Choosing the Proper Parameters in Frequency Spread Spectrum (FSS) Design

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Introduction

The frequency spread spectrum (FSS) technique has been widely applied in power converters to reduce electromagnetic interference (EMI) noise. However, in practice, there are multiple parameters in FSS design that must be considered to optimize EMI performance with minimal side effects. This article introduces FSS parameters such as modulation shape, frequency, and depth, and analyzes their impact on the EMI spectrum. Three key methods to evaluate frequency spread spectrum techniques are then discussed to optimize the FSS parameters, in addition to examining flexible MPS solutions for FSS design in various applications.

Introduction to Frequency Spread Spectrum (FSS)

The active switches in a power converter operate at high frequencies, generating high dV/dt nodes and high dI/dt loops in the circuit. This leads to undesired EMI noise flowing into the circuit. Figure 1 shows the switching waveform of the dV/dt node in a buck converter.

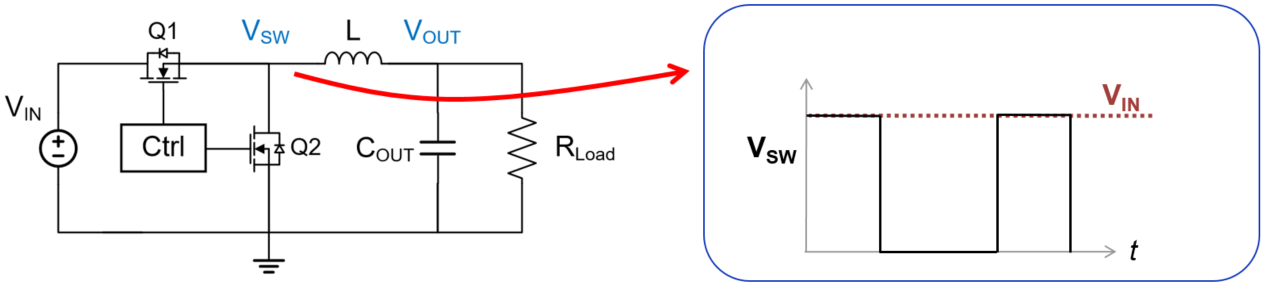


Figure 1: High dV/dt Switching Node in a Power Converter

When the switching frequency (f_{SW}) is fixed, EMI noise spikes occur at the fundamental and harmonics frequencies of f_{SW} (see Figure 2(a)). EMI standards (e.g. CISPR 25) require the peak noise spectrum to not exceed a given threshold. The main principle of the FSS technique is to modulate the power converter's f_{SW} to distribute the noise energy in the spectrum, which reduces the peak EMI noise spectrum (see Figure 2(b)).

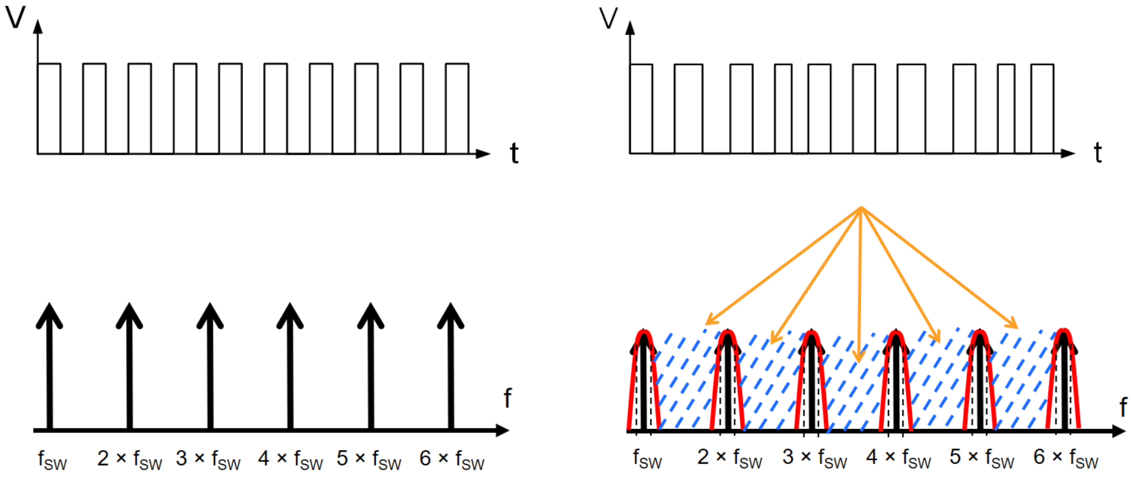


Figure 2: Fundamental and Harmonic Components in Frequency Spectrum (a) and FSS Technique to Decrease the Peak Noise Spectrum (b)

