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The Engineer's Guide To EMI In DC-DC Converters (Part 18): Advanced Spread-Spectrum Techniques

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As the automotive industry advances toward higher levels of electrification, ever-increasing power demands impose unprecedented challenges on power density and the cost of power delivery systems. Effective solutions for reducing electromagnetic interference (EMI) in switching power supplies are a necessity to ensure safety and reliability. To this end, it is imperative to meet electromagnetic compatibility (EMC) standards in automotive electronic systems.

As described in parts 15 and 16 of this article series,[1-17] a straightforward approach to mitigate EMI is to include appropriate passive filtering in the EMI propagation path. However, this requires additional components, thus reversing the original intent to increase power density and reduce cost. Part 17 described various active EMI filter solutions that seek to improve the performance-cost ratio over conventional passive filter designs. However, both passive and active filter designs only reduce EMI already caused by the power electronic system.

Spread-spectrum modulation, on the other hand, is an *active* solution to partially prevent the occurrence of high-amplitude disturbances without adding components to the bill of materials. Power electronic converters normally operate at a fixed switching frequency, which causes concentrated harmonic peaks in the frequency domain. By applying spread spectrum, the switching frequency varies in the time domain such that the power of the distinctive harmonics spreads in the frequency domain, decreasing the respective peak spectral values.

Part 9 offered an insight into periodic spread-spectrum techniques to provide a systematic reduction of conducted and radiated emissions, while referring specifically to an implementation using a triangular modulation profile.[9] This article describes an enhanced multirate spread-spectrum technique developed by Texas Instruments that suppresses both acoustic and electromagnetic noise using a combination of periodic and pseudo-randomized modulations. This hybrid technique, known as dual random spread-spectrum, enhances EMI performance across the multiple resolution bandwidth (RBW) settings specified in industry-standard automotive EMC tests such as CISPR 25 and EN 55025.

This multirate spread-spectrum technique is implemented in a new synchronous buck controller IC, the LM25148-Q1. A design example based on this controller is presented here, demonstrating the impact of the technique in attenuating noise across the low and high frequency ranges specified in CISPR 25 conducted emissions testing.

This article begins by reviewing the principles of spread spectrum modulation and where the different modulation techniques fit among the host of EMI mitigation techniques. It then explains the relationship between modulating frequency and EMI receiver resolution bandwidth (RBW), and how the choice of modulating frequency determines the effectiveness of spread spectrum modulation in achieving electromagnetic compliance (EMC). The necessity for tradeoffs in modulating frequency selection and RBW setting in the different EMI test bands motivated the development of the hybrid technique presented here.

Spread-Spectrum Modulation

Fig. 1 classifies various EMI mitigation techniques applicable at the noise source or along the propagation path. In particular, spread spectrum with periodic or random modulation represents a low-cost technique to reduce the magnitudes of EMI noise sources.

The basic idea of spread spectrum is to introduce an intentional dither in the clock frequency, thus avoiding perfect periodicity and reshaping the interfering power spectrum from a delta-like function to a wideband spectrum with lower amplitude. In most practical applications with spread spectrum, the switching frequency $f_s = 1/T_s$ varies with a certain modulating frequency f_m within a defined frequency span $\pm\Delta f_s$ using a periodic triangular modulation profile or a pseudo-random signal generator.[18, 19] Equation 1 represents the Fourier series of the periodic interfering signal in a dc-dc converter:

$$v(t)=\sum_{k=-\infty}^{\infty} c_k \exp\left[j2\pi k f_s t\right] \tag{1}$$

Spread-spectrum modulation translates the original signal, $v(t)$, into equation 2:

$$v_{ss}(t)=\sum_{k=-\infty}^{\infty} c_k \exp\left[j2\pi k f_s\left(t+\delta\int_{-\infty}^{t}\xi(\tau)d\tau\right)\right] \tag{2}$$

where $-1\leq\xi(t)\leq 1$ describes the modulation profile and $\delta=\Delta f_s/f_s$ is the modulation depth.

