EMI filter components and their nonidealities for automotive DC/DC regulators

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Introduction

When releasing a product to market, it is necessary to pass the specific electromagnetic interference (EMI) standard to which the product is confined. Some designs require more careful attention than others due to stringent EMI standards or system requirements. This article describes the EMI filter architecture used in switch-mode power supplies with a focus on the needs and limitations of the EMI filter's individual sections.

The need for power-supply filtering

It does not matter if a switching power supply is simple or low noise, it is going to need some form of input filtering to pass an EMI standard, such as the Comité International Spécial des Perturbations Radioélectriques (CISPR)-25 Class 5.

The switching nature of a buck converter results in EMI generation. The noise generated in the converter has two noise paths—conducted and radiated—that couple to other circuits and to the EMI-compliance test setup. To meet EMI regulatory standards, a starting point is to review the design and layout information available for the converter. For example, the LM5146-Q1 datasheet[1] provides detailed information for various appications. Then, additional evaluation may be required to determine specific EMI problems in the converter circuit.

To illustrate a specific EMI problem, Figure 1 shows an EMI sweep on a well-laid-out board without an EMI filter. The horizontal red lines are the emission limit lines set by CISPR. The turquoise and yellow lines are the average and peak conducted emissions levels, respectively. This test shows that the design fails to meet average and peak emission levels by 20 dB in the FM band (76 MHz to 108 MHz).

Since an EMI filter is often required, the scope of this article will be about understanding the components related to the EMI filter so that a converter can be designed to have excellent performance without having to add additional components.

A general power-supply EMI filter

For reference in the following discussion, Figure 2 illustrates a typical EMI filter implementation that is powered by a line-impedance stabilization network (LISN) power source.

Low-frequency differential-mode filtering

Fourier analysis shows that a trapezoidal waveform contains even and odd harmonics of the fundamental frequency (switching frequency), whose energies often extend to high frequencies. The input current of a buck converter requires that the input capacitor must supply

Figure 1. A CISPR-25 Class-5 conducted EMI sweep without an EMI filter installed

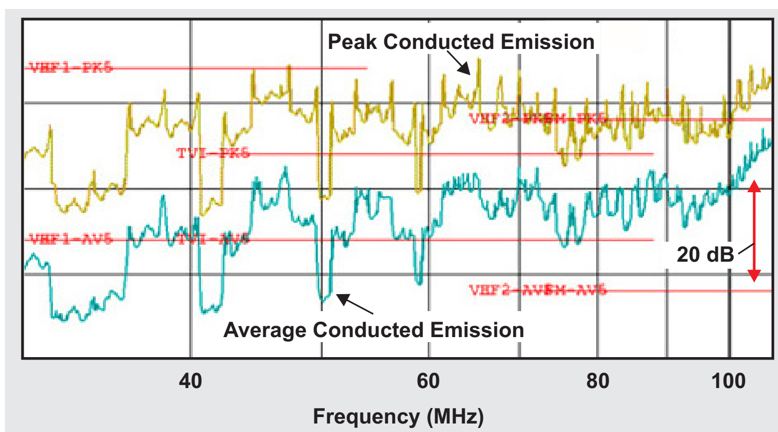
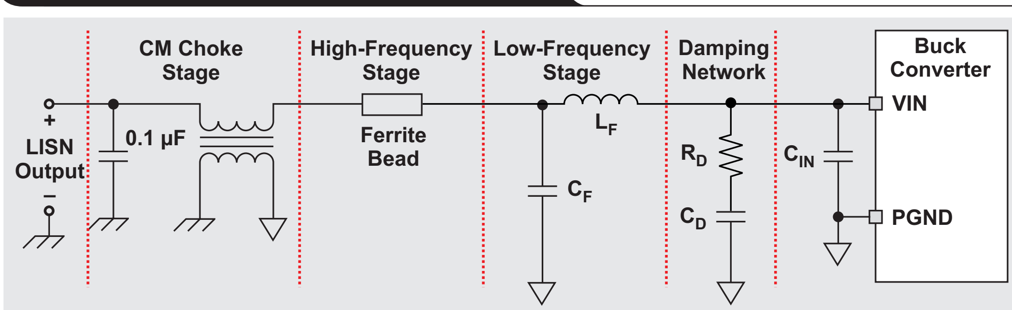