The effectiveness of the frequency spread spectrum technique was questioned for a long time, as it reduces the peak values of the EMI spectrum to meet EMI standards rather than reducing the total noise energy. Since then, the FSS technique has become commonly adopted, and its functionality can be demonstrated using the frequency domain and time domain[1]:

- Frequency domain: The EMI victim circuit is sensitive to only a few frequency ranges, and the FSS technique reduces the power density on these ranges.
- Time domain: The EMI victim circuit has a settling time; interference is reduced if the time interval for the sensitivity frequency band signal is shorter than the settling time. The FSS technique decreases the time interval of the sensitive frequency band.

In past years, various frequency spread spectrum techniques with different modulation shapes have been proposed and applied by varying the frequency vs. time relationship. Figure 3 shows the typical frequency spread spectrum modulation waveforms, including sinusoidal, triangular, Hershey Kiss, and pseudo-random, each of which impact FSS performance differently.

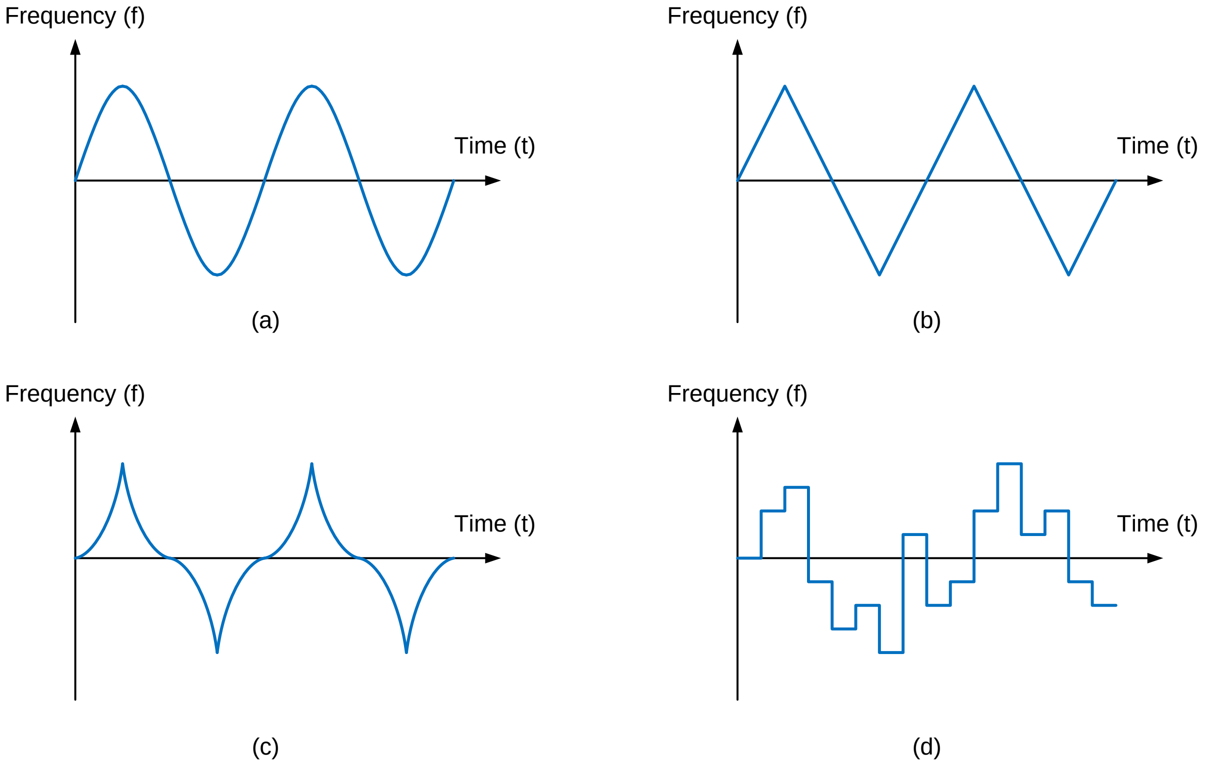


Figure 3: Various FSS Methods Including Sinusoidal (a), Triangular (b), Hershey Kiss (c), and Pseudo-Random (d)

Figure 4 shows typical parameters such as modulation frequency (f_M), span, and the modulation index (m) that impact FSS performance, where T_M is the modulation period.