The actual shape of the spectrum of $v_{ss}(t)$ depends on the modulation parameters δ and $\xi(t)$. If $\xi(t)$ is a periodic modulating function, the spectrum of $v_{ss}(t)$ is *discrete*, with numerous sidebands each spaced by f_m distributed around the original harmonic frequency components. A truly *continuous* power spectrum is possible only with a nonperiodic modulating function such as that achieved using a chaotic or random sequence generator.[20]

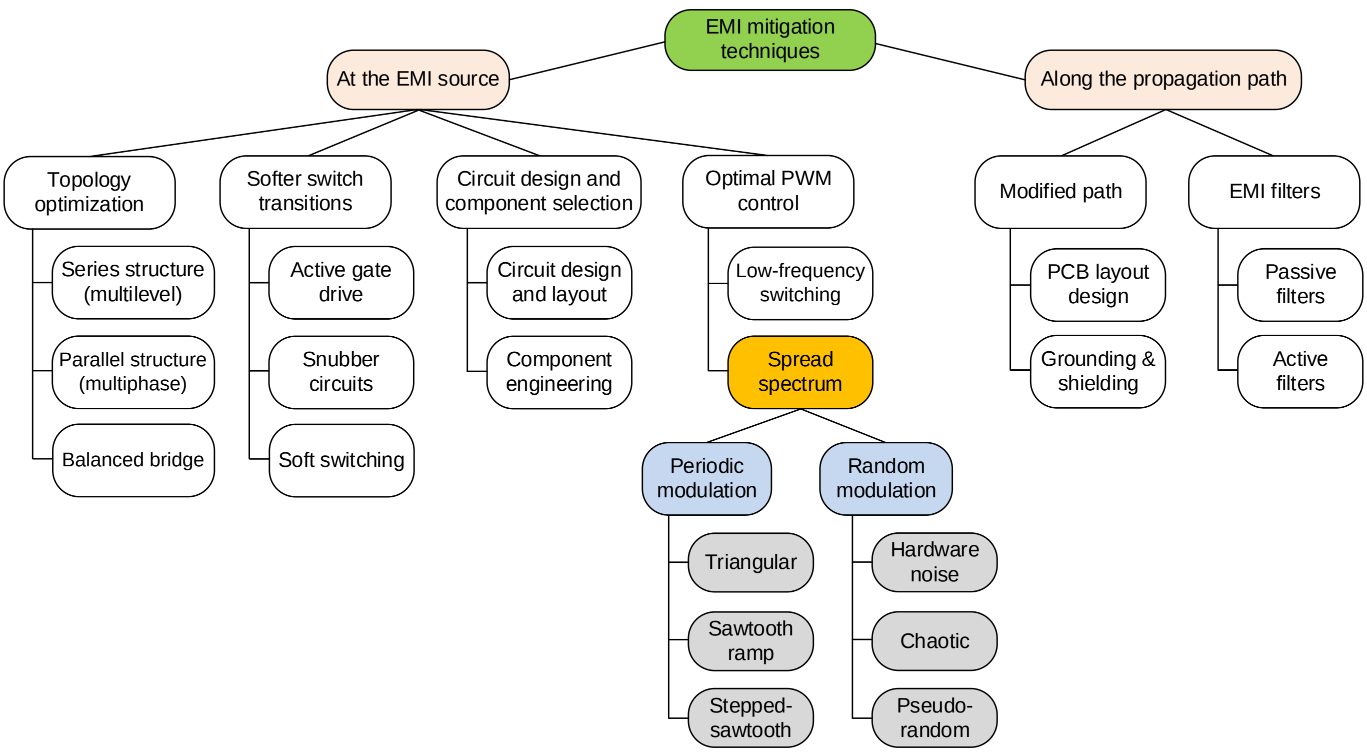


Fig. 1. Summary of EMI mitigation techniques.

Modulating Frequency And RBW

Recent results for periodic modulation, both simulated and experimental, achieve consensus that an optimal modulating frequency exists, depending on the corresponding RBW of the EMI receiver specified for different frequency measurement ranges[18-20] by the EMC standard.

The RBW defines the separation of two harmonics that the EMI receiver can resolve and consequently determines the effectiveness of spread spectrum. Using a periodic modulation profile and peak or quasi-peak detectors, a modulating frequency f_m that is close to the RBW of the measuring receiver produces a stronger EMI reduction[9] and seems to work best. In other words, the modulation frequency setting should not be too low or too high.

As shown in Fig. 2a, the instantaneous carrier frequency continuously stays too long inside the passband of the RBW filter (that is, longer than the filter's settling time, where $t_{settling} = 1/\mathrm{RBW}$). With this time-domain effect, the input signal appears almost unmodulated to the EMI receiver.[20] While Fig. 2b depicts randomized frequency modulations, similar considerations apply to periodic profiles.

