Exclusive Technology Feature

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The Engineer's Guide To EMI In DC-DC Converters (Part 4): Radiated Emissions

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Part 4 of this article series[1,2,3] offers some perspective on radiated emissions from switching power converters, particularly those intended for applications in the industrial and automotive sectors. Radiated electromagnetic interference (EMI) is a dynamic and situational problem that depends on parasitic effects,[3] circuit layout and component placement within the power converter itself as well as the overall system in which it operates. Thus, the issue of radiated EMI is typically more challenging and complex from the design engineer's perspective, particularly when multiple dc-dc power stages are located on the system board.

It's important to understand the basic mechanisms for radiated EMI, as well as the measurement requirements, frequency ranges and applicable limits. This article focuses on these aspects and presents radiated EMI measurement setups and results for two dc-dc buck converters.

We begin by explaining near-field and far-field coupling mechanisms (Fig. 1), and where the boundary between the two lies. We then discuss the standards that apply to radiated EMI in industrial and multimedia equipment including FCC Part 15 Subpart B and CISPR 22. An example radiated emissions test setup for the LMR16030 60-V/3-A buck converter is presented along with the measured test results.

What follows then is a discussion of radiated EMI in automotive systems including the CISPR 25 standard and UNECE Regulation 10. An example radiated emissions test setup for the LM53635-Q1 automotive-grade synchronous buck converter is shown along with the measured emissions.

These discussions include explanations of key antenna concepts such as vertical and horizontal polarization, the different antenna types required and other details of how to make the physical test setups. The goal throughout is to enable pre-compliance testing during the design of the power system.

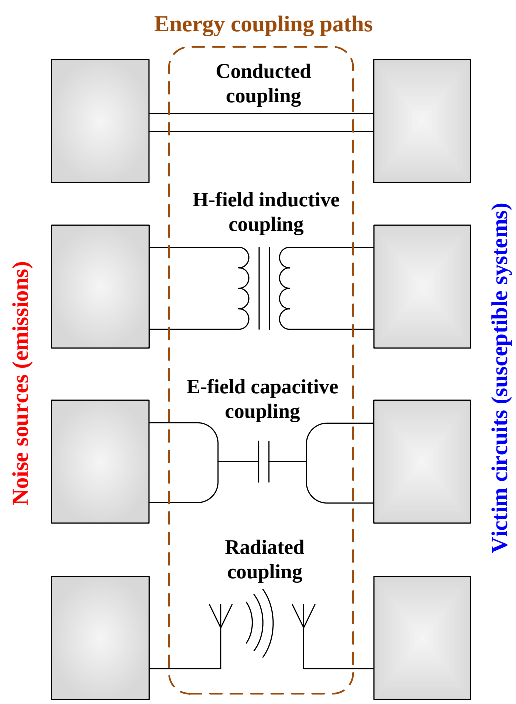


Fig. 1. EMI coupling modes.

Near-Field Coupling

Fig. 1 provides an overview of the fundamental EMI coupling modes between noise source and victim circuits. In particular, inductive or H-field coupling requires a time-varying, high di/dt current source and two magnetically coupled loops (or parallel wires with return paths). Capacitive or E-field coupling, on the other hand, requires a time-varying, high dv/dt voltage source and two closely spaced metal plates. Both mechanisms are described as near-field coupling where the noise source and victim circuits are in close proximity and can be measured using near-field sniffer probes.

As an example, modern power switches, particularly gallium nitride (GaN) and silicon carbide (SiC)-based transistors, have low output capacitance C_{OSS} and gate charge Q_G, and can switch at extremely high dv/dt and di/dt slew rates. The possibility for H-field and E-field coupling and crosstalk to adjacent circuits is high. However, near-field coupling is significantly reduced with larger distances between the coupled structures as the mutual inductance or capacitance decreases.

Far-Field Coupling

A classic electromagnetic (EM) wave propagates as a combination of E and H fields. The structure of the fields near the radiating antenna source is a complex, three-dimensional pattern. Further from the source, the EM wave in the far-field region comprises E-field and H-field components oriented orthogonally to each other and to the direction of propagation. Fig. 2 depicts this plane wave,[4] as it represents the primary basis for radiated EMI that is limited by various emissions standards.

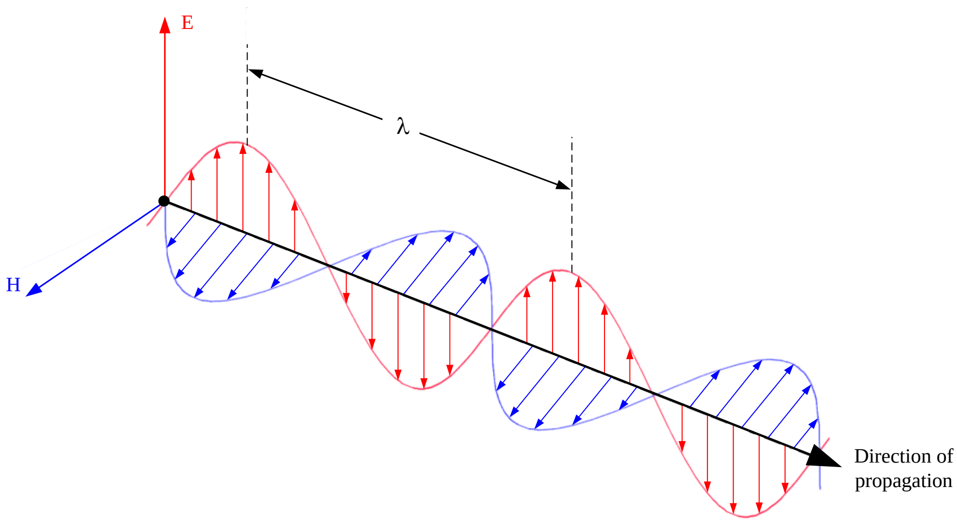


Fig. 2. EM plane-wave propagation.