Modulation Frequency, f_M:

$$f_M = \frac{1}{T_M}$$

Modulation Frequency Span, $Span$:

$$Span = \frac{2 \times \Delta f}{f_{SW}}$$

Modulation Index, *m*:

$$m = \frac{\Delta f}{f_M}$$

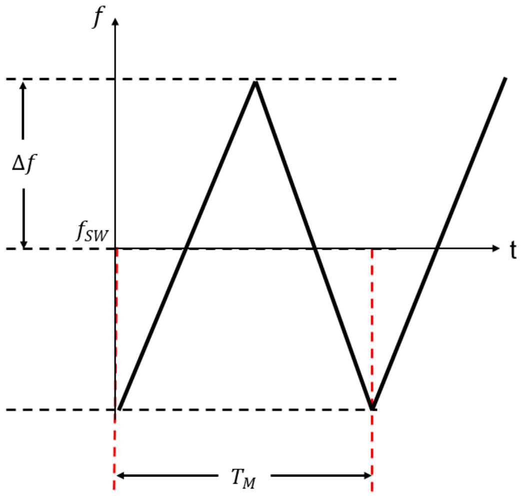


Figure 4: Typical Parameters in FSS Technique

To optimize the FSS parameters, it is necessary to evaluate FSS performance for various parameters, as well as the influence of the FSS parameters in each method.

Evaluation Methods for FSS Performance

There are three key methods to evaluate FSS performance: simulation, evaluation using ICs, and using a signal generator. These methods are described in further detail below.

Simulation Method

A straightforward approach to evaluating frequency spread spectrum is to generate the switching waveform using a circuit simulation tool, then analyze its spectrum. However, the simulation tool typically only provides the fast Fourier transform (FFT) result, which is different from the spectrum measured by an EMI receiver in practice. Therefore, FSS simulation should be based on the principle of EMI receivers instead of FFT.

Figure 5 shows the diagram of a stepped-frequency EMI receiver, where the key blocks include the mixer, the intermediate frequency (IF) filter, envelope detector, and EMI noise detectors.

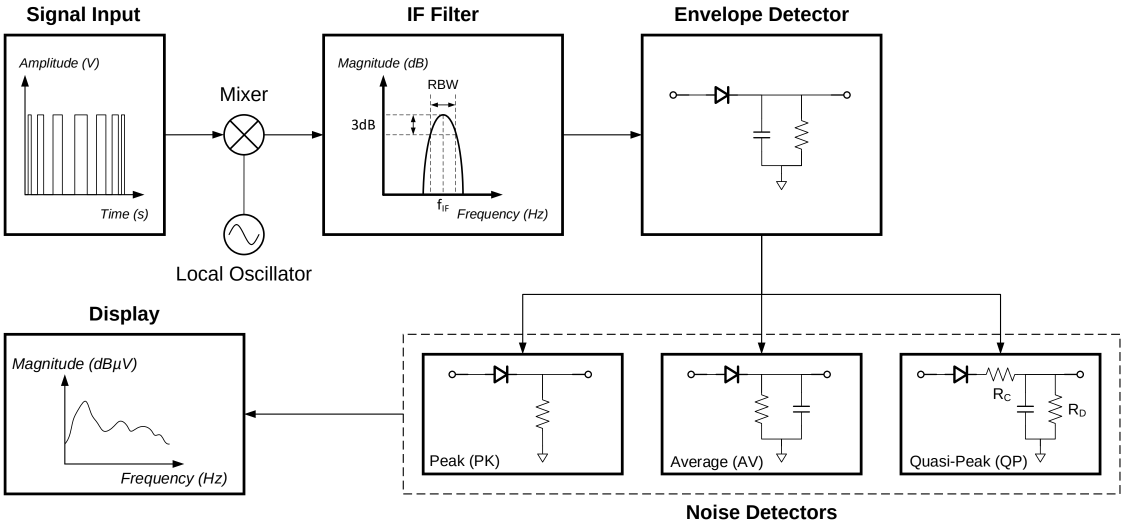


Figure 5: Diagram of a Stepped-Frequency EMI Receiver

The EMI receiver can convert the input signal via a mixer and local oscillator (LO) to the IF. Since the LO frequency is tunable, the entire input frequency range can be converted to a constant IF by varying the LO frequency. An IF filter is applied to extract the components around the targeted frequency.

The resolution of the analyzer is then determined by the IF filter. EMI standards (e.g. CISPR 16) regulate the IF filter's transfer gain requirement. In the simulation, the IF filter can be modeled as a bandpass Gaussian filter, where the transfer gain can be calculated with Equation (1):

$$|G_{IF}(f, f_{IF})| = e^{-\frac{(f-f_{IF})^2}{c^2}} \tag{1}$$

The RBW coefficient (c) can be calculated with Equation (2):

$$\mathrm{c} = \frac{\mathrm{RBW}}{2\sqrt{ln2}} \tag{2}$$

Where RBW is the EMI receiver's resolution bandwidth.

