Electronic systems throughout the world are powered by direct current (usually after AC rectification), which in most cases is converted by DC-DC converters to the voltages needed by each part of the system. Today, power conversion is usually accomplished by high-density DC-DC converter components based on high-frequency switching technologies. Efficient high-frequency operation has long been recognized as the key to achieving high-power density and improved performance in switch-mode converters. High-frequency operation translates into smaller magnetics and capacitors, faster response times, lower noise levels and smaller filters. Unfortunately, however, all DC-DC converters generate electromagnetic interference (EMI) or noise. This noise – common-mode, differential-mode, and radiated noise – can vary widely among DC-DC converters from supplier to supplier and topology to topology. The reasons for this are diverse, but they include fundamental differences in the way noise is produced.

Although many different topologies are used, none is superior in every respect. Some applications have requirements that are best satisfied by a specific topology. Although the number of designs, or topologies, of DC-DC converter components certainly number in the hundreds, two are dominant: pulse-width modulation (PWM) and quasi-resonant zero-current switching (ZCS).

Full consideration of the large number of topologies available could be a daunting task, so it is helpful to consider the noise performance of the two main topological classes. Specifically, a comparison is made between DC-DC converters using fixed frequency PWM and variable frequency quasi-resonant ZCS.

**Pulse-width modulation vs quasi-resonant zero-current switching.** PWM converters are power density limited because they inherently trade off efficiency against operating frequency. The problem is "switching losses": heat is generated in the switching element each time it discontinuously makes and breaks inductive current flow during its brief turn-on and turn-off transitions. Power dissipation, due to switching losses, increases directly with operating frequency in PWM converters until it becomes a dominant loss factor. At that point, efficiency declines rapidly, and the thermal and electrical stresses on the switch element become unmanageable. Losses attributable to non-zero-current-switching result in a "frequency barrier" which limits achievable power density in conventional converters.

Quasi-resonant ZCS converters overcome the frequency barrier by implementing a forward converter switching at zero current. Each switch cycle delivers a quantized "packet" of energy to the converter output, with switch turn-on and turn-off occurring at zero current. Zero-current switching results in an essentially lossless switch. ZCS converters can operate at frequencies in excess of 1 MHz. By eliminating the fast current discontinuities characteristic of conventional topologies, zero-current switching results in a virtually lossless transfer of energy from input to output with dramatically reduced levels of conducted and radiated noise.

The noise generated by the switch is a major difference between PWM and ZCS converters. Figure 1 shows a comparison of conducted input noise generated by ZCS and PWM DC-DC converters. Among other differences (because ZCS converters have sinusoidal waveforms rather than square waveforms), the lack of sharp edges and lower harmonic content results in much less excitation of the parasitic elements, resulting in less noise. With the pulse-width modulation approach, the input voltage is switched at a constant frequency (usually several hundred kilohertz) to create a pulse train. The width of the pulses is adjusted to provide the necessary power to the load at the correct voltage. At full load, the current waveform looks much like a square wave (see Figure 2).

Many designers intuitively assume that it’s easier to design a filter for a fixed frequency converter than for a variable frequency converter. In actuality, the opposite is true. The perception is, in all likelihood, attributable to the term “fixed frequency”, which is actually a misnomer. Both topologies, in fact, have frequency elements that are more or less fixed and frequency elements that vary as a function of operating conditions.
Figure 2 compared the waveforms of the current flowing through the main switch. In a module using a quasi-resonant topology, the pulse width, T1, is fixed, while the repetition rate, T2, is variable, and in a module using PWM, the opposite is true; the repetition rate is fixed and the pulse width is variable. Each of these topologies generates characteristic noise spectra as shown in Figure 3.

In the variable-frequency design, however, there are no high-frequency components associated with the leading and falling edges of the current waveform, T3, because it is essentially a half-wave rectified sine wave. The spectral content of the variable frequency waveform is lower in amplitude and contained in a narrower band.