Figure 2. EMI filter with three input stages



large AC trapezoidal currents to the high-side MOSFET. These currents flow in and out of the input capacitor, which generates a voltage across the finite impedance of the input capacitor. Positioning an EMI filter at the input of a buck converter will attenuate the generated voltage and achieve EMI compliance.

An LC filter attenuates noise at the input (see the low-frequency stage in Figure 2). A second-order LC filter will have a –40dB/decade rolloff. This information allows the required corner frequency (f_C) to be determined based on the required attenuation (A), in decibel microvolts, of the noise at a particular frequency (f).

Equation 1 solves for the required attenuation (A) based on the specific EMI standard-emission limits and noise level of the initial sweep data:

$$A\left[\text{dB}\mu\text{V}\right] = 40\log\left(\frac{f}{f_C}\right) \quad (1)$$

Equation 2 solves for the required corner frequency (f_C) to achieve the required attenuation (A) based on the specific EMI standard-emission limits and noise level of the initial sweep data:

$$f_C = f \times 10^{-A/40} \quad (2)$$

Optimizing the corner frequency ensures that the component sizes are feasible. Using large-value, high-voltage capacitors can increase bill-of-materials cost. In addition, an increase in inductance value, while improving low-frequency attenuation, may compromise high-frequency performance.

Component nonidealities

Unfortunately, the component limitations of an LC filter pose a problem for filtering in the FM band. An inductor has a finite self-resonant frequency (SRF), which can create a high impedance in the FM band. Figure 3 illustrates a typical impedance curve of an inductor with identified regions of the impedance curve that are most affected by each component.

For low frequencies, the nonideal inductor impedance behaves as expected, with a positive slope related to its inductance. At some frequency, the inductor reaches its maximum impedance. At this point, the SRF of the inductor has been reached, where the parasitic capacitances of the inductor resonates with the ideal inductance, making the device appear as a very high impedance. Beyond this point, the impedance of the inductor often falls off rapidly.

Inductor selection must factor in SRF. Often, the SRF of a particular inductor series increases with smaller package size and inductance. One way to achieve the highest level of attenuation is to select the smallest possible package size for the required inductance and current capabilities. This enables improved high-frequency attenuation of the filter, as illustrated in Figure 3.

The resonant frequency of the input capacitor also has to be acknowledged when designing a filter. Often, the equivalent series inductance (ESL) of a capacitor limits the high-frequency performance. Just as in the case of the inductor, ESL can be minimized by limiting the value and size of a given capacitor.

Figure 3. Impedance curve of an inductor based on real inductor parasitics[2]