The IF filter's output is first fed to an envelope detector, then the detector extracts the magnitude of the input signal overtime (see Figure 5). This detector can also be modelled in the simulation with a transfer function.[2]

The noise detector is the last stage of the EMI receiver. Figure 6 shows the EMI receiver that can display the peak value, average value, or quasi-peak (QP) value regulated by various EMI standards. These standards are achieved using different analog filters, and their behaviors can be modeled in the simulation.

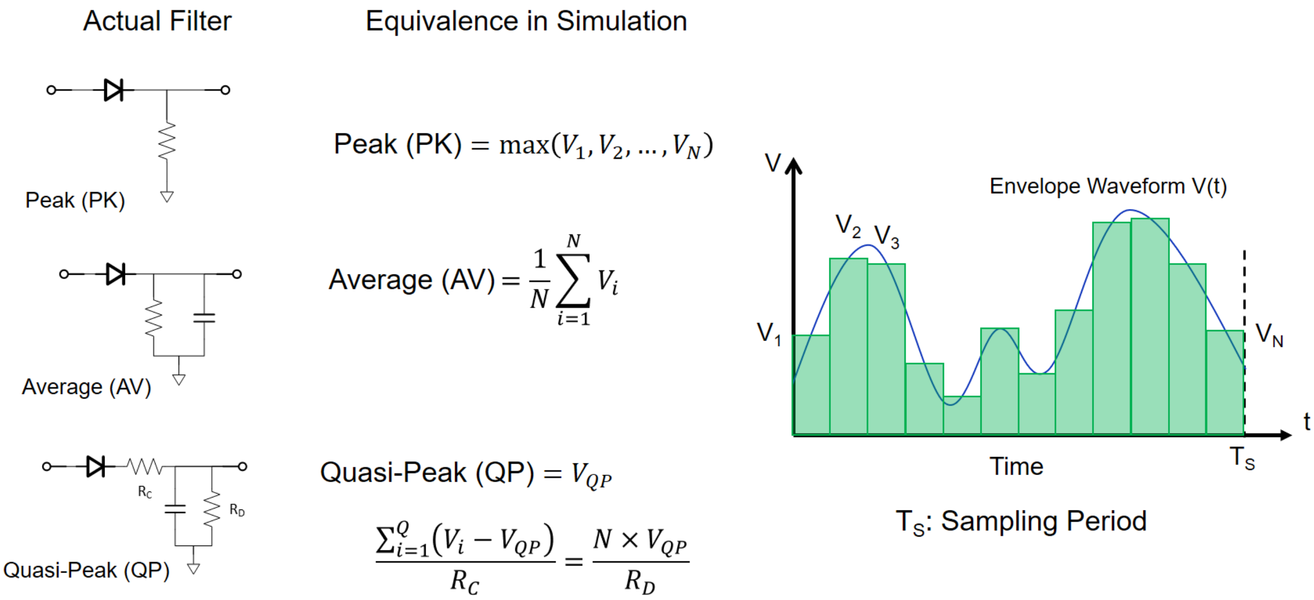


Figure 6: Noise Detectors and Their Equivalences in Simulation

With the above procedure using the stepped-frequency EMI receiver, it is feasible to emulate the EMI receiver with a simulation tool. Figure 7 shows a comparison between the measured EMI spectrum and the simulated spectrum based on the MPQ7200-AEC1, a buck-boost LED driver. The simulation results show that the spread spectrum effect corresponds with the measured results.