In PWM converters, most of the energy is at the fixed frequency and odd multiples (harmonics) of it. A 100 kHz PWM converter will have most of its conducted noise at 100 kHz and some at 300 and 500 kHz. They also have significant harmonics at or above 10 – 30 MHz due to the shape of the current waveform, i.e., high d/dt's that excite parasitic elements within the converter. The input conducted filter has to be sized to handle maximum power at 100 kHz. In the fixed frequency waveform, the spectral content is higher in amplitude and spread over a broader range of harmonics.

It is clear that an effective first step to minimize noise generated by the DC-DC converter is to select a topology – such as zero-current switching – that is inherently lower in common-mode noise. Incidentally, some products should be avoided in noise-sensitive applications. Control devices mounted on copper plates, for example, create parasitic capacitance from primary referenced control devices to secondary referenced control devices through the copper base, resulting in high common-mode noise.
Passive EMI filter examples. Although component power modules usually incorporate some internal input and output filtering, additional external filtering is often needed to meet either system requirements or agency specifications. For example, FCC and European agencies specify the allowable levels of power supply noise that may be conducted back into the AC line. Many designers tackle these issues on their own, but most DC-DC converter manufacturers provide detailed application notes and offer the assistance of a knowledgeable, experienced, and easily accessible applications engineering staff. In addition, some DC-DC converter suppliers also offer AC front ends and EMI filters as modular accessories. These filters not only save time; they are a means of risk prevention as well. The EMI filter is designed to work with the supplier’s converter modules, and, assuming proper layout, the combination is certified to meet the specified EMC directives.

In the U.S. and Europe, conducted noise emissions are governed by the Class A and Class B limits of both FCC and VDE standards. In the U.S., the FCC requires compliance with Class A for equipment operating in factory settings and Class B — the stricter standard — for equipment destined for home use. In Europe, all countries require that equipment for both home and factory use meets the VDE Class B standard.

Most switching power supplies today operate in the frequency range between 100 kHz and 1 MHz. Usually, the dominant peaks in the conducted noise spectrum reflected back to the power line correspond to the fundamental switching frequency and its harmonic components.

Conducted emissions standards such as EN55011 and EN55022 set quasi-peak and average limits on conducted noise reflected from the input of converters or power supply systems back to the source over the frequency range of 150 kHz to 30 MHz. In order to comply, all of the conducted noise – the peaks in the spectrum – must fall below the specified limits.

EMI filters are most often constructed in a single package (with configurations similar to that shown in Figure 4). The EMI filter is a through-hole filter with a common-mode choke and Y-capacitors (line-ground) plus two additional inductors and an X-capacitor (line-line). Transient protection is provided by Z1. This filter configuration provides sufficient attenuation to comply with the Level-B conducted emissions limit.

Nevertheless, capacitors, inductors, and filters (both active and passive) are commonly used in power supply designs to attenuate the amount of conducted noise, both common-mode and normal-mode. First, the effects on the noise spectrum of adding individual components or filters are shown leading up to the result with a full common-mode filter. Then, one approach to meeting EMI compliance in a contemporary application is discussed.

The 48 Volt input DC-DC converter shown on the left in Figure 5a has a differential-mode capacitor, C1, on the input. This single-mode electrolytic capacitor, 120 µF, 100 Volts, is used to ensure low input impedance, stability, and good transient response. It’s an energy reservoir for the converter. To reap the most benefit, the capacitor must be as close to the input pins of the module as possible.

The module alone and that one capacitor provide a baseline from which to start. The spectra in Figure 5a on the right shows the harmonic content of the noise and the EMI limits, A and B levels, for this converter and differential-mode capacitor combination. These measurements were made at 100% load, nominal line for a 48 V, 150 W DC-DC converter.
With this differential-mode capacitor only, the converter is clearly not meeting the limits, but the power component is not designed to meet any specific EMI limits.

The effect of adding bypass caps to the converter and differential-mode capacitor combination, shown in Figure 5b is rather dramatic. Notice the bypass cap on each input pin to the base plate, which is ground, and each output pin to the base plate. These electrolytic capacitors are 4,700 pf, 100 V Y-caps that are commonly used in the industry. The Y-caps are very effective in attenuating the type of noise that the power component generates.