The wave impedance, plotted in Fig. 3, is the ratio of the electric and magnetic field strengths. As the E and H components in the far-field region are in phase with each other, the far-field impedance is resistive and given by the plane-wave solution of Maxwell's equations, shown here as equation 1:

$$Z_{W(\text{far-field})} = \frac{E}{H} = Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx \sqrt{\frac{4\pi \times 10^{-7}\ \text{H/m}}{\frac{1}{36\pi} \times 10^{-9}\ \text{F/m}}} \approx 120\pi\,\Omega \approx 377\,\Omega \qquad (1)$$

If λ is the wavelength and *f* is the frequency of concern, equation 2 usually denotes the boundary in meters between the near-field and far-field regions:

$$d_{\text{NF-FF}} = \frac{\lambda}{2\pi} \approx \frac{48}{f\,(\text{MHz})} \qquad (2)$$

This boundary, however, is not a precise criterion but is only intended to indicate a general transition region (Fig. 3 delineates λ/16 to 3λ) where the fields evolve from complicated distributions to planar waves.

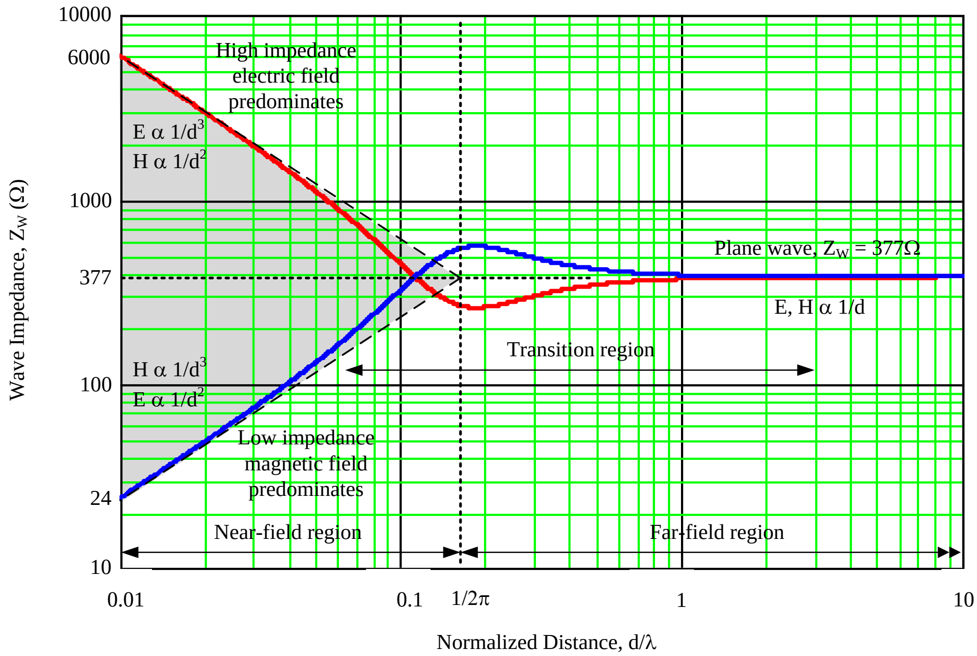


Fig. 3. The wave impedance in near-field and far-field regions from Maxwell's laws.

Given that most antennas are designed to detect and respond to E-fields, the radiated EM wave is often described as vertically or horizontally polarized, depending on the direction of the E-field. In general, a measuring E-field antenna should be oriented in the same plane as the propagating E-field to detect the maximum field strength. As a result, radiated EMI test standards typically describe measurements with the receiving antenna mounted in both vertical and horizontal polarizations.

Radiated EMI In Industrial And Multimedia Equipment

Table 1 presents the specified Class A and Class B radiated emissions limits from FCC Part 15 Subpart B[5] for unintentional radiators. In addition, clause 15.109(g) of the specification allows the use of the CISPR 22 limits[6] for radiated emissions as given in Table 2, using the measurement methods specified in American National Standards Institute (ANSI) C63.4-2014. The use of CISPR limits facilitates harmonization of requirements for the U.S. and Europe. Note that CISPR 32 now replaces CISPR 22, though as of this writing, FCC Part 15 has not yet been updated to reflect this change.

The limits in Tables 1 and 2 assume a CISPR quasi-peak (QP) detector function and a resolution bandwidth (RBW) of 120 kHz for frequencies below 1 GHz. Tables 3 and 4 present limits for frequencies above 1 GHz using peak (PK) and average (AVG) detectors and a receiver RBW of 1 MHz.

For a given measurement distance, Class B limits for residential or domestic applications are generally more restrictive by a 6-dB-to-10-dB margin than Class A limits for commercial or industrial use. Note also that Tables 1 and 2 include an inverse linear distance (1/d) proportionality factor of 20 dB/decade, used per 15.31(f)(1), to normalize limits for 3-m and 10-m antenna measurement distances to determine compliance. For example, if the antenna is placed at 3 m instead of 10 m to stay within the test facility boundaries, then the limit amplitudes are adjusted by approximately 10.5 dB.

Table 1. Radiated emissions field strength QP limits per 47 CFR 15.109(a) and (b), 30 MHz to 1 GHz.

Frequency range (MHz)	3-m distance		10-m distance	
	Class A (dBμV/m)	Class B[1] (dBμV/m)	Class A[2] (dBμV/m)	Class B (dBμV/m)
30 to 88	49.6	40	39.1	29.5
88 to 216	54	43.5	43.5	33
216 to 960	56.9	46	46.4	35.5

Notes: 1. Class B limits are specified by the FCC at a distance of 3 m and extrapolated here for 10 m by subtracting 10.5 dB.
2. Class A limits are specified by the FCC at a distance of 10 m and extrapolated here for 3 m by adding 10.5 dB.

Table 2. Radiated emissions field strength QP limits per 47 CFR 15.109(g)/CISPR 22/32, 30 MHz to 1 GHz.

Frequency range (MHz)	3-m distance		10-m distance	
	Class A (dBμV/m)	Class B (dBμV/m)	Class A (dBμV/m)	Class B (dBμV/m)
30 to 230	50.5	40.5	40	30
230 to 1000	57.5	47.5	47	37

Note: The limits are specified in CISPR 22 at 10 m and extrapolated here for 3 m by adding 10.5 dB.