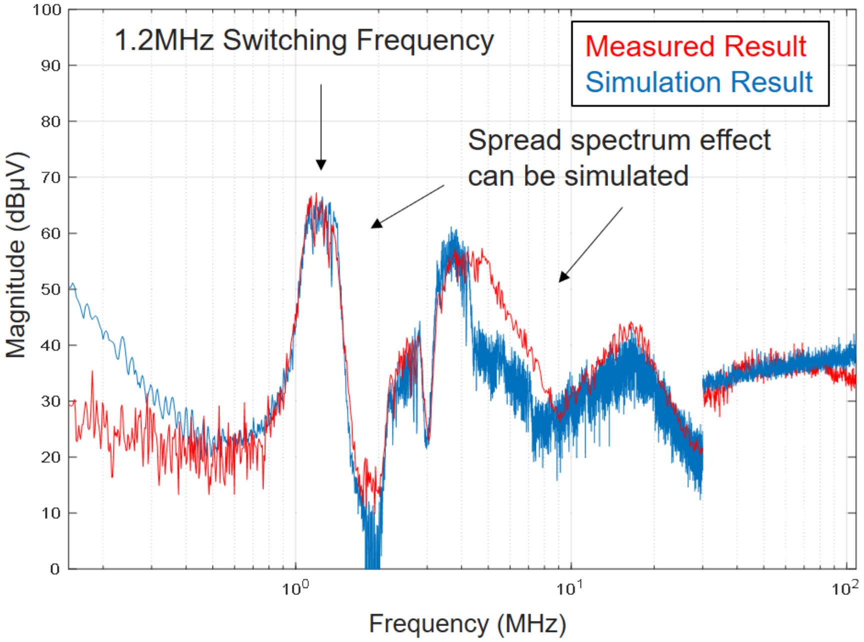
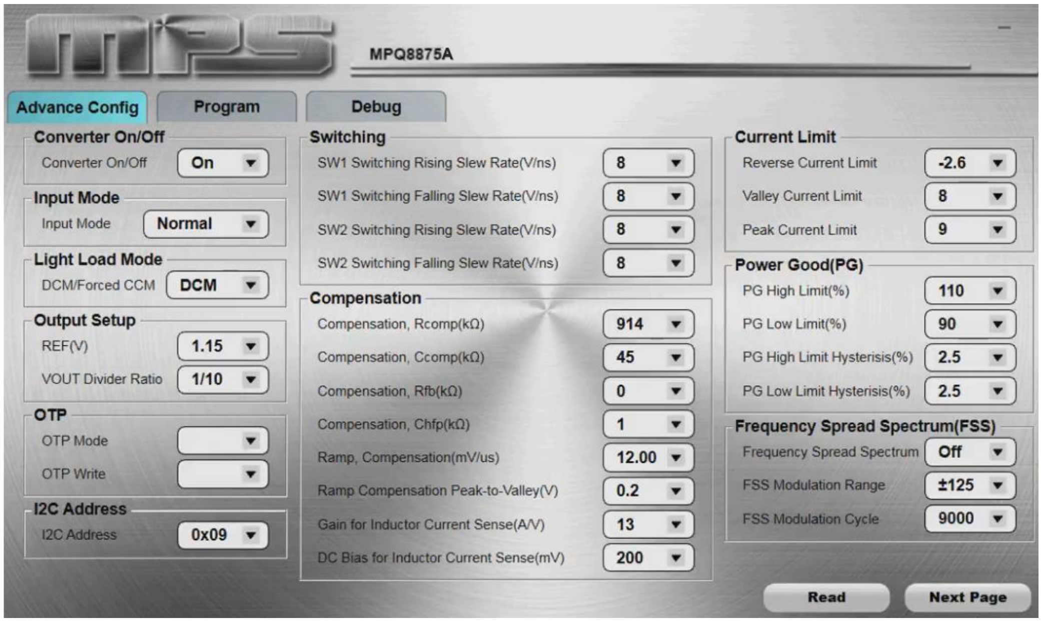


Figure 7: Comparison of Simulated and Measured EMI

Obtaining the simulated results is typically a time-consuming task. Thus, predicting the impact of different FSS parameters may require a more convenient evaluation method, such as using ICs.

Evaluation Using ICs Method

For some IC devices, the frequency spread spectrum parameters are configurable via a digital interface. Using an evaluation board with a digital interface simplifies the process of checking the EMI performance of different settings. Many MPS products provide a digital interface that supports parameter configuration. Figure 8 shows an example with the configuration table of the MPQ8875A-AEC1, an integrated buck-boost converter. FSS can be enabled or disabled, and its f_M and span can also be adjusted, allowing the performance to be evaluated digitally.



Converter On/Off

Converter On/Off	On

Input Mode

Input Mode	Normal

Light Load Mode

DCM/Forced CCM	DCM

Output Setup

REF(V)	1.15
VOUT Divider Ratio	1/10

OTP

OTP Mode	
OTP Write	

I2C Address

I2C Address	0x09

Switching

SW1 Switching Rising Slew Rate(V/ns)	8
SW1 Switching Falling Slew Rate(V/ns)	8
SW2 Switching Rising Slew Rate(V/ns)	8
SW2 Switching Falling Slew Rate(V/ns)	8

Compensation

Compensation, Rcomp(kΩ)	914
Compensation, Ccomp(kΩ)	45
Compensation, Rfb(kΩ)	0
Compensation, Chfp(kΩ)	1
Ramp, Compensation(mV/us)	12.00
Ramp Compensation Peak-to-Valley(V)	0.2
Gain for Inductor Current Sense(A/V)	13
DC Bias for Inductor Current Sense(mV)	200