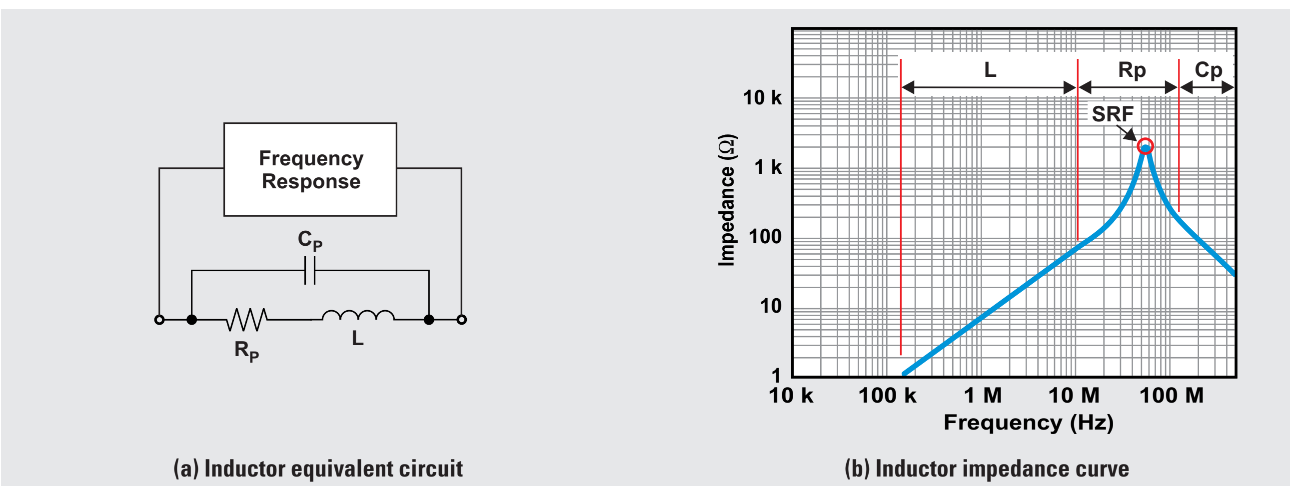


Figure 4 provides the impedance characteristics for a family of capacitors in the same package size. The figure illustrates that a lower-value capacitance behaves like an ideal capacitor up to higher frequencies compared to a higher-value capacitor. With this in mind, one technique to achieve a better frequency response is to parallel capacitances of the same value to form a large capacitance. This reduces the effective ESL and avoids the need to use a single capacitor with a large capacitance and high voltage rating, which increases design size and cost.

Additionally, as depicted in Figure 4, paralleling a couple of capacitors of different values, typically a decade apart, enables reduced impedance between the signal path and ground at higher frequencies.

Filter damping

A filter requires damping to reduce the peaking at the corner frequency of the filter. Peaking can result in significant amplification of noise at low frequencies, resulting in a noncompliant design.

A poorly damped filter can also have significant effects on the stability of a power converter. The damping of the filter is directly related to the output impedance of the EMI filter. A typical approach for damping the filter is to use a parallel RC circuit (the damping network shown in Figure 2). This replicates the electrical characteristics of an electrolytic capacitor, providing similar rejection at low frequencies without taking up a significant portion of the available board space.

Equation 3 expresses the optimal damping resistor, R_D:

$$R_D = \sqrt{\frac{L_F}{C_{IN}}} \tag{3}$$

Equation 4 determines the optimal damping capacitance, C_D. These equations are formed for optimal impedance of C_D at the filter's resonant frequency and the R_D used to reduce the filter's output impedance at resonance. Parallel damping ensures that sufficient damping can be achieved without creating excessive power loss, in contrast to placing a series resistance in the power path.

$$C_D = 4C_{IN} \tag{4}$$

Figure 4. General impedance curve for similar capacitors of increasing value[3]