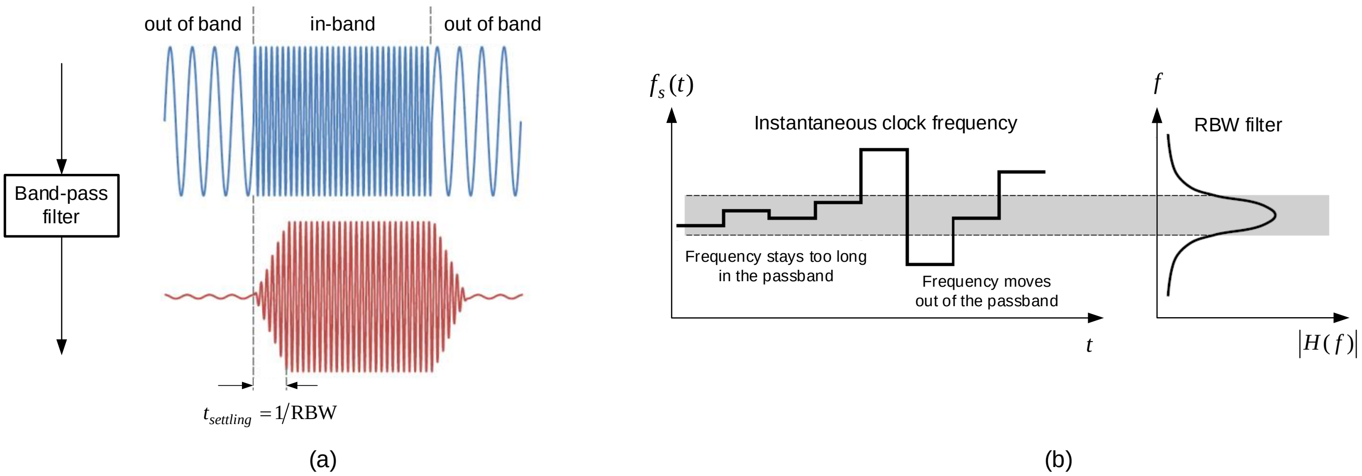


Fig. 2. Intuitive depiction in the time domain (a) and frequency domain (b) where the instantaneous frequency can remain for a relatively long time and settles in the RBW filter passband. Reducing the time in the window avoids the short-term overestimation effect.

Overall, the imperative is that variations of the switching frequency in the observation window are relevant enough leading to an effective short-term spreading of EMI spectral energy and to spectral peak reduction in standard EMC compliance tests.

In contrast, choosing a high modulating frequency implies that the RBW filter cannot settle out of band. Moreover, the result is a low modulation index and very few sidebands. The energy cannot be sufficiently distributed within Carson's bandwidth B_T, and the attenuation of the switching harmonics is again compromised.

Within this context, equation 3 calculates the number of relevant sidebands for energy spreading of the fundamental (as mentioned previously, each sideband ensuing from a periodic modulation process is evenly spaced by the modulating frequency):

$$\text{Number of modulation sidebands} = \frac{B_T}{f_m} = \frac{2\left(\Delta f_s + f_m\right)}{f_m} = 2m+1 \qquad (3)$$

where *m* is the modulation index.

As shown in the table, the ideal modulating frequency approximates to the RBW settings of 9 kHz and 120 kHz in the respective lower and higher ranges for CISPR 25 conducted emissions measurements.

Equation 4 provides an expression for a minimum rate of frequency change, amounting to 81 MHz/s and 14.4 GHz/s at RBW settings of 9 kHz and 120 kHz, respectively:

$$\frac{df_{sw}(t)}{dt} > \frac{\text{RBW}}{t_{settling}} \approx \frac{\text{RBW}}{(1/\text{RBW})} = \text{RBW}^2 \quad (4)$$

While a modulating frequency close to 9 kHz will usually provide the most attenuation, an inherent compromise clearly exists at the higher RBW where the absolute EMI reduction may be suboptimal.

So how do you resolve the requirement for two frequency change rates with one modulation profile?

Table. Relevant parameters and optimization for CISPR 25 emissions testing.