The 48 V design with 100% load generates a little higher noise than, for example, a 3.3 V design with a 50% load would, but, nevertheless, the spectrum in Figure 5b shows some significant improvement.

Even with the addition of a 27μH differential inductor, L1, Figure 5c shows that the 48 Volt design is still not compliant at the lower frequencies, where noise is still present above the B limits.

Figure 5d shows the next stage. We’re adding a common-mode choke. The differential-mode choke is eliminated because the common-mode choke does have differential-mode inductance. The common-mode inductor accentuates the capabilities of the Y-capacitor. That’s because it provides a high impedance to common-mode noise being conducted out of the converter; therefore, the noise follows the path of least resistance to ground which is through these Y caps.

The spectrum of the 48 Volt converter is just peeking over the top of the B limit; so, a little more filtering would be needed on a 48 Volt converter design. The noise spectrum of a 3.3 Volt converter with a common-mode filter would be below the B limit both at 50% and full load.

Active EMI filter example. The trend toward smaller devices with more functionality in smaller spaces continues unabated in the electronics industry. As spaces shrink, the potential interference between devices increases as systems pack more functions in densely packed boards and racks. As frequencies rise and voltage levels fall, the control of conducted EMI becomes an even more important design task. EMI control,
a complex design task that is highly dependent on many design elements, makes use of filters, both passive and active, to manage conducted noise.

Active EMI filters, in contrast to passive solutions, reduce the volume of the common-mode choke – allowing the filter to be packaged in a 1" x 1" x 0.2" package – and provide a low-profile, surface-mount device. Smaller size saves valuable board real estate, and the reduced height enhances airflow for better heat management.

Active EMI filters (labeled QPI in Figure 6) are available that attenuate conducted-mode and differential-mode noise over the frequency range of 150 kHz to 30 MHz required by conducted emissions standard EN55022 (CISPR22).

![Figure 6 - Typical diagram for an active EMI filter (labeled QPI) for a DC-DC converter. Values of Cin and C1, C2, C3, and C4 are those normally recommended by the converter manufacturer.](image)

Figure 7 shows before and after plots of a DC-DC converter noise profile to demonstrate the performance of an active filter. The plots were taken using the standard measurement technique and set up as defined in CISPR22. The results show the total noise spectrum for a standard DC-DC converter under load compared to the EN55022 Class B Quasi-peak detection limit. The plot shows that an active filter is effective in reducing the total conducted noise spectrum to well below the required limits.

![Figure 7 - Conducted EMI profiles of a DC-DC converter with no filter (top) and with an active EMI filter (bottom).](image)

Designers should be aware that to select and qualify an EMI filter for conducted noise, they must test the filter in their product under the set up and conditions specified in the applicable EMI standards. Filter selection or design must be based on the pre-filtered noise magnitudes and the frequency spectrum of concern. A product’s conducted noise profile includes differential and common-mode noise. It may also include radiated noise depending on the EUT shielding and cabling screening in the measurement setup. The IEC (International Electrotechnical Commission) special committee on radio interference specification CISPR 16-2-1 describes the methods of measurement for conducted disturbances.
Filter performance in the application is highly dependent on the input bus and load impedance and cannot be extrapolated from zero bias 50-Ohm insertion loss data alone. Final noise performance is a complex function of filter elements, equipment grounding and noise source impedances, which vary in magnitude and phase over the frequency spectrum of interest.

The active EMI filters provide active common-mode attenuation of conducted noise over the EN55022 range from 150 kHz to 30 MHz by sensing the common-mode current flowing in the bus lines and creating a low impedance at the shield plane to re-circulate the noise back to the generating source. When connected as shown in Figure 6, the control loop will actively drive the shield pin and reduce the common-mode current in the bus lines to values approaching the common-mode current ratio attenuation curve in Figure 7.

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