally flat group delay (maximally linear phase response) that preserves the wave shape of signals in the pass-band.

Increasing the number of filter elements increases the performance of the filter. The following curves are the results of 5th-order, low-pass filters:


Butterworth


Chebyshev type 1


Chebyshev type 2


Elliptic

Source: *http://en.wikipedia.org/wiki/Electronic_filter*

TECHNICAL ARTICLE

Selecting Common Mode Filter Chokes for High-Speed Data Interfaces

Introduction

High-speed data interfaces like USB, HDBaseT™, HDMI, DVI, and DisplayPort require careful consideration to ensure reliable communication that is free of disruptive EMI. Of the many tools at the designer's disposal, like trace routing, termination, and component placement, the common mode filter choke remains one of the most powerful. For the variety of signal sizes, thermal variations, and spectral density in high-speed communications, the common-mode filter choke is an effective and widely used interface circuit component. Common-mode chokes help maintain the integrity of high-speed communications and may be necessary for FCC and international regulatory standards conformance. FCC CFR 47 applies generally to radio frequency devices (Part 15) and includes particular requirements for Industrial, Scientific, and Medical Equipment (Part 18). In addition to required standards conformance, there may be other application-specific requirements. For example, major automakers maintain their own EMI requirements for vehicles.

Common Mode Choke Selection

The optimal common mode choke for a particular application depends on many factors. The first step in choosing the best part is to select only those that will not adversely attenuate the differential signal. The communication standard (**Table 1**) determines the data rate and, therefore, the required bandwidth for the differential mode performance.

Table 1. *Typical Data Rates*

Signal Interface	Data Rates	Signal Interface	Data Rates
USB2.0 (High Speed)	480 Mbit/s	FireWire S1600/S3200	1.57 Gbit/s and 3.15 Gbit/s
USB3.1 Gen 1 (SuperSpeed) (former USB3.0)	5 Gbit/s	LVDS per ANSI/TIA/EIA-644-A	Up to 1.9 Gbit/s
USB3.1 Gen 2 (SuperSpeed+)	10Gbit/s	PCI Express® 2.0	500 Mbit/s
HDMI®	1.65 Gbit/s to 6 Gbit/s;	SATA 1.0/2.0/3.0/3.1/3.2	1.5 Gbit/s;3 Gbit/s;6 Gbit/s;6 Gbit/s;16 Gbit/s
HDBaseT	Up to 10.2 Gbit/s	DVI	Up to 3.96 Gbit/s
FireWire 800/S800T (IEEE1394b-2002/ IEEE1394c-2006)	Up to 800 Mbit/s	DisplayPort	Up to 8.1 Gbit/s

It is important, but relatively straightforward, to select a part with low differential mode attenuation within the signal frequency range. **Figure 12** shows the -3dB differential mode cutoff frequency for Coilcraft's 0805USBN Series (**Figure 13**), which is clearly above 1GHz and up to 6.5GHz. Therefore, distortion of the high-frequency differential mode signal and its harmonics can be kept at a very small level, making our 0805USBN parts suitable for typical USB3.1 Gen 1 data rates, as are our 0805USBF and 0603USB Series.