Parameter	**CISPR 25 conducted EMI frequency range**	
	150 kHz to 30 MHz	**30 MHz to 108 MHz**
EMI receiver detectors	Peak/quasi-peak and average	
Ideal modulating frequency (which aligns with the 6-dB RBW setting)	9 kHz	120 kHz
RBW filter settling time, $t_{settling} = 1/\text{RBW}$	111 µs	8.3 µs
Frequency slew rate, $df_{sw}(t)/dt > \text{RBW}^2$	> 81 MHz/s	> 14.4 GHz/s

Advanced Dithering For Multiple RBW Settings

To address this challenge, this article describes a multirate spread-spectrum modulation for EMI suppression. Compared with classic triangular modulation, the proposed technique redistributes the energy in the noise spectrum more effectively by considering the multiple RBW settings of the measuring receiver from CISPR 25, and thus reduces peak EMI more effectively.

To provide some context, Fig. 3 shows a dual random spread-spectrum (DRSS) technique that combines low-frequency triangular modulation (a) and high-frequency cycle-by-cycle random modulation (b) profiles.[21-23]

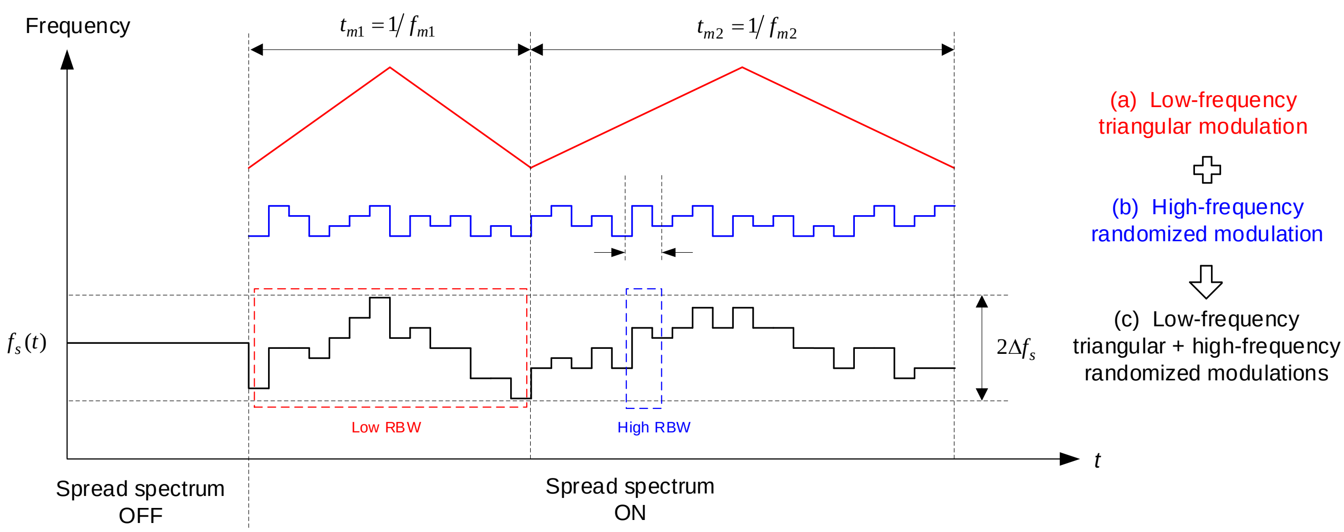


Fig. 3. DRSS modulation profile with randomizations at low frequency to mitigate audio tones (under 20 kHz) and at high frequency for better attenuation in the high RBW setting (30 MHz to 108 MHz).

The triangular modulation maintains performance in lower frequency bands (for example, in the AM band for automotive applications), while the high-frequency random modulation optimizes attenuation in higher frequency bands (for example, in the FM band). In addition, randomly modulating the frequency of the triangular modulation reduces the likelihood of audible modulation tones.[24]

Practical Implementation

Fig. 4 presents the LM25148-Q1 synchronous buck controller[25] from Texas Instruments (TI). The controller incorporates an all-digital implementation of DRSS, enabled or disabled using the CNFG pin.