Table 3. Radiated emissions field strength limits at 3 m per 47 CFR 15.109(a) and (b), 1 GHz to 6 GHz.

Frequency range (GHz)	Class A (dBμV/m)		Class B (dBμV/m)	
	AVG	PK	AVG	PK
0.96 to 40	60	80	54	74

Table 4. Radiated emissions field strength limits at 3 m per 47 CFR 15.109(g)/CISPR 22/32, 1 GHz to 6 GHz.

Frequency range (GHz)	Class A (dBµV/m)		Class B (dBµV/m)	
	AVG	PK	AVG	PK
1 to 3	56	76	50	70
3 to 6	60	80	54	74

Fig. 4 plots the relevant limit lines for Class A and Class B at a 3-m antenna distance. As an example of an FCC-compliant design, a battery-powered gas-sensor implementation using Bluetooth low energy is available for purchase from Texas Instruments.[7] The FCC Class A compliance reports with radiated emissions test data and plots for this design are available by download for review.

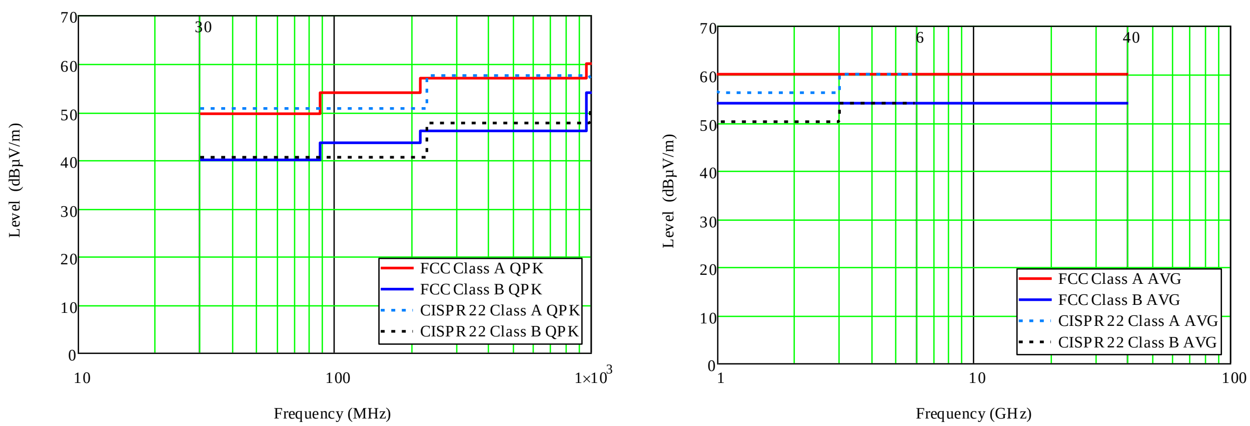


Fig. 4. FCC Part 15 and CISPR 22 radiated limits for Class A and Class B (using QP and AVG detectors below and above 1 GHz, respectively).

As Fig. 5 depicts, a radiated EMI test procedure involves placing the equipment under test (EUT) and support equipment on a nonconductive turntable 0.8 m above the reference ground plane in a semi-anechoic chamber (SAC) or open area test site (OATS), as defined in CISPR 16-1. The EUT is set 3 m away from the receiving antenna, which is mounted on an antenna tower.

A PK detector pre-scan using a calibrated broadband antenna (a combined biconical and log-periodic antenna, or bilog) detects emissions from 30 MHz to 1 GHz with both horizontal and vertical antenna polarizations. Such an exploratory test determines the frequencies of all significant emissions. This is followed by a QP detector check of relevant trouble spots to record the final compliance measurements.

The RBW of the EMI receiver is set at 120 kHz during the test. The antenna is configured for horizontal and vertical polarizations (by rotating it 90 degrees relative to the ground plane) and adjusted in height between 1 m and 4 m above the ground plane to maximize the field strength reading at each test frequency in consideration of ground-plane reflections. The antenna-to-EUT azimuth also varies during the measurements by rotating the EUT on a turntable 0 to 360 degrees to find the maximum field-strength readings from an EUT directional standpoint. The antenna is in the EUT's far-field region, which corresponds to a 3-m antenna distance at a frequency of 15.9 MHz.

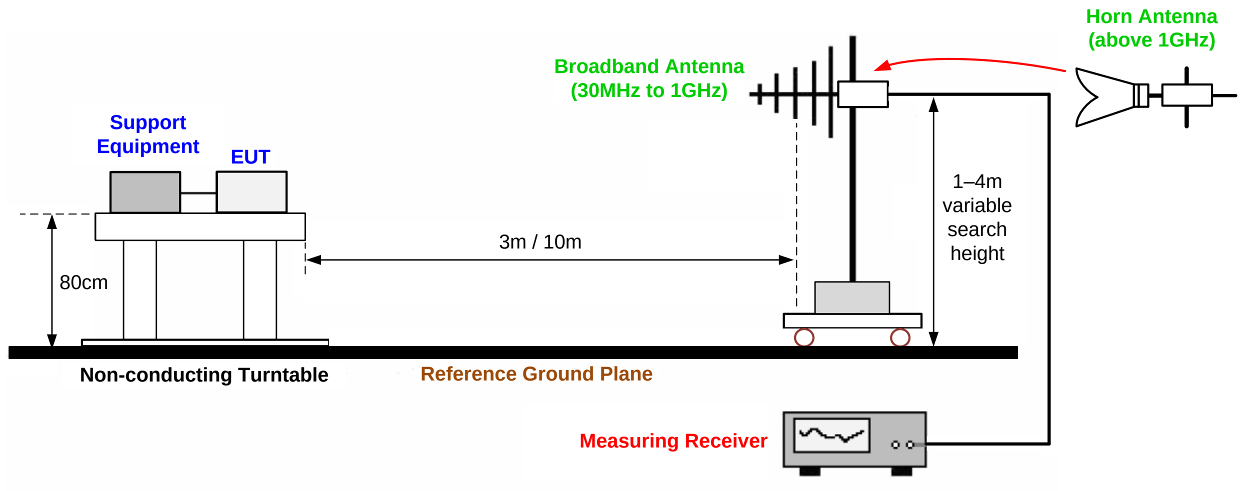


Fig. 5. Radiated emissions measurement setup for FCC Part 15 and CISPR 22/32.

