Time-Saving and Cost-Effective Innovations for EMI Reduction in Power Supplies

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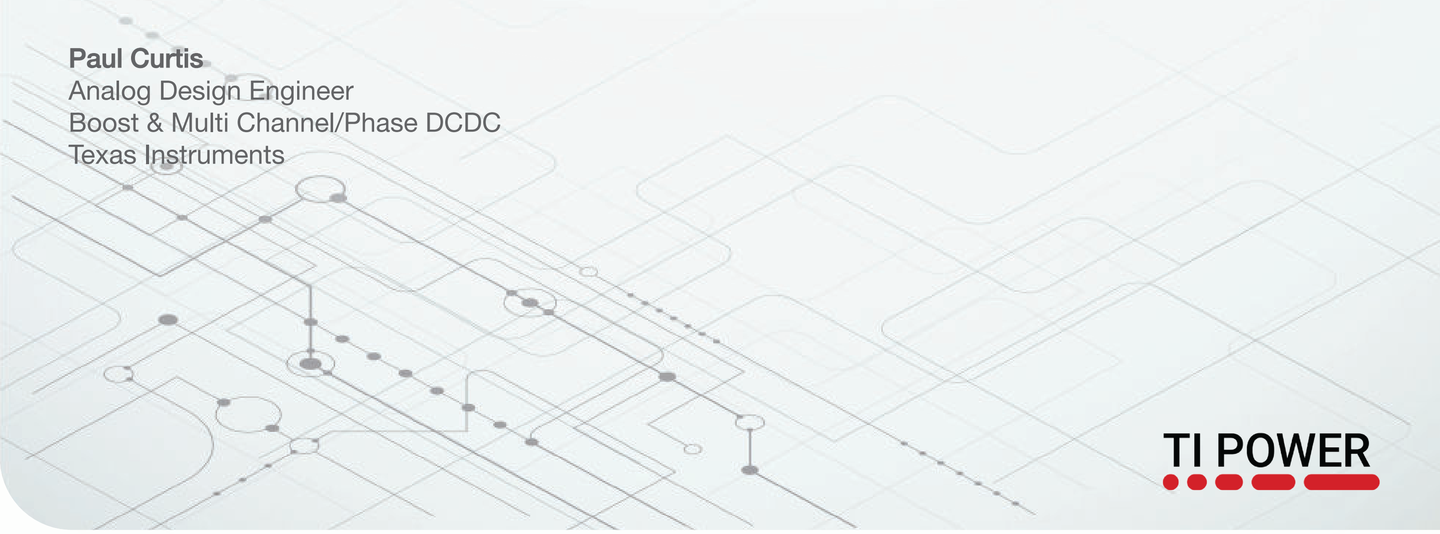


As electronic systems become increasingly dense and interconnected, reducing the effects of electromagnetic interference (EMI) becomes an increasingly critical system design consideration.

At a glance

1

What is EMI?

EMI is electromagnetic energy — produced as an undesirable byproduct of switching currents and voltages — that comes from a variety of physical phenomena and manifests during stringent EMI tests.

2

Conventional methods to reduce EMI in the low- and high-frequency ranges

Reducing EMI is an endeavor plagued with trade-offs. Conventional methods to reduce EMI include using large, expensive filters or reducing switching slew rates, a technique that directly impacts efficiency.

3

Innovations in reducing low-frequency emissions

To realize all of the benefits of a switchmode power supply, it is paramount for EMI reduction techniques to resolve the traditional trade-offs. This requires creative solutions for both low- and high-frequency EMI, as well as accurate modeling techniques.

EMI can no longer be an afterthought, given its potential to cause significant setbacks late in the design phase that cost both time and money. One of the most ubiquitous circuits in modern technology is the switch-mode power supply (SMPS), which provides drastic improvements in efficiency over linear regulators in most applications. But this efficiency comes at a price, as the switching of power metal-oxide semiconductor field-effect transistors (MOSFETs) in the SMPS causes it to be a major source of EMI, which in turn can affect reliability. EMI primarily comes from discontinuous input currents, fast slew rates on switching nodes, and additional ringing along switching edges caused by parasitic inductances in the power loop.

Figure 1 on the following page illustrates how each of these elements manifests itself in different frequency bands, using a buck converter topology as an example. As pressures mount to increase switching frequencies for reduced size and cost, as well as to increase slew rates for improved efficiency, EMI problems are exacerbated. Thus, it is becoming necessary to incorporate cost-effective and easily integrated EMI mitigation techniques that do not compromise the power-supply design.

What is EMI?

In a system that requires electromagnetic compatibility (EMC), components acting as electromagnetic sources are designed to reduce their interference, and components that are susceptible to interference are designed to reduce their susceptibility. When end-equipment manufacturers integrate components from various suppliers, the only way to ensure that the interferers and susceptible circuits can peacefully coexist is through the establishment of a common set of rules, where interference is limited to a certain level, and susceptible circuits are capable of handling that level of interference.