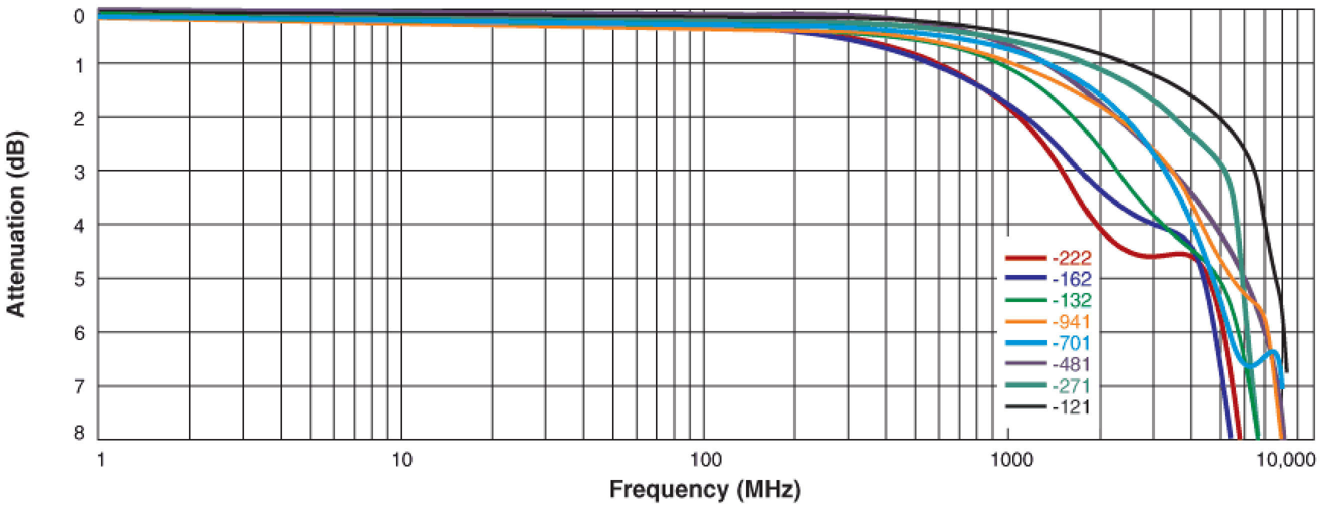


Figure 12. *Differential mode attenuation for 0805USBN.*

Even though the differential mode performance is straightforward, and the requirement is predictable for a given data rate, the real focus should be on determining the required common mode performance. The amount of filtering required also depends on the data rate but is harder to predict because of all the possible physical aspects of the application that may affect the amount of undesirable EMI generated. Design considerations such as impedance matching, connector pin impedance, trace widths, and shielding may impact the final design.

Figure 13. *Coilcraft 0805USBN common mode chokes.*

How Common Mode Chokes Operate

As illustrated below, common mode chokes impede noise common to both lines by flux addition when they are connected as shown. In differential mode, the flux cancels and the desired signal is not attenuated as shown in **Figure 14**.

When a challenge does arise, it is important to identify the right solution. One easy choice is to identify application-specific chokes; that is, filter chokes that have been designed with specific applications in mind, like the Coilcraft line of USB common mode chokes. Since real-world EMI challenges do not always fit nicely into pre-arranged solutions, ready access to filter performance data is key. Selecting the appropriate common mode choke has been simplified with Coilcraft's online Common Mode Choke Finder tool at: https://www.coilcraft.com/en-us/tools/common-mode-choke-finder/#/.

To start, specify the filtering requirements of your application: the desired amount of impedance or the attenuation at a particular frequency (or frequency range). Alternatively, if a specific inductance value has already been identified, the tool can search from that input as well.

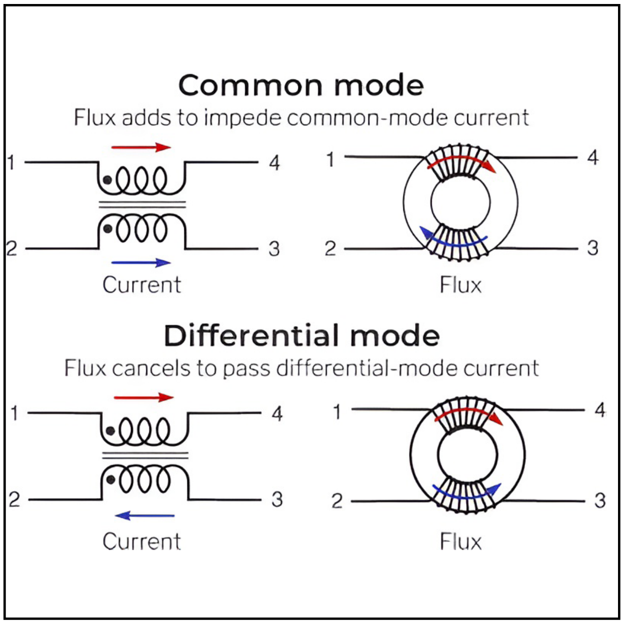
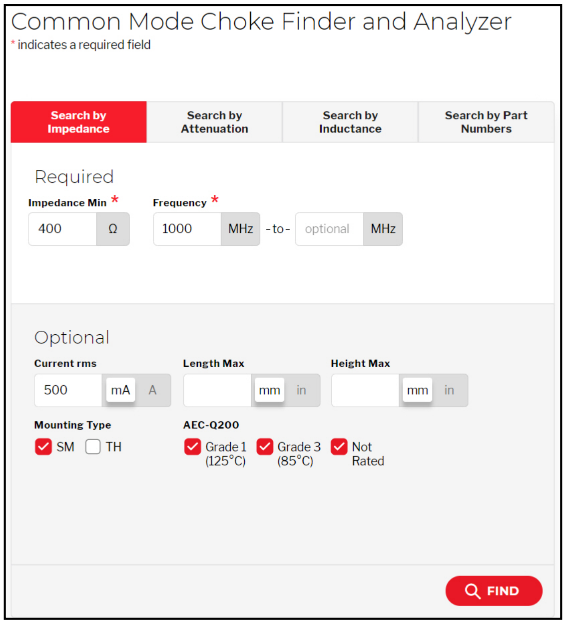


Figure 14. Flux adds to impeded common mode current and cancels to pass differential mode current.