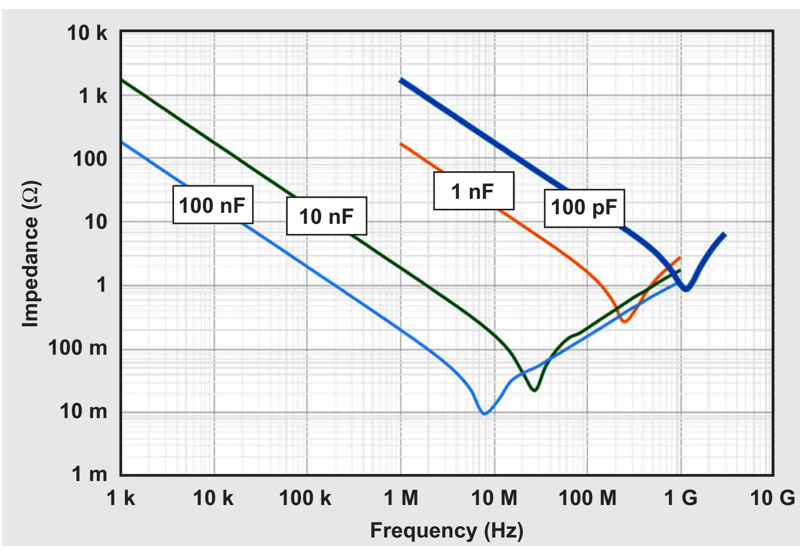
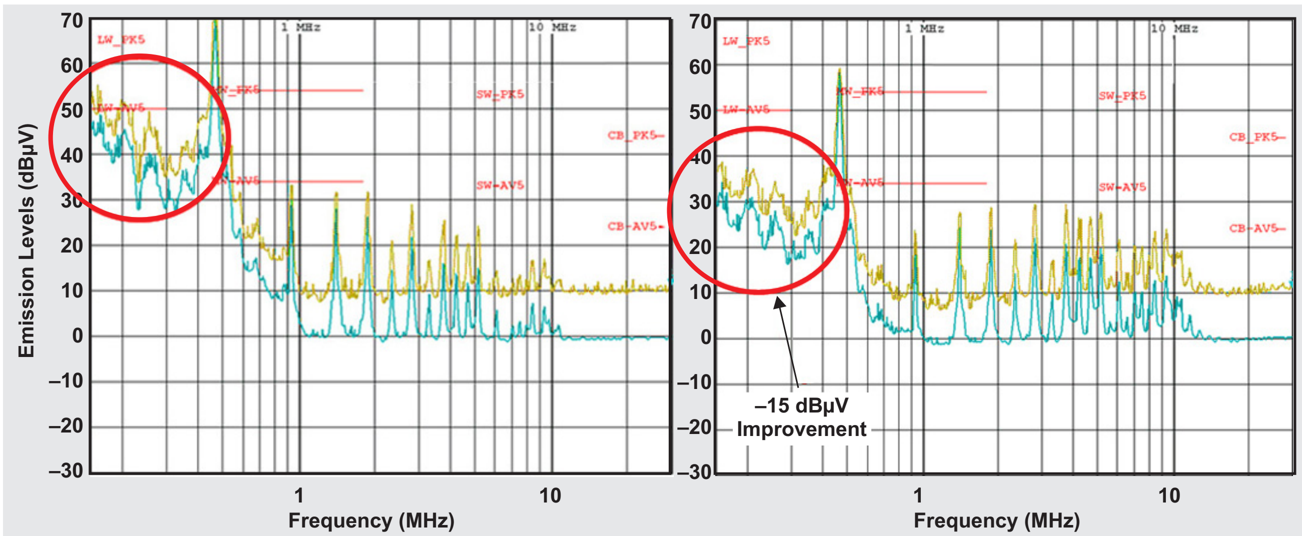


Figure 5. Low-frequency improvement with parallel RC damping



(a) Without damping

(b) With damping

Figure 5 demonstrates a reduction in EMI when implementing a parallel RC network as outlined in Equations 3 and 4.

Filtering common-mode (CM) noise

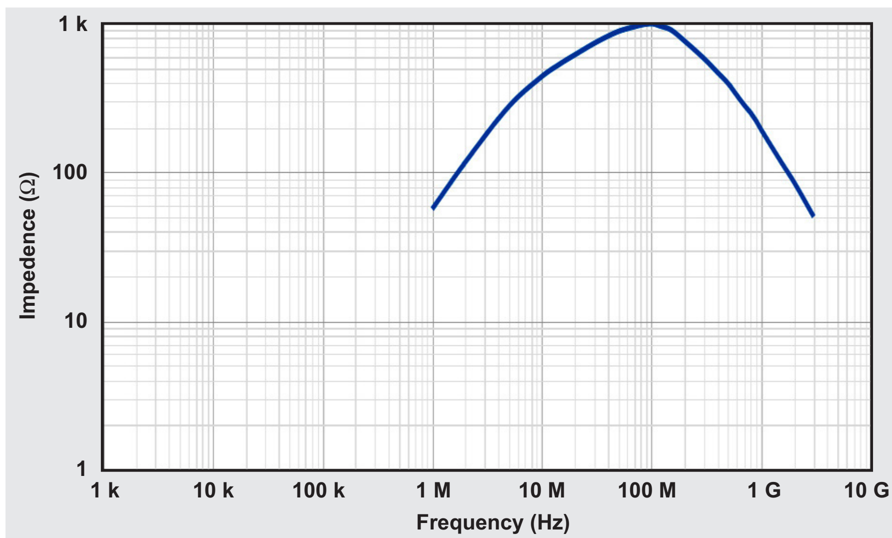
CM noise can be one of the most difficult noise sources to deal with in a switch-mode power supply. CM noise is especially difficult to deal with in the FM band, due to stringent standards. While there may not be any true half-wave-length dipole antennas in a system to capacitively couple CM noise, plenty of traces are efficient enough to couple this noise and make a design fail in this region.