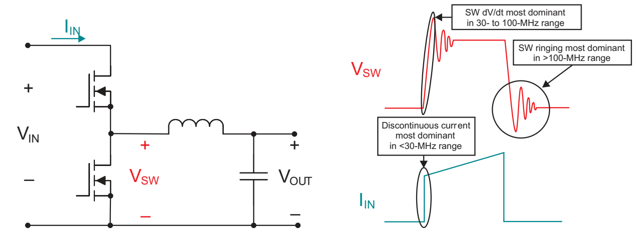


Figure 1. *Example of EMI sources in an SMPS.*

These rules are established in industry-standard specifications such as Comité International Spécial des Perturbations Radioélectriques (CISPR) 25 for the automotive industry, and CISPR 32 for multimedia equipment. CISPR standards are critical for EMI design, as they will dictate the targeted performance of any EMI mitigation technique. This paper's focus will be on reducing interference, as the SMPS is typically the electromagnetic interferer. For a comprehensive list of EMI standards, see **An overview of conducted EMI specifications for power supplies** and **An overview of radiated EMI specifications for power supplies**.

In addition to knowing the appropriate standard for a given application, it is also important to understand how to measure EMI, as this knowledge will give you insight into reducing EMI. EMI measurements are typically divided into conducted and radiated, which reveal both the method of measurement and how the EMI was generated. Although conducted emissions are typically associated with lower frequencies (<30 MHz) and radiated emissions are typically associated with higher frequencies (>30 MHz), the distinction between the two is not quite so simple, as conducted and radiated frequency ranges do overlap.

Conducted emissions measurements are designed to quantify the EMI generated from a device and returned to its power source. It's important to reduce these emissions for many applications, as it is common for other sensitive circuits to connect to the same power-supply lines. Reducing conducted EMI is particularly important when dealing with long wire harnesses, which are increasing in number in modern automobiles.

Figure 2 shows a generic test setup for conducted emissions, including a power source, line impedance stabilization network (LISN), EMI receiver, supply wires and a device under test (DUT). The LISN plays a key role, acting as a low-pass filter that ensures the repeatability and comparability of EMI measurements, and providing a precise impedance to the DUT. **Figure 2** also illustrates an important subdivision of conducted emissions into common-mode (CM) and differential-mode (DM) currents. DM currents flow between the power-supply line and its return path, and are the dominant factor at lower frequencies. CM currents flow between each of the power lines and ground, and are the dominant factor at higher frequencies.

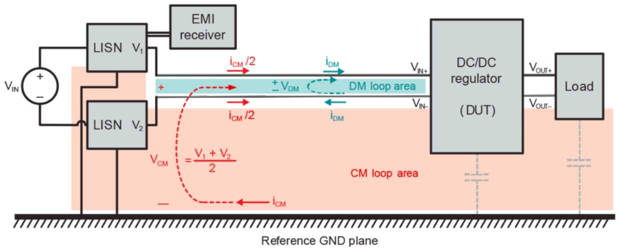


Figure 2. *Generic test setup for conducted emissions measurements, with DM and CM loops highlighted in teal and red, respectively.*

Radiated measurements have a setup similar to conducted measurements; the main difference is that the EMI receiver is not connected directly to the LISN but to a nearby antenna. Radiated energy in an SMPS comes from fast transient current loops generating magnetic fields, and fast transient voltage surfaces generating electric fields. Because the same current loops that generate radiated magnetic fields also generate DM conducted emissions, and the same surfaces that generate radiated electric fields also generate CM conducted emissions, many EMI mitigation techniques reduce both conducted and radiated emissions, but may be targeted specifically for one or the other.

In general, lower-frequency emissions are mitigated by using large passive filters, which add board area and cost to the solution. High-frequency emissions present different challenges in terms of measurement, modeling and mitigation, primarily as a result of their parasitic nature. Common mitigation techniques for high-frequency emissions include controlling slew rates and reducing parasitics. **Figure 3** summarizes the mitigation techniques contained in this paper, the frequency bands in which they are most beneficial and an example of the frequency ranges covered by the CISPR 25 standard.

Conventional methods to reduce EMI in the low- and high-frequency ranges

Input voltage ripple generated by discontinuous currents in an SMPS can conduct to other systems when the systems share common physical contacts. Without proper mitigation, excessive input or output voltage ripple can compromise operation of the source, load or adjacent system. Traditionally, you could minimize the input ripple by using a passive inductor-capacitor (LC)-based EMI filter, as shown in **Figure 4**. An LC filter offers the required attenuation necessary to meet EMI specifications. The trade-off is a size and cost penalty for the system depending on the required attenuation, which will lower the overall power density. Also, large-sized inductors for input EMI filter design lose attenuation at frequencies greater than 30 MHz because of their lower self-resonant frequency, necessitating additional components like ferrite beads to handle the high-frequency attenuation.

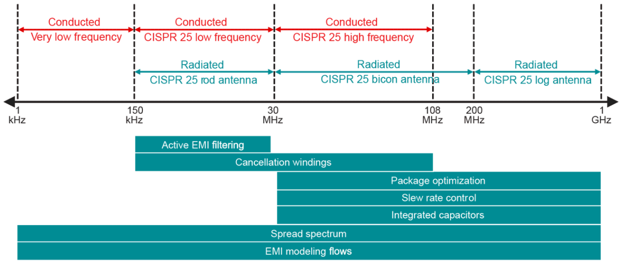


Figure 3. *A summary of the EMI mitigation techniques presented in this paper.*

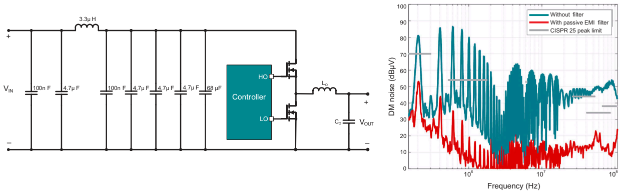


Figure 4. *A typical LC-based passive filter for EMI reduction, along with the attenuation obtained.*

Another conventional approach to mitigating EMI is to use spread spectrum (or clock dithering) to modulate the switching frequency of an SMPS, which will reduce peaks in the frequency spectrum associated with the fundamental switching frequency and its harmonics — but at the expense of an increased noise floor, as shown in **Figure 5**.