It's possible to conduct a PK detector pre-scan using a horn antenna for scans above 1 GHz, followed by an AVG detector at frequencies close to the limit. The EMI receiver RBW is set at 1 MHz. In this case, a height scan is not required, as the antenna is more directional and reflections from the ground plane and chamber walls are less troublesome.

The EUT's emissions at these frequencies are also more directional, however, so the turntable is again rotated through 360 degrees and antenna polarization is oriented for maximum response. According to Table 5, the upper range of concern varies with the EUT's highest internal frequency.

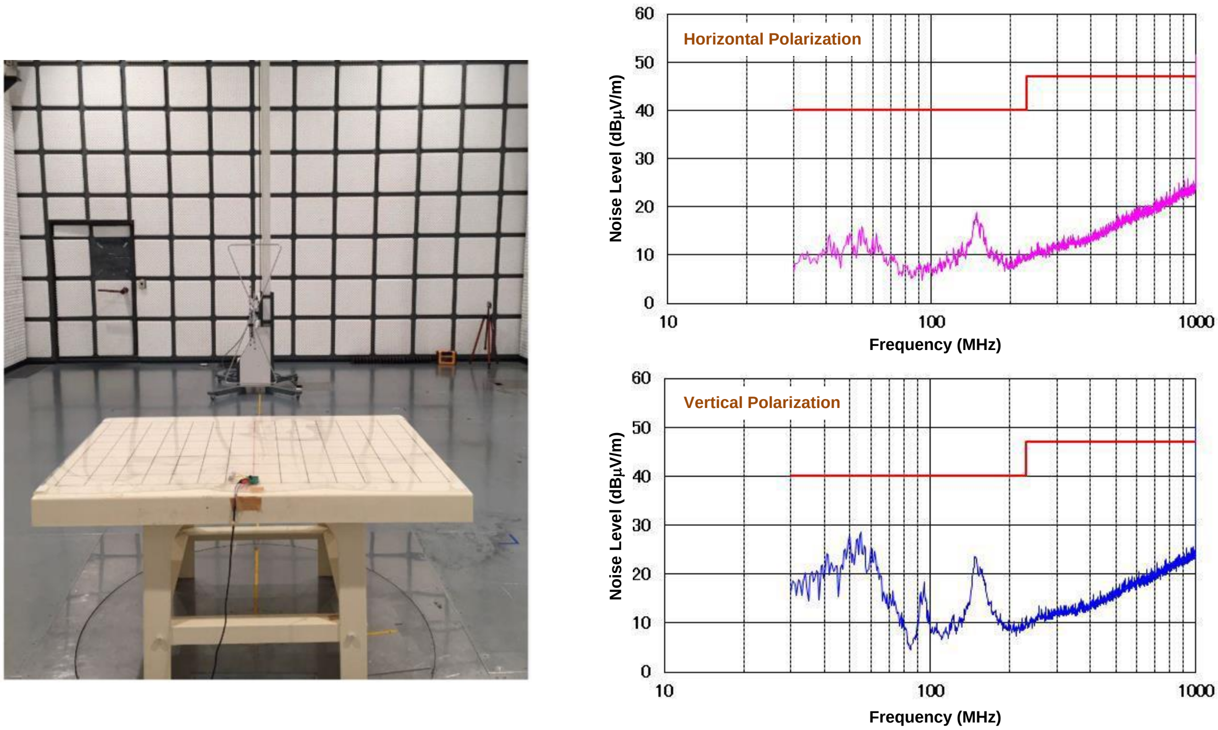
Table 5. FCC Part 15 and CISPR 22 radiated-emissions maximum measurement frequency based on the highest frequency of the EUT internal clock source(s).

EUT highest internal frequency	Upper frequency of measurement range
Below 1.705 MHz	Testing not required
1.705 MHz to 108 MHz	1 GHz
108 MHz to 500 MHz	2 GHz
500 MHz to 1 GHz	5 GHz
Above 1 GHz	Fifth harmonic of highest frequency or 6 GHz (CISPR 22/32) and 40 GHz (FCC Part 15), whichever is lower

Radiated emissions tests measure the electric field strength calibrated in units of decibel microvolts per meter (dB/µV). The antenna factor (AF) is the ratio of the electric field (in µV/m) present at the plane of the antenna to the voltage measured by the spectrum analyzer (SA) or scanning EMI receiver (in dB/µV). In general, a corrected emission level is derived from equation 3, considering the AF, cable loss (CL), attenuator and RF limiter loss factor (AL), and amplifier pre-gain (AG).

$$\text{Emission level (dB}\mu\text{V/m)} = \text{SA reading (dB}\mu\text{V)} + \text{AF (dB/m)} + \text{CL (dB)} + \text{AL (dB)} - \text{AG (dB)} \quad (3)$$

Fig. 6 shows the radiated emissions test setup photo and results for the LMR16030 60-V/3-A buck converter.[8] The measurements are taken at 24-V input, 5-V output at a 3-A load and a 400-kHz switching frequency.



(a) (b)

Fig. 6. CISPR 22 radiated EMI test: setup photo (a) and radiated EMI results with horizontally and vertically polarized antenna (b).

Radiated EMI In Automotive Systems

Although shielded cables reduce interference effects in automotive systems, EMI can efficiently couple to susceptible circuits through crosstalk. And as a consequence of field-to-wire coupling effects, radiated emissions may also imply radiated-immunity problems to signal interconnects in the relatively small volume of a vehicle with densely packed arrangements of power and signal runs in the cable harness. For these reasons, assessing EMI performance is an issue of heightened concern for automotive engineers involved in electric-vehicle design and testing.