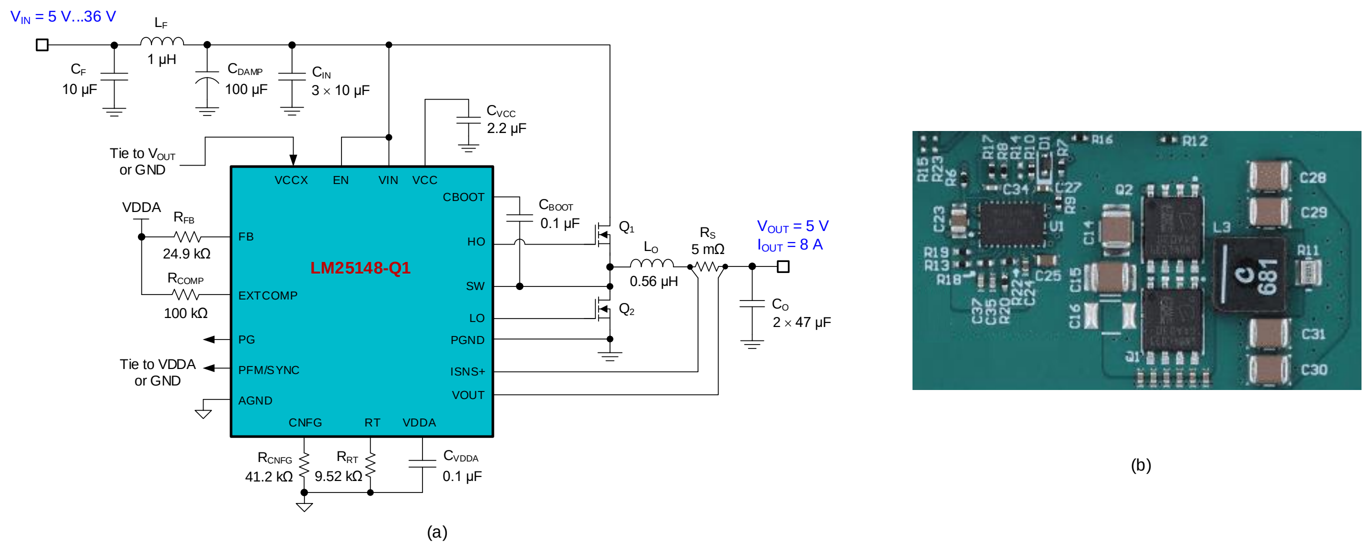


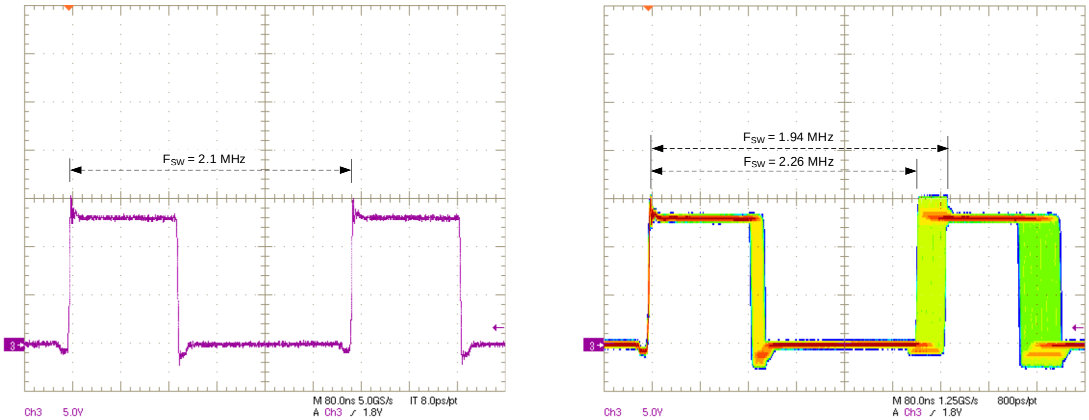
Fig. 4. Schematic (a) and hardware implementation (b) of a synchronous buck controller design with DRSS.

With a nominal switching frequency of 2.1 MHz set by resistor R_{RT}, the frequency deviation Δf_s of the fundamental frequency with DRSS enabled is ±7.8%, or ±164 kHz (center-spread modulation). Equation 5 derives the modulation index based on a modulating frequency that has a 2-bit pseudo-randomized variation between 9 kHz and 14 kHz:

$$m = \frac{\Delta f_s}{f_m} = \frac{164\,\text{kHz}}{9...14\,\text{kHz}} = 12...18 \qquad (5)$$

This combination of frequency span and modulating frequency range provides a high modulation index.