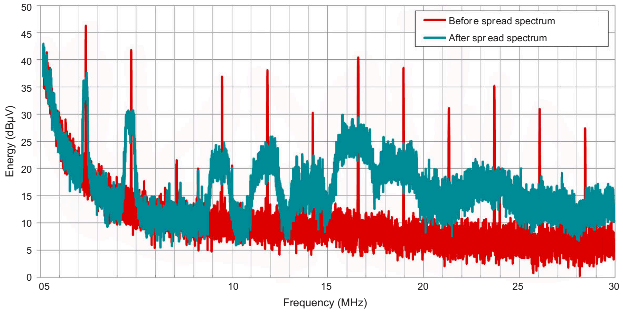


Figure 5. *Example of the frequency spectrum of an SMPS with and without spread spectrum.*

Spread spectrum is an attractive technique, given its ease of implementation and the fact that you can use it in conjunction with other EMI reduction methods. It is not a panacea, however, as it can only provide relative reductions to existing EMI, and by nature its performance diminishes with lower switching frequencies. Furthermore, you can traditionally only apply spread spectrum to a single frequency band, for reasons that we will explore in the next section.

To minimize the size of the filter inductors, you can choose higher switching frequencies for your SMPS design. It is important to avoid sensitive frequency bands for switcher operation, however. For example, the preferred switching frequency for automotive power solutions has traditionally been in the sub-AM bands (approximately 400 kHz). Choosing a higher switching frequency to minimize inductor size means that you must avoid the entire AM band (525 to 1,705 kHz) so as to not have fundamental switching spurs in the more stringent automotive EMI frequency bands.

Switching converters from Texas Instruments (TI) have a switching frequency above 1.8 MHz to satisfy the EMI band requirements. The push to higher switching frequencies imposes a severe restriction on the switching transition rise and fall times to reduce switching losses. However, a switch node with very short rise and fall times maintains high energy content even at high frequencies close to its 100th harmonic, as shown in **Figure 6**, again highlighting the trade-off between high efficiency and low EMI.

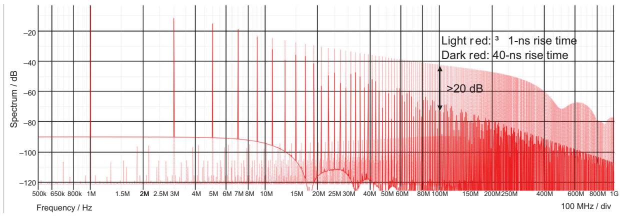


Figure 6. *EMI plots of square waveforms with different rise times.*

High slew rates will additionally result in high-frequency switch-node ringing, due to the presence of parasitic inductances in the power path of DC/DC converters, which further increases emissions at the ringing frequency and above. **Figure 8** shows how the slew rate and the associated ringing on the switch node affect emissions. The traditional way to limit EMI emissions caused by the switching transition is to slow them down by adding intentional resistance in the gate-drive path of the switching device. This causes the transitions to happen more slowly, leading to faster roll-off of the emissions and an 8- to 10-dB reduction in emissions at the ringing frequency. This slowdown of the switching edges comes with a penalty of 2% to 3% in the peak current efficiency of the switching converter, however.

Innovations in reducing low-frequency emissions

Look at a few techniques that TI uses when building its converters and controllers to address the fundamental trade-offs involving efficiency, EMI, size and cost.

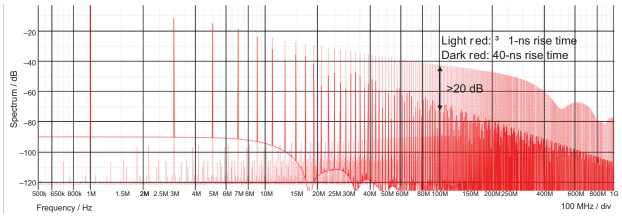


Figure 7. *EMI plots of square waveforms with different rise times.*

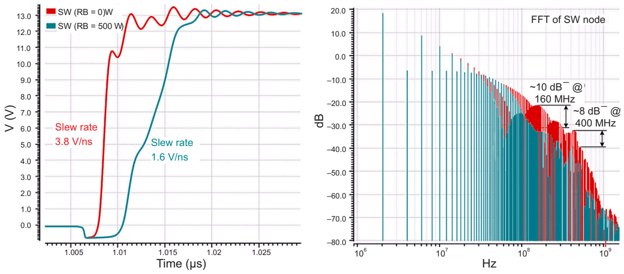


Figure 8. *The effect of different switch-node slew rates and associated ringing on high-frequency emissions. Reduced slew rates impact EMI roll-off in the 30- to 200-MHz band while the reduced ringing impacts EMI at the ringing frequency around 400 MHz.*

Spread spectrum

Spread spectrum uses the principle of conservation of energy to reduce EMI peaks by spreading energy across multiple frequencies. However, the peak energy that a susceptible circuit "sees" may not reduce; it depends on the relationship between the susceptible circuit's bandwidth and the method of frequency modulation. When measuring EMI, the spectrum analyzer is acting as the susceptible circuit, and industry standards set the resolution bandwidth (RBW). Thus, it is important to modulate the frequency in the most effective way for the standard you are targeting. A general rule of thumb is to have the modulation frequency, f_m, approximately equal to your targeted RBW, with the spreading bandwidth, Δf_C, around ±5% to ±10%. **Figure 9** illustrates these parameters in both the time and frequency domains.