Common Mode Choke Finder and Analyzer

* indicates a required field

Required

Impedance Min *: 400 Ω

Frequency *: 1000 MHz -to- optional MHz

Optional

Current rms: 500 mA A

Length Max: mm in

Height Max: mm in

Mounting Type: ☑ SM ☐ TH

AEC-Q200: ☑ Grade 1 (125°C) ☑ Grade 3 (85°C) ☑ Not Rated

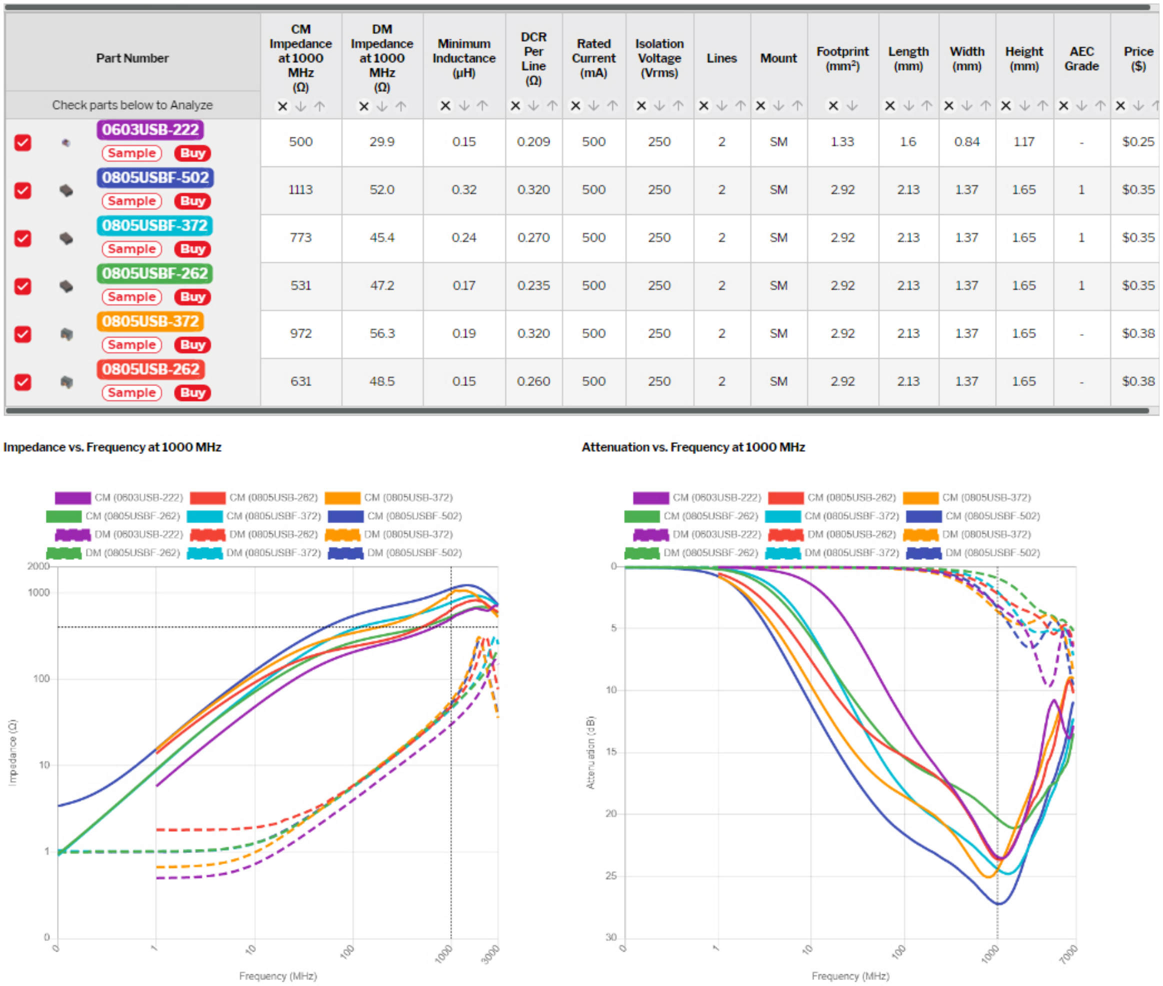
Figure 15. Coilcraft Common Mode Choke Finder and Analyzer search results page

From this information, the tool searches a wide database and presents the best solutions. All of the recommended common-mode chokes are presented in a sortable table (see **Figure 15**) that includes all the pertinent specifications and actual-size photos. The table is initially listed with the smallest size (shortest length) parts at the top. You can then sort the results by other specifications such as impedance or attenuation, current rating, height, and many other characteristics. Pricing information is also included in the table.