UNECE Regulation 10 And CISPR 25

CISPR 12 and CISPR 25 are international standards containing limits and procedures for the measurement of radio disturbances to protect automotive off- and onboard receivers, respectively. CISPR 25[9] in particular applies at the vehicle level and also to any electronic subassemblies (ESAs) intended for use in vehicles. In contrast to other standards, CISPR 25 is typically used as the basis for product specifications defined by an automotive manufacturer and its suppliers, but is not the basis for regulatory compliance and conformity assessments. That distinction goes to the UNECE Regulation 10[10] since the discontinuation of the European Union’s Automotive EMC Directive.

CISPR 25 defines several methods and limit classes for emission measurements for vehicle components and considers both broadband (BB) and narrowband (NB) sources. Fig. 7 shows the Class 5 limits using PK and AVG detectors for components and modules. Measurements are taken apropos receivers in the broadcast and mobile service bands operating within the vehicle. The lowest measurement frequency relates to the European long wave (LW) broadcast band of 150 kHz to 300 kHz, and the highest frequency is 2.5 GHz in consideration of Bluetooth transmissions.

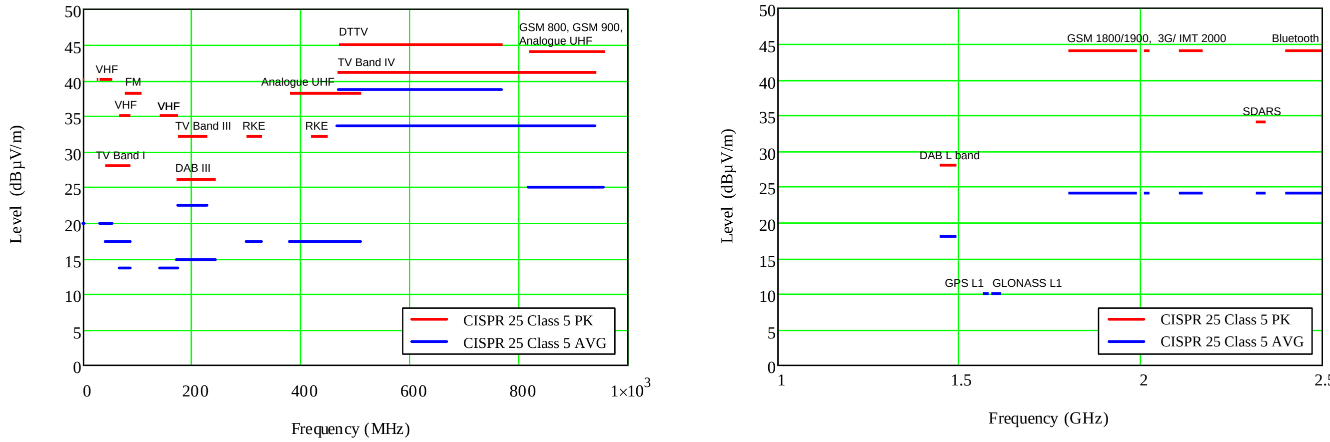


Fig. 7. CISPR 25 Class 5 radiated limits for components and modules using the absorber-lined shielded enclosure (ALSE) method with peak and average detectors (linear frequency scale).

The scanning receiver's RBW is 9 kHz and 120 kHz for detection below and above 30 MHz, respectively. Exceptions are the GPS L1 civil (1.567 GHz to 1.583 GHz) and Global Navigation Satellite System (GLONASS) L1 (1.591 GHz to 1.613 GHz) bands, where an RBW of 9 kHz and a maximum step size of 5 kHz are required to detect the applicable NB emissions using only an AVG detector.

Antenna Systems For CISPR 25

Measurements are made using linearly polarized electric field antennas that have a nominal 50-Ω output impedance. Table 6 and Fig. 8 show the antenna recommended in CISPR 25 to increase the consistency of results between laboratories.

Table 6. Recommended electric field antennas per CISPR 25; the biconical and log-periodic antenna overlap in frequency, whereas a bilog antenna covers their respective frequency ranges.

Frequency range	Recommended antenna	Measurement polarization
150 kHz to 30 MHz	1-m vertical monopole with counterpoise	Vertical only
30 MHz to 300 MHz	Biconical	Horizontal and vertical
200 MHz to 1 GHz	Log-periodic	
30 MHz to 1 GHz	Broadband (bilog)	
1 GHz to 2.5 GHz	Horn or log-periodic	

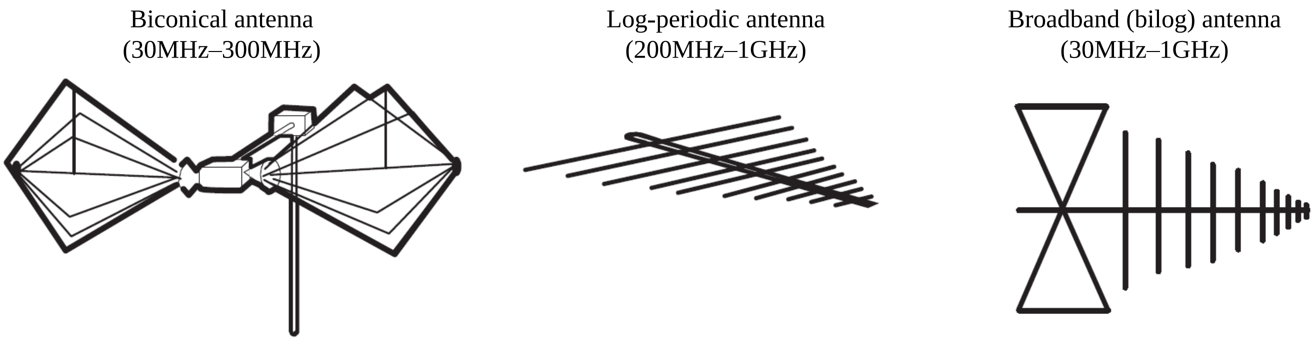


Fig. 8. Measurement antennas per the CISPR 25 specification.