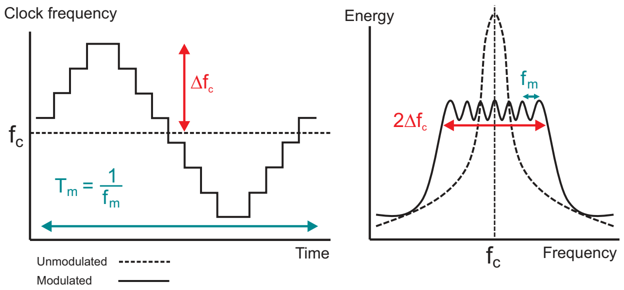


Figure 9. *Spread-spectrum parameters f_m and Δf_C in both the time and frequency domains.*

It is common to set f_m around 9 kHz to optimize for the low-frequency band in standards such as CISPR 25, but this happens to also be in the audible range. To combat this, you can further modulate the triangular modulation in a pseudo random fashion to spread the audible energy without having a significant impact on the conducted and radiated EMI performance. **Figure 10** illustrates this modulation profile both in the time and the frequency domains, a feature present on the **TPS55165-Q1**, a synchronous buck-boost converter.

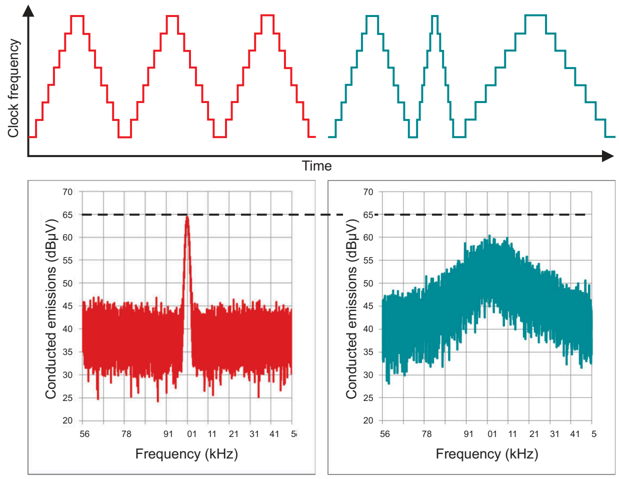


Figure 10. *Audible tone reduction achieved by pseudo randomly modulating the triangle waveform at the conclusion of every modulation cycle.*

The fact that EMI is not limited to a single band (and thus a single RBW) but multiple bands presents a predicament, as spread spectrum can typically only target improvements in a single band. A new solution to this problem is a digital spread-spectrum technique called dual random spread spectrum (DRSS). The basic principle behind DRSS is to superimpose two modulation profiles, each targeting a different RBW. For more information, see the application report, **EMI Reduction Technique, Dual Random Spread Spectrum**. **Figure 11** shows a DRSS modulation profile in the time domain, with a triangular envelope targeting lower RBWs, and a superimposed pseudo random sequence targeting higher RBWs.

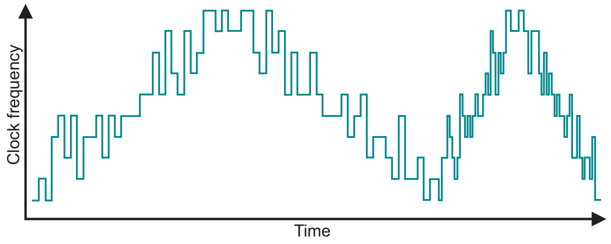


Figure 11. *Time domain modulation profile of DRSS.*

Figure 12 shows the conducted emissions performance of the **LM5156-Q1**, a non-synchronous boost controller, with and without DRSS. You can see significantly reduced spectral peaks in both the 150-kHz to 30-MHz band, as well as the 30- to 108-MHz band, which are the two key bands for the CISPR 25 automotive standard. The **LM5157-Q1** non-synchronous boost converter also features DRSS and achieves similar performance.

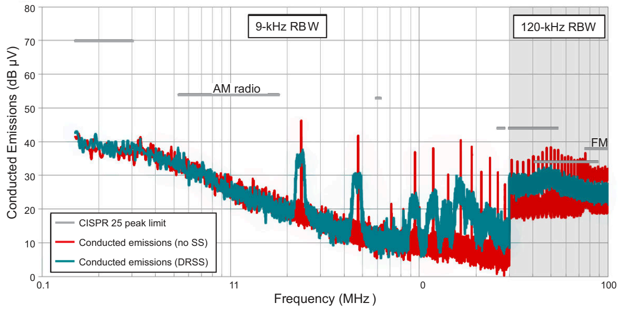


Figure 12. *EMI performance of the LM5156-Q1 boost controller before and after spread spectrum, using a printed circuit board (PCB) not specifically designed for lower EMI.*

Spread-spectrum techniques are applicable for both non-isolated and isolated topologies, as the EMI sources are similar for both, and frequency spreading provides the same benefit. The **UCC12040** and **UCC12050** isolated DC/DC converters with integrated transformers are able to pass CISPR 32 Class B EMI testing limits in part due to internal spread-spectrum techniques.