Current Limit

Reverse Current Limit	-2.6
Valley Current Limit	8
Peak Current Limit	9

Power Good(PG)

PG High Limit(%)	110
PG Low Limit(%)	90
PG High Limit Hysteresis(%)	2.5
PG Low Limit Hysteresis(%)	2.5

Frequency Spread Spectrum(FSS)

Frequency Spread Spectrum	Off
FSS Modulation Range	±125
FSS Modulation Cycle	9000

Figure 8: MPQ8875A-AEC1 Configuration Table

For products that do not provide a digital interface, an analog pin can be used to set f_{SW}. An external circuit can be designed to make f_{SW} follow a triangular waveform, where f_M and span are determined by the R and C values. Figure 9 shows the external circuit of the MPQ4430, a step-down switching regulator, to configure f_{SW}.

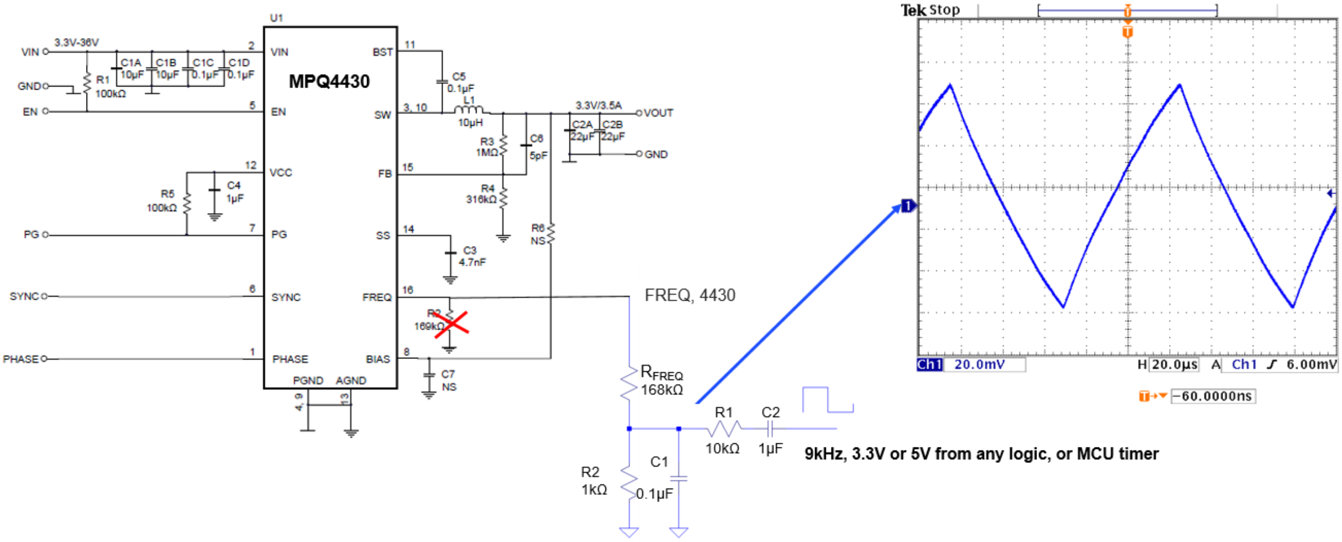


Figure 9: Using an External Circuit to Configure the MPQ4430's Switching Frequency

Signal Generator Method

If no suitable IC is available to configure the frequency spread spectrum setting via a digital interface or analog pin, or if it is necessary to evaluate FSS parameters that are not included in the IC setting, then a signal generator can be used to perform the evaluation.

The output of the signal generator is connected to an EMI receiver for analysis. With the proper settings, the signal generator can also generate switching waveforms using various FSS techniques. In this way, the noise source’s EMI spectrum is emulated and can be directly displayed with a PC connected to the EMI receiver. The result without FSS can be set as a baseline to compare the noise reduction effort of various FSS techniques.

Most signal generators support frequency modulation (FM) to emulate the sinusoidal or triangular frequency spread spectrum. For pseudo-random or other complex modulations, the waveform file can be generated with the associated waveform editor.

The amplitude of the signal should be small enough, and it is recommended to be about 100mV to protect the EMI receiver’s radio frequency (RF) input.

Selecting the Proper FSS Parameters

Frequency Spread Spectrum Modulation Shapes

Figure 10 shows the spectrum of different frequency spread spectrum modulation shapes. For example, the spectrum of sinusoidal modulation has a spike at the edges, while the Hershey Kiss modulation provides a much flatter spectrum.