One of the most powerful capabilities of this tool is the ability to compare up to 6 different filters on the same graph, making direct, side-by-side comparisons between products much easier. Impedance and attenuation curves are shown for each selected part over the desired frequency range (**Figure 16**). By moving the cursor over the curves, users can see the exact data point at any frequency of interest via a small pop-up window.

Coilcraft's Common Mode Choke Finder is the most sophisticated and easy-to-use online tool available in the industry. It is a great supplement to the development of your EMI filter design projects, making your common mode chokes selection effective and efficient.

Of course, you can also search the old-fashioned way by browsing web pages. We've also made this easier by collecting all our common mode chokes on one handy page: https://www.coilcraft.com/en-us/Products/emi/.



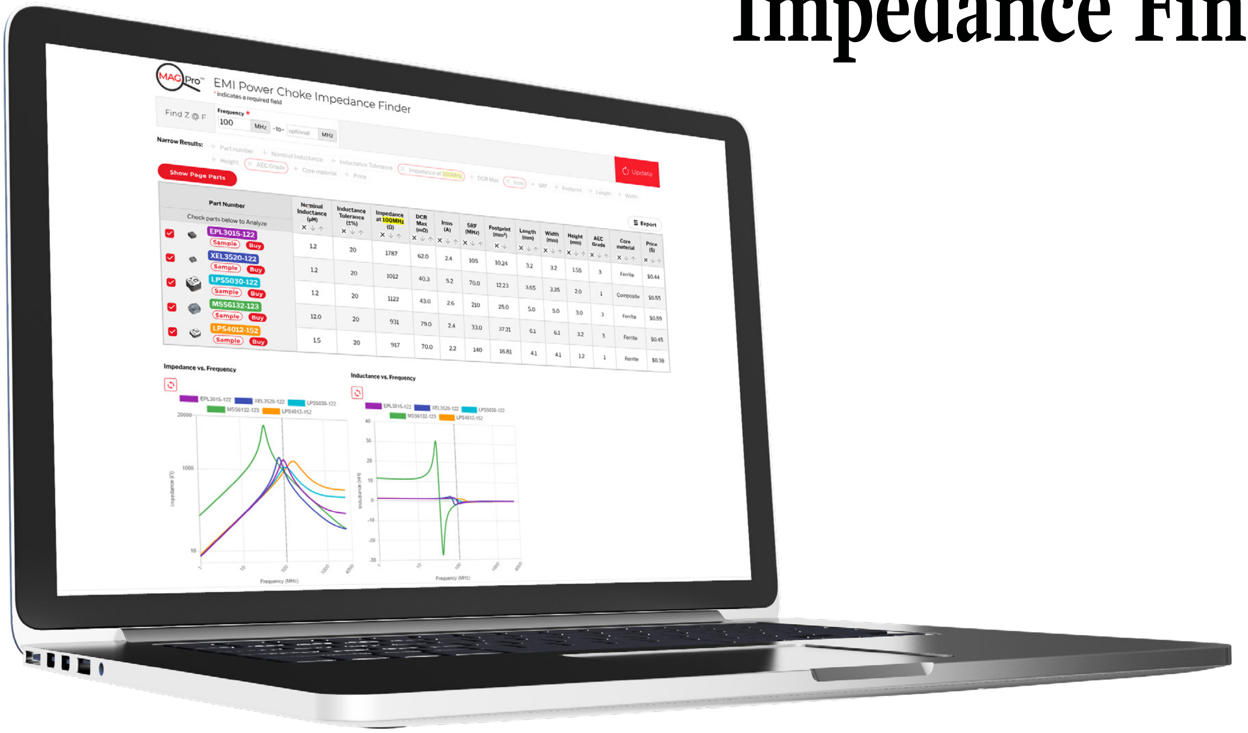
Part Number Check parts below to Analyze	CM Impedance at 1000 MHz (Ω)	DM Impedance at 1000 MHz (Ω)	Minimum Inductance (µH)	DCR Per Line (Ω)	Rated Current (mA)	Isolation Voltage (Vrms)	Lines	Mount	Footprint (mm²)	Length (mm)	Width (mm)	Height (mm)	AEC Grade	Price ($)
☑ 0603USB-222 Sample Buy	500	29.9	0.15	0.209	500	250	2	SM	1.33	1.6	0.84	1.17	-	$0.25
☑ 0805USBF-502 Sample Buy	1113	52.0	0.32	0.320	500	250	2	SM	2.92	2.13	1.37	1.65	1	$0.35
☑ 0805USBF-372 Sample Buy	773	45.4	0.24	0.270	500	250	2	SM	2.92	2.13	1.37	1.65	1	$0.35
☑ 0805USBF-262 Sample Buy	531	47.2	0.17	0.235	500	250	2	SM	2.92	2.13	1.37	1.65	1	$0.35
☑ 0805USB-372 Sample Buy	972	56.3	0.19	0.320	500	250	2	SM	2.92	2.13	1.37	1.65	-	$0.38
☑ 0805USB-262 Sample Buy	631	48.5	0.15	0.260	500	250	2	SM	2.92	2.13	1.37	1.65	-	$0.38