Active EMI filtering

To substantially improve emissions in the low-frequency spectrum, the **LM25149-Q1** buck controller incorporates an active EMI filtering approach. The integrated active EMI filter reduces DM conducted emissions at the input by acting as an effective low-impedance shunt. **Figure 13** shows how the active EMI filter of the buck controller connects to the input line. The sense and inject pins hook up to the input through their respective capacitors. The active element within the active EMI filter block amplifies the sensed signal and injects an appropriate anti-polarity signal through the inject capacitor in order to minimize the overall disturbance on the input line. This reduces the filtering burden on the passive elements needed, thereby reducing their size, volume and cost.

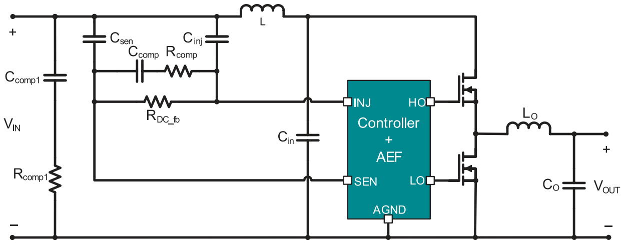


Figure 13. *Active EMI filter showing the sense, inject capacitors and components for compensation.*

Figure 14 shows the EMI measurement results of a buck converter operating at a 400-kHz switching frequency, comparing the active and passive EMI filtering approaches. To effectively meet the CISPR 25 Class 5 spectral mask, the passive EMI filter needs a 3.3-μH DM inductor with a 10-μF DM capacitor. The active filtering approach can achieve the same effective attenuation with a DM inductor of only 1 μH along with 100-nF sense and inject capacitors. This helps reduce the size and volume of the passive filter to about 43% and 27% of the original values, respectively. For higher-current converters, it is possible to obtain further benefits in cost and efficiency from a reduction in inductor DC resistance.

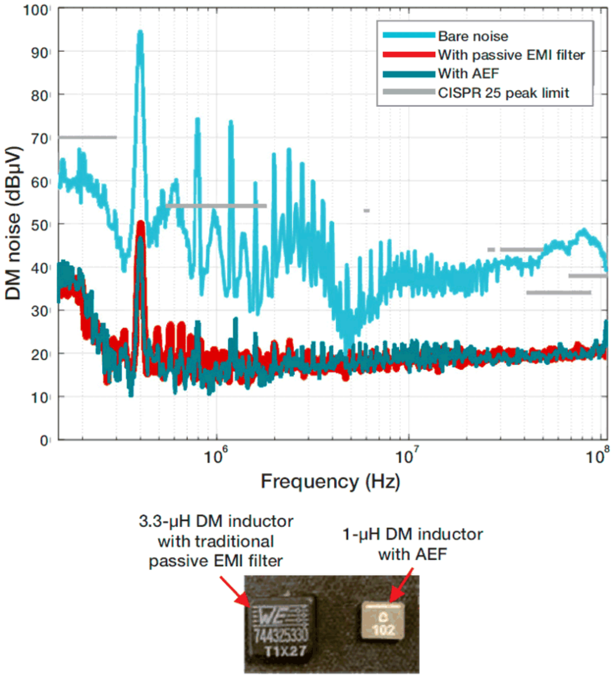


Figure 14. *EMI attenuation obtained using passive and active filtering and comparison of the passive inductor needed for filtering in both approaches for a 12-V input, 5-V/5-A output buck converter.*

Cancellation windings

Unlike non-isolated converters, an additional emissions path across the isolation boundary is a key cause of common-mode (CM) EMI in isolated converters. **Figure 15** on the following page shows the presence of the parasitic capacitances across the isolation transformer in a standard flyback converter. CM currents can flow directly from primary to earth through the parasitic capacitance associated with each switched node. The CM currents also flow from primary to secondary because of parasitic capacitance between the windings, causing an increase in the measured CM EMI. Conventionally, you could attenuate this additional disturbance by using a large CM choke in the input power path.

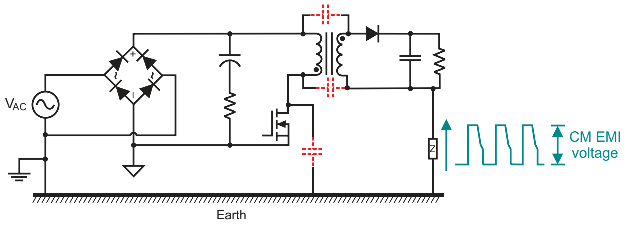


Figure 15. *CM EMI generating parasitics in a flyback converter.*

To help minimize the size of the passive filtering, the **65-W active clamp flyback with silicon FETs reference design for a high-power-density 5- to 20-V AC/DC adapter** employs cancellation winding- and shielding-based approaches specific to isolated converters. As shown in **Figure 16**, an improved internal transformer structure has an extra auxiliary winding layer (shown in black) inserted in between the inner primary and secondary layers for CM balance. The auxiliary CM balance layer shields the inner half-primary to secondary interface and helps generate a canceling CM voltage to null the CM injection from the outer half-primary layer. Equalizing the parasitic capacitances to the secondary layer from the auxiliary winding and primary outer layers helps null the CM current injected into the secondary layer from the outer half-primary layer, by pushing an opposite-phase CM current from the cancellation layer. The net effect — close to zero CM current flowing into the secondary layer — reduces CM emissions, significantly helping the design meet EMI spectral standards with minimal CM filtering.