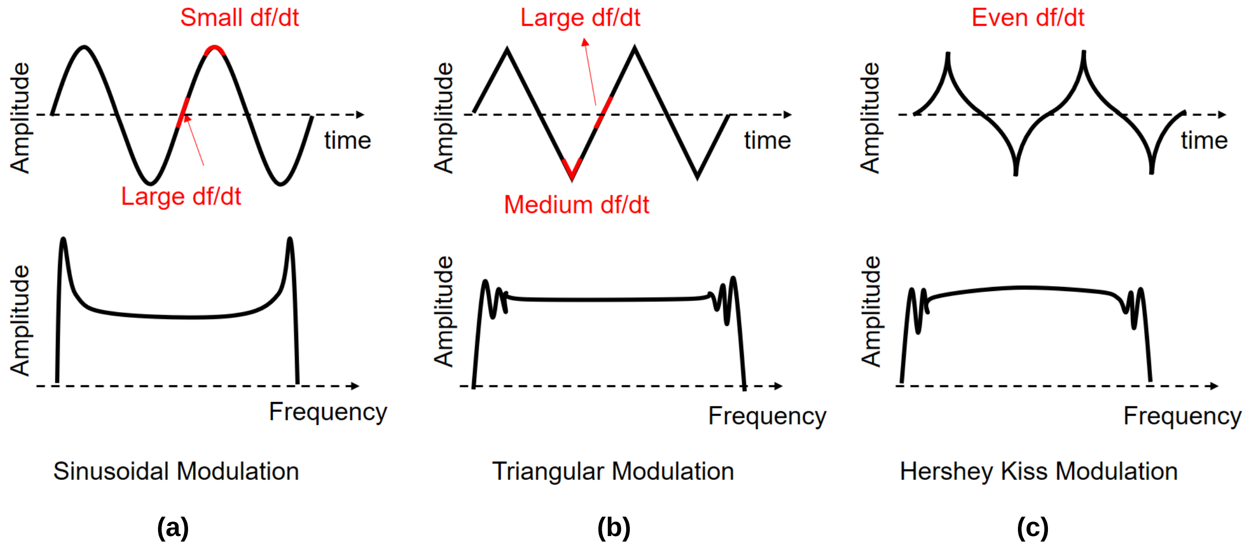


Figure 10: Waveforms and Spectrum of Sinusoidal Modulation (a), Triangular Modulation (b), and Hershey Kiss Modulation (c)

Consider the slew rate of the frequency (df/dt) for sinusoidal modulation, where df/dt is small at the sides of the entire frequency range, and df/dt is large at the center frequency. This indicates that f_{SW} is not spread out well at the edges, resulting in a spike at the edges. For triangular modulation, although df/dt at the center frequency exceeds df/dt at the edge frequency, df/dt is more constant compared to sinusoidal modulation, resulting in a flatter spectrum.

To reduce peak EMI noise, a flat spectrum is recommended, and df/dt and time should be constant. The performance of triangular modulation is typically sufficient and easy to implement, leading it to be widely applied in power supply design.

Modulation Span, Frequency, Index, and RBW

As discussed earlier, parameters such as the modulation span, frequency, and index impact EMI performance. The EMI receiver's RBW also influences the results. The impact of each of these parameters is explored below.

Figure 11 shows the EMI spectrum with different modulation spans varying between 1% and 40%. The red line is the envelope of the noise spectrum where FSS is disabled, and it can be set as the baseline.