Figure 16. *Coilcraft Common Mode Choke Finder and Analyzer side-by-side comparison graphs.*

References

1. United States Code of Federal Regulations, Title 47, Telecommunication, Pt. 0-1
2. Universal Serial Bus Specification Revision 2.0, Compaq, Hewlett-Packard, Intel, Lucent, Microsoft, NEC, Philips, April 27, 2000
3. Universal Serial Bus Specification 3.0, Hewlett-Packard Company, Intel Corporation, Microsoft Corporation, NEC Corporation, ST-Ericsson, Texas Instruments, Revision 1.0, June 6, 2011
4. High-Definition Multimedia Interface Specification Version 1.3a, Hitachi, Ltd., Matsushita Electric Industrial Co., Ltd., Philips Consumer Electronics, International B.V., Silicon Image, Inc., Sony Corporation, Thomson Inc., Toshiba Corporation, November 10, 2006.
5. IEEE Std 1394.1-2004, E-ISBN: 0-7381-4648-X
6. Electrical Characteristics of Low Voltage Differential Signaling (LVDS) Interface Circuits (ANSI/ TIA/ EIA-644-A-2001).
7. *Creating a PCI Express™ Interconnect*, White Paper, Ajay V. Bhatt, Technology and Research Labs, Intel Corporation.

Eliminate unwanted EMI with our MAGPro® Power Choke Impedance Finder



Part Number Check parts below to Analyze	Nominal Inductance (µH)	Inductance Tolerance (±%)	Impedance at 100MHz (Ω)	DCR Max (mΩ)	Irms (A)	SRF (MHz)	Footprint (mm²)	Length (mm)	Width (mm)	Height (mm)	AEC Grade	Core material	Price ($)
☑ EPL3015-122 Sample Buy	1.2	20	1787	62.0	2.4	105	10.24	3.2	3.2	1.55	3	Ferrite	$0.44
☑ XEL3520-122 Sample Buy	1.2	20	1012	40.3	5.2	70.0	12.23	3.65	3.35	2.0	1	Composite	$0.55
☑ LPS5030-122 Sample Buy	1.2	20	1122	43.0	2.6	210	25.0	5.0	5.0	3.0	3	Ferrite	$0.59
☑ MSS6132-123 Sample Buy	12.0	20	931	79.0	2.4	33.0	37.21	6.1	6.1	3.2	3	Ferrite	$0.45
☑ LPS4012-152 Sample Buy	1.5	20	917	70.0	2.2	140	16.81	4.1	4.1	1.2	1	Ferrite	$0.38

Find off-the-shelf, inductors/chokes for your EMI noise-filtering applications with this powerful new tool

Coilcraft's patented MAGPro EMI Power Choke Impedance Finder is a powerful search and analysis tool developed by engineers for engineers to help you identify the optimal inductors/chokes for various types of EMI filters.

It helps you optimize the design of an input EMI filter or a second stage output filter for switching power supplies and other applications requiring noise reduction.

The Z @ Frequency search option locates inductors that perform at your desired impedance and frequency, allowing you to analyze and compare multiple part numbers of your choice quickly and easily, and then order free evaluation samples for further review.

So take the first step toward suppressing unwanted EMI noise. Start your search today at **www.coilcraft.com/tools**.

Coilcraft®

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