Typically, the biggest generator of CM noise in a buck converter design is the switch node. The switched waveform, with magnitude equal to the converter's input voltage, radiates an electric field and become worse in applications with higher input voltages.

The amplitude of the electric field falls inversely with distance in the near field. This is a problem, as designers want to shrink implementation size but keep the switching frequency relatively fixed, which results in no change in output-inductor and switch-node sizes.

One way to filter CM noise is to place mutually paired inductors, or a CM choke, in series with the input paths (the CM choke stage shown in Figure 2). This method can provide sufficient CM noise rejection up into the hundreds of megahertz.

Figure 6. Typical CM impedance curve for a CM choke[4, 5]

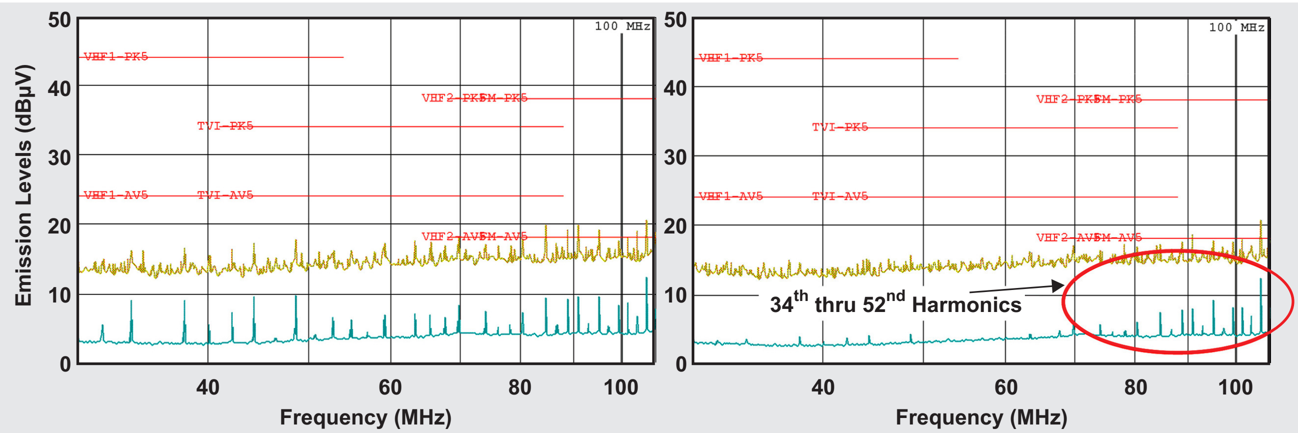


Component selection for CM filter

When selecting a CM choke, the plot for impedance versus frequency is crucial. For a wideband CM choke, the CM impedance curve resembles Figure 6.

A typical approach when determining what CM choke to use is to consider the impedance at the noise band in need of attenuation and the DC losses associated with the choke. These two values are used to determine the trade-offs for the cost and size of the CM choke.