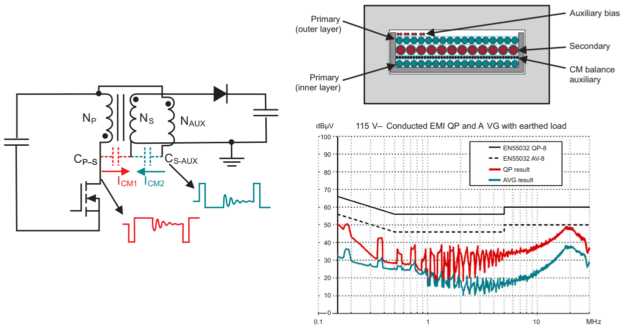


Figure 16. *Using shielding and cancellation windings to reduce EMI in a flyback converter.*

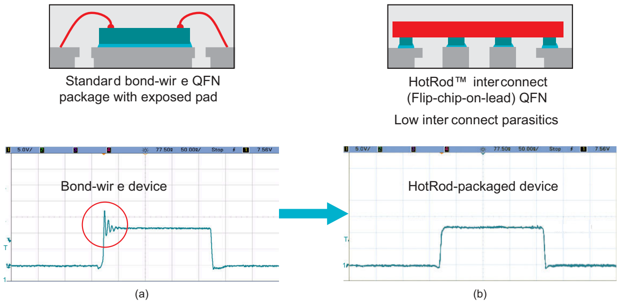
Innovations in reducing high-frequency emissions

The EMI mitigation techniques described so far generally reduce low-frequency emissions (<30 MHz), with a corresponding reduction in the amount of passive filtering required and associated size, volume and cost benefits. Look at techniques designed to mitigate high-frequency emissions (>30 MHz).

HotRod™ package

One of the main approaches to reducing high-frequency emissions is to minimize the power-loop inductance. Step-down converters from TI such as the **LM53635-Q1**, **LMS3655-Q1**, **LM61495-Q1**, **LMR33630-Q1** and **LM61460-Q1** move away from bond-wire packages to leadframe-based flip-chip (HotRod) packages that help lower the power-loop inductance and in turn reduce switch-node ringing.

HotRod packages flip the silicon die and place it directly on a lead frame in order to minimize the parasitic inductance caused by bond-wires on pins running switching currents. **Figure 17** shows the construction and benefit of HotRod packages. Along with an improvement in power-loop inductance, HotRod-style packages also help lower resistance in the power path, leading to higher efficiency while making a smaller solution size possible.



(a)

(b)

Figure 17. *Standard QFN with bond-wires to electrically connect to the die (a); HotRod package with copper pillars and flip-chip interconnect between the leadframe and die (b).*

An additional benefit of devices in the HotRod package is that they facilitate parallel input path pinouts — the layout arrangement of a DC/DC converter's input capacitors. By optimizing the pinout of the DC/DC converter so that there is symmetry in the input capacitors' layout, the opposing magnetic fields generated by the input power loops are within the symmetric loops, thereby minimizing emissions to nearby systems. A parallel input path further minimizes high-frequency EMI, particularly in the most stringent FM band, as shown in **Figure 18**.

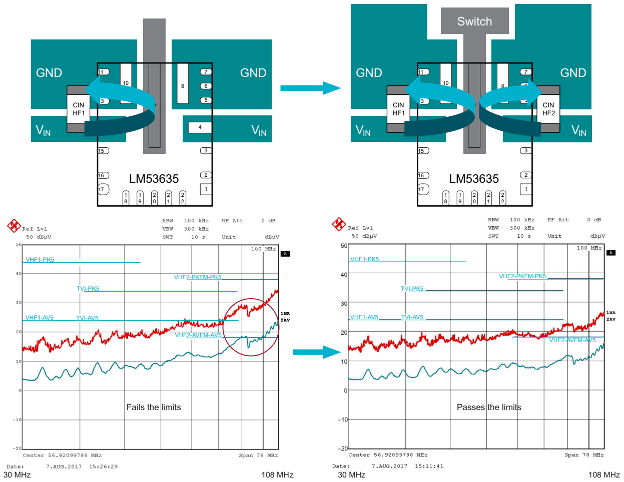


Figure 18. Effect of the parallel input path on EMI in an SMPS.

Enhanced HotRod QFN

The Enhanced HotRod quad flat no-lead (QFN) package offers all of the EMI reduction capabilities of the HotRod package and has an added advantage of even lower switch-node capacitance, resulting in much lower ringing. The resistor inductor- capacitor (RLC) parasitic on the input-voltage (VIN) and ground (GND) pins is also lower in devices with the Enhanced HotRod QFN compared to the HotRod package.