A passive/active rod monopole antenna with counterpoise is used for low-frequency measurements. Biconical and log-periodic dipole array (LPDA) antennas generally cover the frequency ranges of 30 MHz to 200 MHz and 200 MHz to 1 GHz, respectively. Finally, a dual-ridge horn antenna (DRHA) is commonly used from 1 GHz to 2.5 GHz. The broadband bilog antenna is a larger format than the biconical or log-periodic antennas and is sometimes used to cover the frequency range from 30 MHz to 1 GHz.

Radiated EMI Tests Using ALSE

Figs. 9, 10 and 11 depict the typical setups using the CISPR 25 ALSE method, also known as the antenna method, for radiated emission measurements over the frequency ranges specified in Table 6.

The EUT and cable harness are placed on a nonconductive, low relative permittivity material ($\varepsilon_r \leq 1.4$) at 50 mm above the ground plane. The length of the harness parallel to the front of the ground plane is 1.5 m, with the total length of the test harness between the EUT and the load simulator not to exceed 2 m. The long segment of the test harness is located parallel to the edge of the ground plane facing the antenna at a distance 100 mm from the edge.

The requirements on the ground plane are a minimum width and length of 1 m and 2 m, respectively, or underneath the entire equipment plus 200 mm, whichever is larger. Based on the near- to far-field transition given by equation 2 and the antenna distance of 1 m, it is important to note that measurements in the EUT's near-field region occur at frequencies below 48 MHz.

The horn antenna is aligned with the EUT, whereas the other antennas are placed in the midpoint of the wiring harness. All measurements are performed at a 1-m antenna distance. Measurements in the frequency range from 150 kHz to 30 MHz are performed with vertical antenna polarization only. Scans from 30 MHz to 2.5 GHz are performed in both the horizontal and vertical polarizations.

As described earlier, the detected antenna voltage by the EMI receiver combined with the AF provides the electric field strength at the antenna location. Note that independent AFs may apply for horizontal and vertical polarizations, so appropriate AF values are used for measurement in each polarization.

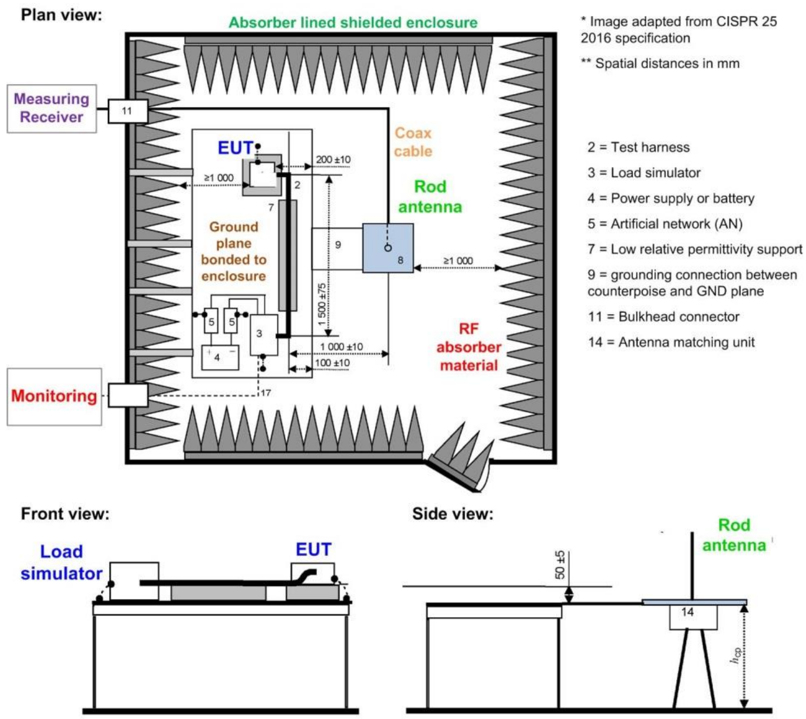


Fig. 9. CISPR 25 radiated emissions measurement setup, monopole rod antenna (150 kHz to 30 MHz).

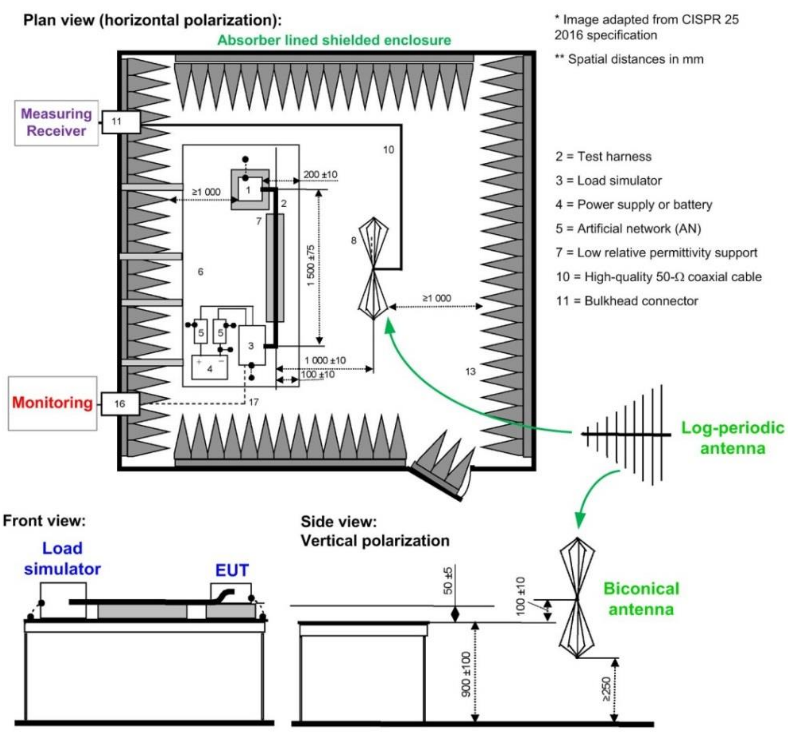


Fig. 10. CISPR 25 radiated emissions measurement setup with biconical antenna (30 MHz to 300 MHz) or log-periodic antenna (200 MHz to 1 GHz).