Fig. 5 shows the switch-node voltage waveform (measured using the regulator circuit in Fig. 4) with DRSS both enabled and disabled. The waveform of Fig. 5b has scope persistence activated to reveal the switching frequency variation.



(a) (b)

Fig. 5. Switch-node voltage waveform (V_{IN} = 13.5 V, V_{OUT} = 5 V and I_{OUT} = 8 A) with DRSS disabled (a) and enabled (b).

Using this hardware platform, I performed conducted EMI measurements to meet the strictest limit (Class 5) of the CISPR 25 automotive specification. The input voltage is set at 13.5 V to emulate an automotive battery source.

Fig. 6 presents conducted EMI results when the buck regulator circuit in Fig. 4 has DRSS enabled and disabled. The results comply with CISPR 25 Class 5 automotive requirements.

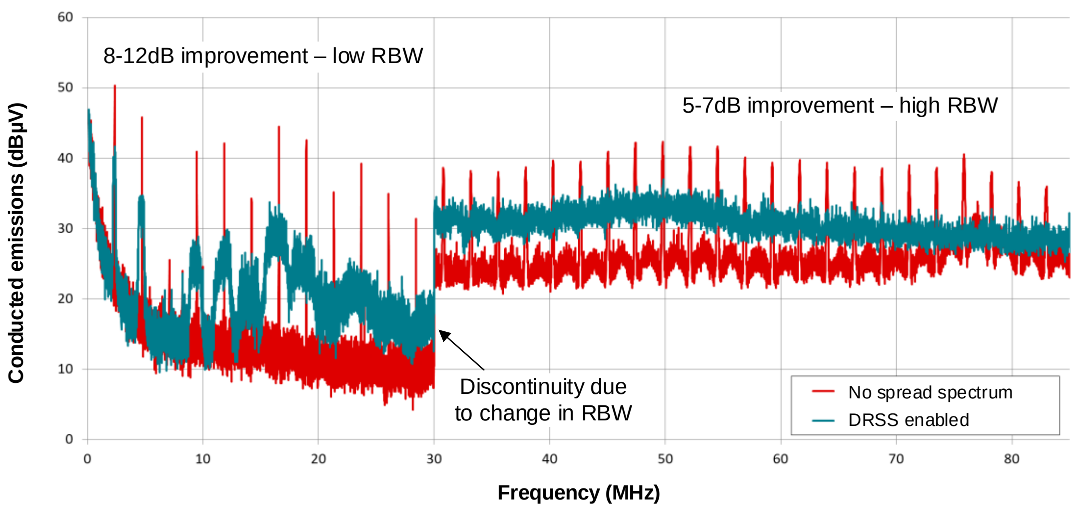


Fig. 6. Conducted EMI results from 150 kHz to 108 MHz: DRSS disabled (red); DRSS enabled (blue).

Noise reduction with DRSS enables improved attenuation across both low (150 kHz to 30 MHz) and high (30 MHz to 108 MHz) frequency ranges for CISPR 25 conducted emissions tests. The fundamental frequency component at 2.1 MHz has its peak EMI level reduced by 8 dB, reducing input filter size. More important is that at high frequencies, where filtering is typically much more challenging, there is a reduction of more than 5 dB at 100 MHz, making it much easier for designers to meet strict EMI requirements.

While the DRSS technique shown here is for a buck controller, it is equally applicable to other topologies[26-27] and would achieve similar results.

Summary

With a crowded electromagnetic spectrum, switching power supplies are a critical factor in the deterioration of automotive electromagnetic environments, necessitating strict enforcement of EMC standards for automotive electronics. The basic idea of spread spectrum is to introduce intentional jitter in the clock frequency such that high-EMI noise spikes, which concentrate at the switching frequency and its harmonics, redistribute to a wider frequency range, leading to peak EMI noise suppression.

An optimized modulation technique known as DRSS combines periodic and pseudo-randomized profiles to reduce power spectrum peak levels across a wide frequency range. With less burden placed on the input filter design, DRSS enables a system-level solution with higher power density and a lower bill-of-materials cost.

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About The Author

Timothy Hegarty is a senior member of technical staff (SMTS) in the Buck Switching Regulators business unit at Texas Instruments. With over 24 years of power management engineering experience, he has written numerous conference papers, articles, seminars, white papers, application notes and blogs.

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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".