The **LM60440-Q1** step-down converter comes in an Enhanced HotRod QFN, and **Figure 19** shows the pinout and board layout. The Enhanced HotRod QFN not only improves efficiency but also includes a footprint that has a large die-attach pad (DAP) at the center of the package. The DAP facilitates better thermal dissipation through the PCB and reduces the rise in junction temperature by more than 15% compared to the HotRod package. In addition, lower RLC parasitics on the VIN, GND and switch-node pins also result in better efficiency and lower EMI. As expected this results in better EMI, particularly around the switch-node ringing frequency band as shown in **Figure 20**.

Integrated input bypass capacitor

As we described earlier, a large input power loop results in higher emissions at high-frequency bands because of increased switch-node ringing. Integrating high-frequency input decoupling capacitors inside the device package helps minimize the input loop parasitic and thus reduces EMI. This technique is used in the LMQ62440-Q1, a step-down converter, as shown in Figure 20 on the following page. Beyond reducing the input power-loop inductance, the package integration of the input high-frequency capacitors also helps make the solution more immune to changes in the board layout of the end system.

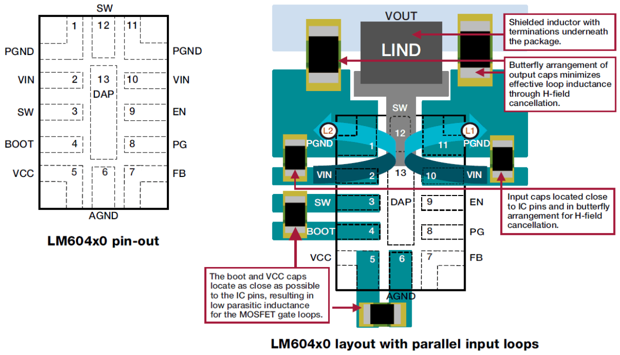


Figure 19. The pinout and PCB layout on an Enhanced HotRod QFN package device.

bands because of increased switch-node ringing. Integrating high-frequency input decoupling capacitors inside the device package helps minimize the input loop parasitic and thus reduces EMI. This technique is used in the **LMQ62440-Q1**, a step-down converter, as shown in **Figure 21**. Beyond reducing the input power-loop inductance, the package integration of the input high-frequency capacitors also helps make the solution more immune to changes in the board layout of the end system.

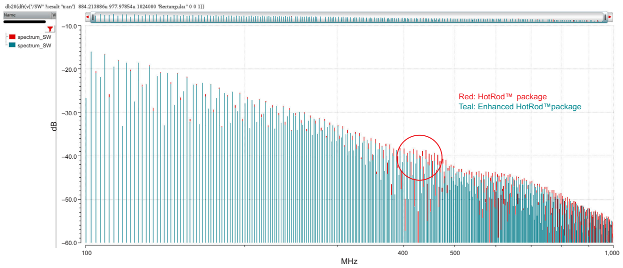


***Figure 20.** SW node FFT comparison of HotRod- vs. Enhanced HotRod-packaged device.*

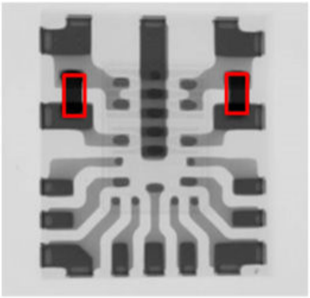


***Figure 21.** Two high-frequency input bypass capacitors integrated in the LMQ62440-Q1 device.*

Figure 22 compares the radiated EMI — identical conditions on identical boards — of the LMQ62440-Q1, with and without the bypass capacitors integrated. The results show a 9-dB reduction in emission in the most stringent TV band (200 to 230 MHz), which helps the system remain under EMI limits set by industry standards without the need for additional components on the board.

True slew-rate control

Despite the aforementioned techniques, in some designs high-frequency EMI (60 to 250 MHz) may still not fall under specified standard limits. One way to mitigate and improve the margin in order to pass industry standards is to use a resistor in series with the boot capacitor of the switching converter. Using a resistor reduces the switching-edge slew rates, which reduces EMI, but comes with the expected penalty of reduced efficiency.

Switching converters such as the LM61440-Q1 and LM62440-Q1 are designed such that a resistor can be used to select the strength of the high-side FET's driver during turn-on. As shown in **Figure 23**, the current drawn through the RBOOT pin (the teal dotted loop) is multiplied and drawn through from CBOOT (the red dashed line) to turn on the high-side power MOSFET. By doing this, the resistor can control the slew rate, but not suffer the efficiency loss that happens when a series BOOT resistor runs the majority of the current. With RBOOT short-circuited to CBOOT, the rise time is rapid; switch-node harmonics will not roll off until above 150 MHz. If CBOOT and RBOOT remain connected through 700 Ω, the slewing time increases to 10 ns when converting 13.5 V to 5 V. This slow rise time enables the energy in switch-node harmonics to roll off near 50 MHz under most conditions.