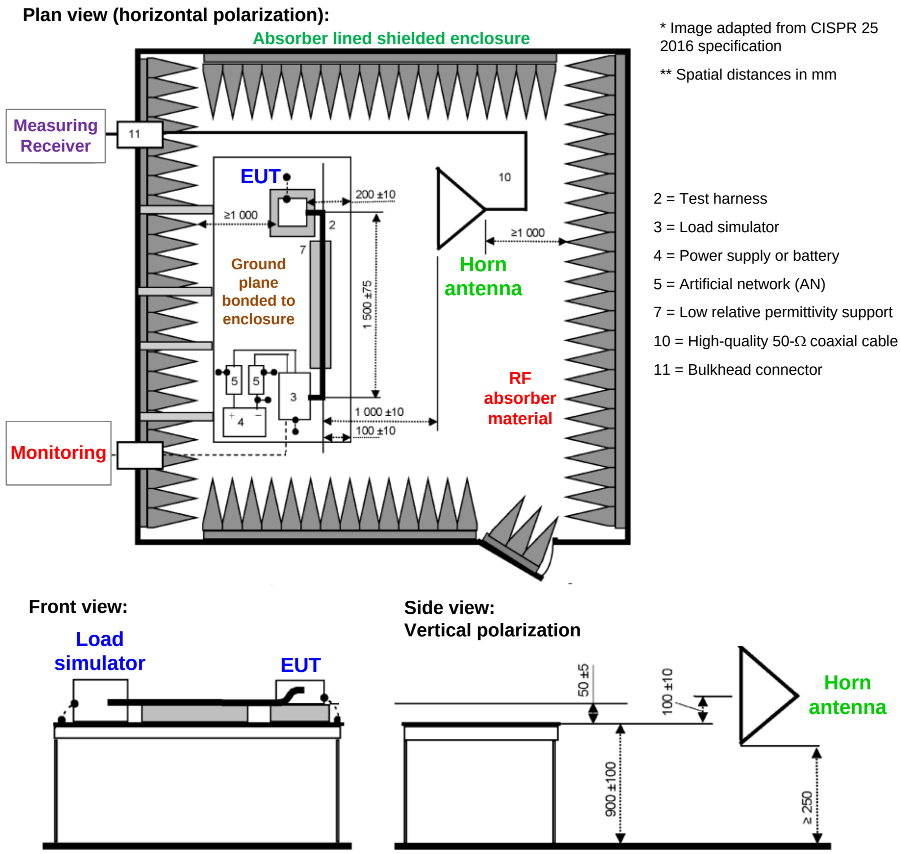


Fig. 11. CISPR 25 radiated emissions measurement setup, horn antenna (above 1 GHz).

Radiated EMI Pre-Compliance Testing And Results

Fig. 12 shows a photo of the radiated emissions test setup for the LM53635-Q1 automotive-grade synchronous buck converter[11]. The EUT is powered by a car battery with a line-impedance stabilization network (LISN) connected on both the positive and negative supply lines. The output is 3.3 V at a 3.5-A resistive load. The switching frequency is 2.1 MHz, above the AM band as required in many automotive systems, and spread-spectrum frequency modulation (SSFM) is enabled. Figs. 13 through 16 show the measurement results using the various test antennas to pass CISPR 25 Class 5 limits.

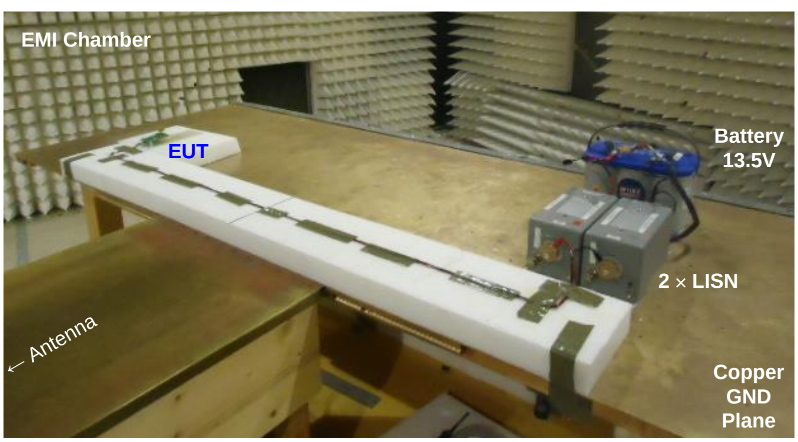


Fig. 12. Photo of CISPR 25 pre-compliance measurement setup.

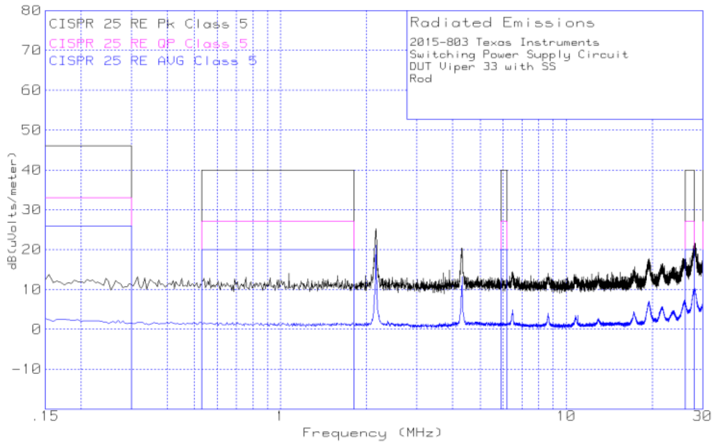


Fig. 13. Radiated emissions results: 150 kHz to 30 MHz, rod antenna, vertical polarization.