Figure 7. Illustrating the impact of the high-frequency stage



(a) Without ferrite bead (b) With ferrite bead

High-frequency differential-mode filtering

One of the limitations of the LC filter stage is the finite SRF of the inductor, which leads to high-frequency noise (typically greater than 85 MHz), which is not getting attenuated as greatly as the lower frequencies.

This issue is extremely troublesome, as it occurs right at the start of the FM band, which often has the most stringent limit lines. An additional high-frequency stage (shown in Figure 2) can alleviate this issue.

Mathematically, the lowest-order harmonic that falls in the FM band is the 41st harmonic for a 2.1-MHz power converter. It may be assumed that this order of harmonic would be relatively low in energy; however, it is significant enough to make the design fail CISPR-25 Class 5 (as shown in Figure 7), even with dithering techniques such as spread spectrum.

There is some additional high-frequency energy captured in the input spectrum of a buck converter. This energy arises from high-frequency ringing on the switch node that capacitively couples back to the input power lines and/or test setup. The energy often falls in the 200- to 300-MHz range, significantly above the SRF of the low-frequency-stage inductor and the resonance frequency of the LC filter. Nevertheless, it is not a concern, as the noise will be CM and can only be attenuated by a CM choke.

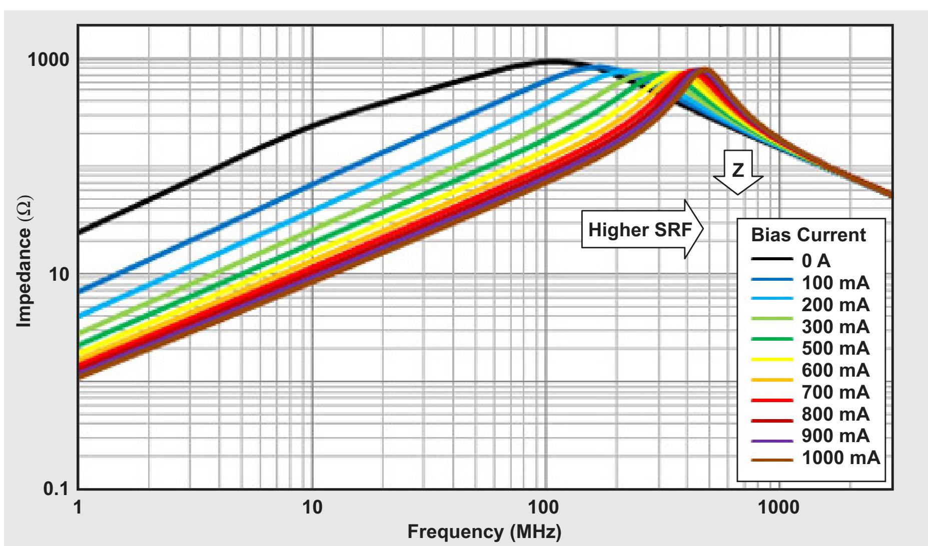
Ferrite bead selection

A ferrite bead is a device with a low inductance and small parasitics that enables a very high SRF, which provides rejection in the hundreds of megahertz. Ferrite beads filter differential-mode noise at frequencies above the SRF of the low-frequency stage.

Ferrite-bead data sheets do not provide much information; they may give only one impedance curve at a zero DC-bias current. In fact, for a buck converter, a ferrite bead could be biased in the order of hundreds of milliamps or more. Figure 8 demonstrates the general derating of rejection with increasing bias current for a ferrite bead, which results in higher noise emissions.

To select an adequate ferrite bead, several ferrite beads rated for the buck converter's input current should be characterized with the highest impedance at frequencies close to the FM band, or at frequencies above the SRF of the low-frequency stage.

Figure 8. General derating/saturation of ferrite beads[6]



Conclusion

Taking the approach outlined in this article for EMI filter design can result in a more efficient converter design before it is released to market. Understanding the individual parts in an EMI filter and how to implement them correctly allows for an EMI-compliant design without impacting the size, cost and reliability of the power supply.

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