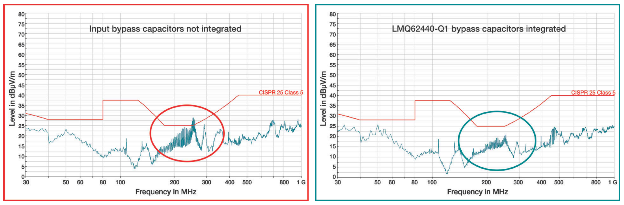


***Figure 22.** Radiated EMI performance of the LMQ62440-Q1 device without and with integrated bypass capacitors.*

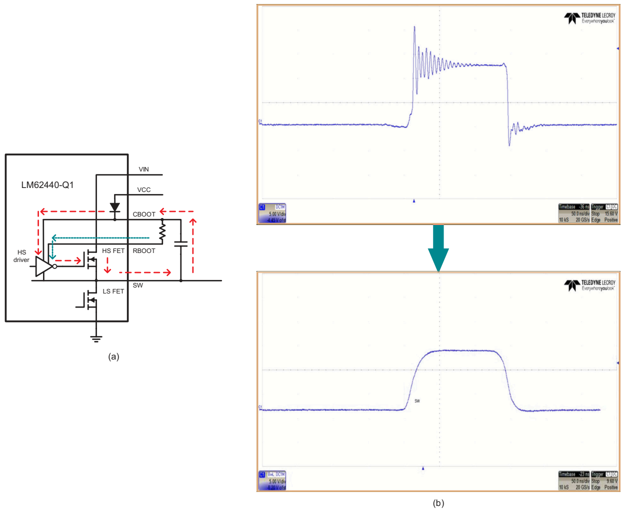


***Figure 23.** True slew-rate control implementation in the LM62440 (a); reduction in switch-node ringing using true slew-rate control (b).*

EMI modeling capabilities

Modeling any circuit is an important way to evaluate a design's performance in the early stages, and thus plays a critical role in reducing design cycle times. EMI modeling is a complex process that involves time-domain circuit analysis as well as frequency domain electromagnetic simulations of the PCB. Modeling EMI emissions makes it easier to meet EMI standard limits more quickly by reducing the number of design iterations.

Low-frequency EMI designs using WEBENCH® design tool

The WEBENCH input filter design tool helps you automatically design a proper input filter to mitigate lower-frequency (<30 MHz) conducted EMI noise for compliance standards like CISPR 32 and CISPR 25. The tool optimizes filter size while ensuring that the design complies with a particular standard. It also ensures filter stability and converter-loop stability while designing the filter. This online tool supports over 100 TI power devices.

It is a common mistake to leave an input EMI filter inductor undamped, which negatively affects overall design stability. The WEBENCH design tool performs impedance analysis on the input filter and SMPS (as shown in **Figure 24**) and suggests the appropriate damping component to ensure stability.

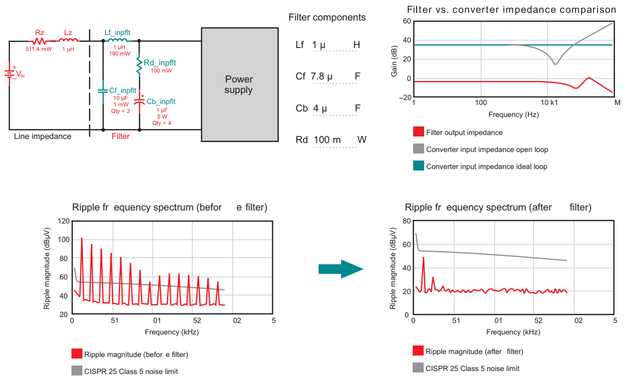


Figure 24. *Input EMI suggestion with impedance analysis in the WEBENCH® design tool.*

Conducted and radiated EMI results published in data sheets

SMPS device evaluation modules are tested against most stringent industrial and automotive EMI standards, and results are published in the data sheet to help you understand the EMI performance of the devices in advance. You can access a detailed EMI report by clicking "Optimized for Ultra-Low EMI Requirements" on the first page of the device-specific data sheet. The EMI report in the **LM62440-Q1** data sheet includes complete data for a CISPR 25 Class 5 conducted and radiated setup.

In addition, TI can perform system-level EMI modeling and measurements in-house to help you validate EMI performance and accelerate cycle times.

Conclusion

The rapid growth of electronics has put tremendous strain on the design of power converters, where complex systems are crammed into ever-smaller spaces. The close proximity of sensitive systems makes it challenging to suppress EMI. You must take extreme care when designing power converters to comply with the limits set forth by standards bodies to ensure that critical systems can operate safely in a noisy environment.

Designing for low EMI can save you significant development cycle time while also reducing board area and solution cost. TI offers multiple features and technologies to mitigate EMI such as spread spectrum, active EMI filtering, cancellation windings, package innovations, integrated input bypass capacitors, and true slew-rate control methodologies.

Employing a combination of techniques with TI's EMI-optimized power-management devices ensures that designs using TI components will pass industry standards without much rework. TI products enable you to remain under end-equipment EMI limits without sacrificing power density or efficiency.

To learn more about TI products that use these technologies, including buck-boost and inverting regulators, isolated bias supplies, multichannel integrated circuits (PMIC), step-down (buck) regulators and step-up (boost) regulators, see ti.com/lowemi.

Keep product categories for low EMI

- Buck-boost and inverting regulators
- Isolated bias supplies
- Multi-channel ICs (PMIC)
- Step-down (buck) regulators
- Step-up (boost) regulators

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