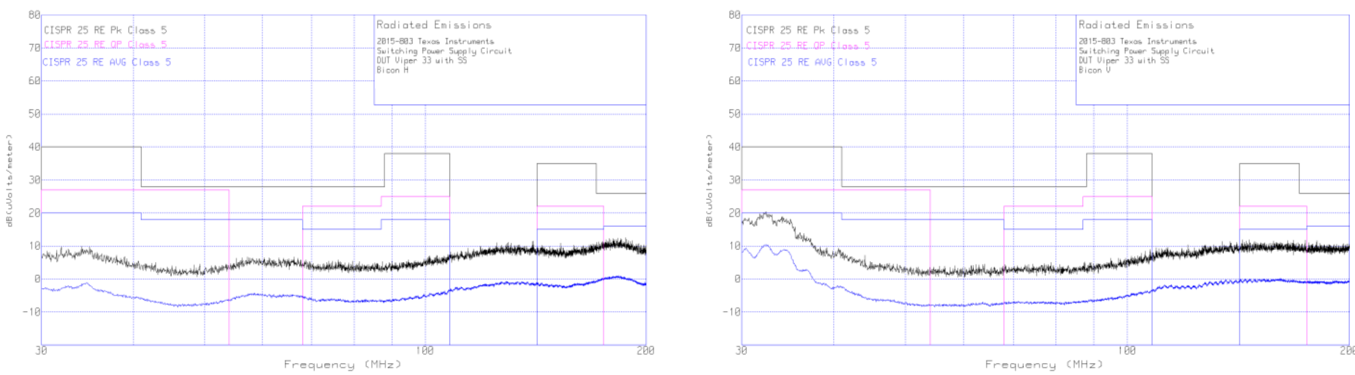


Fig. 14. Radiated emissions results: 30 MHz to 300 MHz, biconical antenna, horizontal (spectrum on left) and vertical (spectrum on right) polarizations.

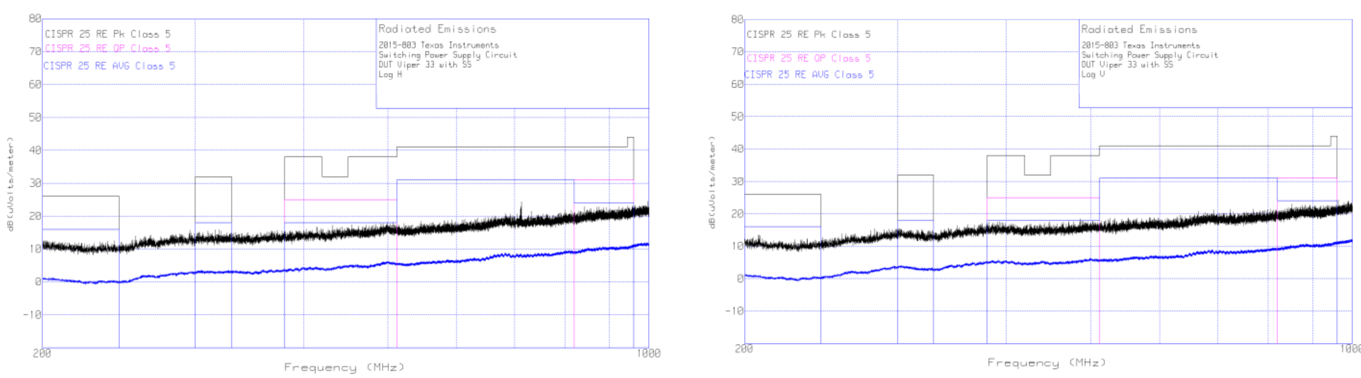


Fig. 15. Radiated emissions results: 200 MHz to 1 GHz, log-periodic antenna, horizontal (spectrum on left) and vertical (spectrum on right) polarizations.

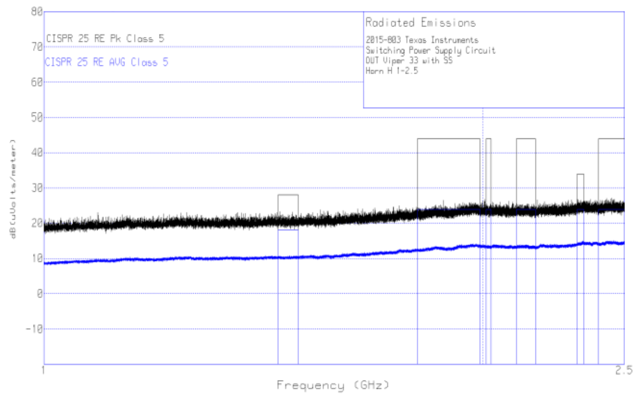


Fig. 16. Radiated emissions results: 1 GHz to 2.5 GHz, horn antenna, horizontal polarization.

Conclusion

Radiated emissions affect a power converter's EMI signature at high frequencies.[12] The upper frequency for radiated tests extends to 1 GHz and higher (depending on the specification)—much higher than for conducted emissions. Performing radiated emissions measurements, while not as straightforward as conducted emissions tests, is necessary for compliance testing and can easily become a bottleneck in a product's development process.

For automotive applications, the cable bundle is often the dominant radiating structure at low frequencies due to its length. The measured radiated emissions profile is largely due to the common-mode current in the attached cables, which is driven by electric near-field coupling between the printed circuit board (PCB) and the cables. I will explore radiated EMI abatement techniques in an upcoming installment of this article series.

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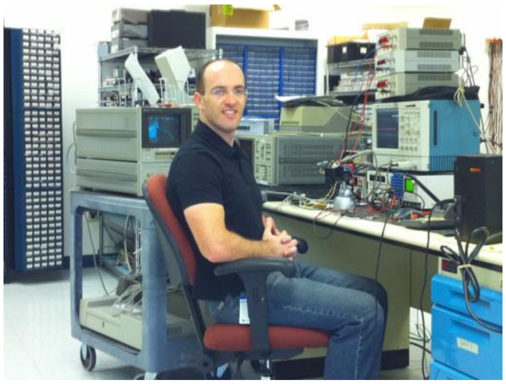
About The Author



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Tim's current focus is on enabling technologies for high-frequency, low-EMI, isolated and nonisolated regulators with wide input voltage range, targeting industrial, communications and automotive applications in particular. He is a senior member of the IEEE and a member of the IEEE Power Electronics, Industrial Applications and EMC Societies.

For more information on EMI, see How2Power's Power Supply EMI Anthology. Also see the How2Power's Design Guide, locate the Design Area category and select "EMI and EMC".