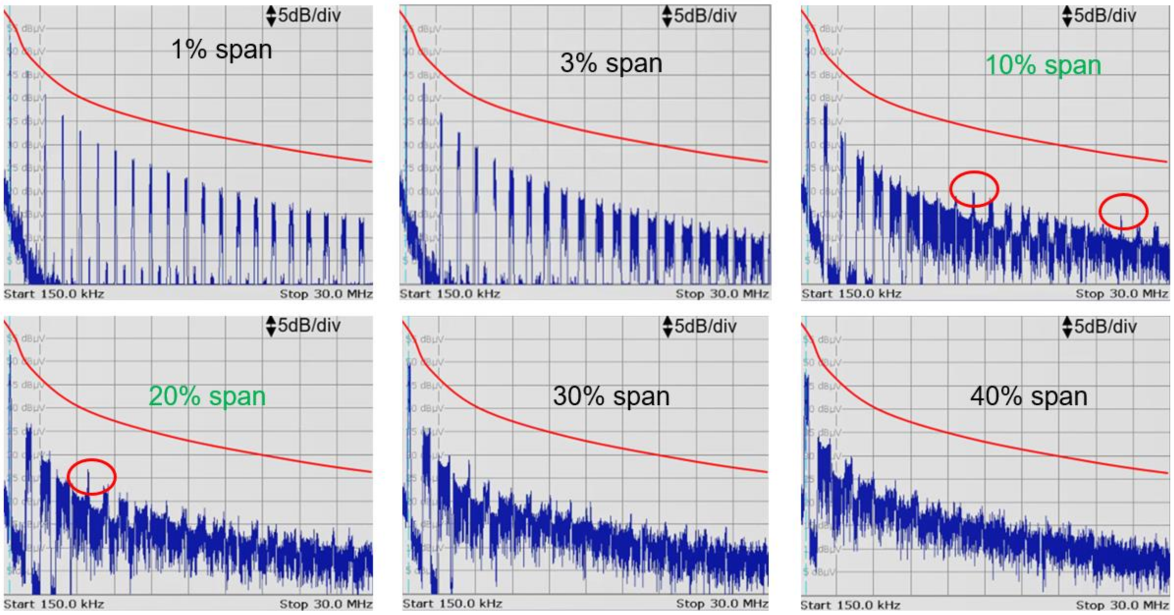


Figure 11: EMI Spectrum for Various Modulation Spans

While a larger span achieves better EMI performance, a span exceeding 20% does not yield significant improvement. In fact, a large FSS span can impact the stability of the converter and overlap with sensitive bands such as the AM band (530kHz to 2MHz). Therefore, a 10% to 20% span is typically selected.

Increasing the frequency span also helps reduce the EMI noise until the adjacent harmonics start to overlap, which occurs at a frequency close to f_{SW} / span, indicated by the red circle in Figure 11.

Selecting the modulation frequency is another factor in FSS performance. Figure 12 shows the EMI spectrum for various modulation frequencies. For a fixed RBW, there is an optimal modulation frequency for peak EMI noise that is typically around RBW in practice. In this example, RBW is selected at 9kHz, and the optimal modulation frequency is also about 9kHz. If RBW and the span (or Δf) is fixed, an optimal *m* is achieved.

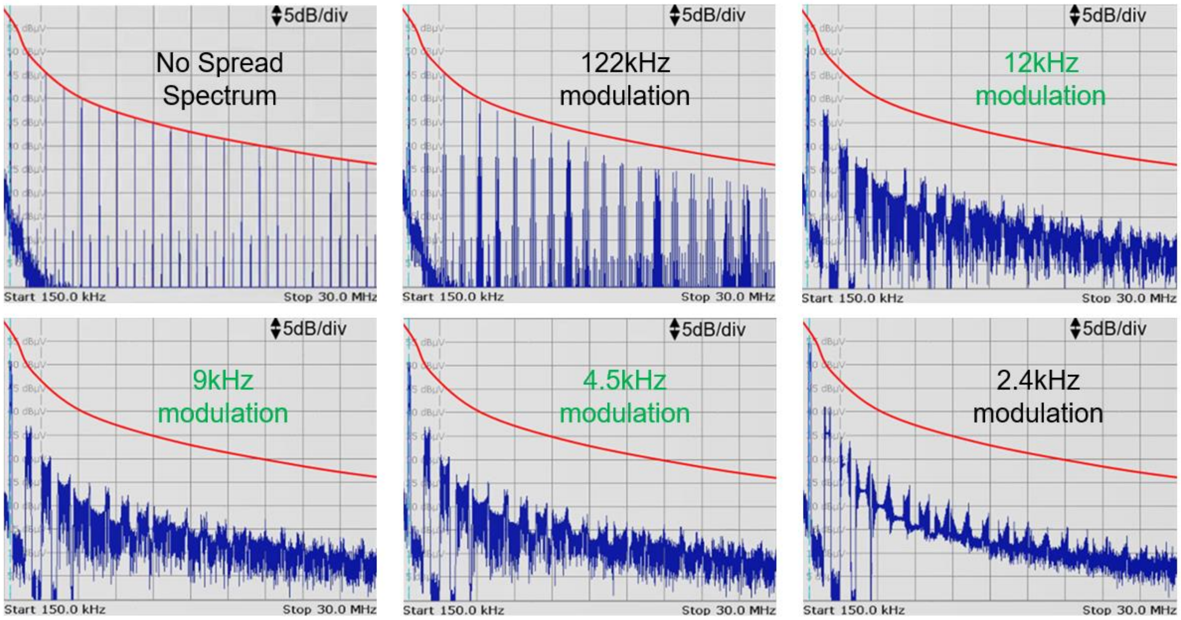
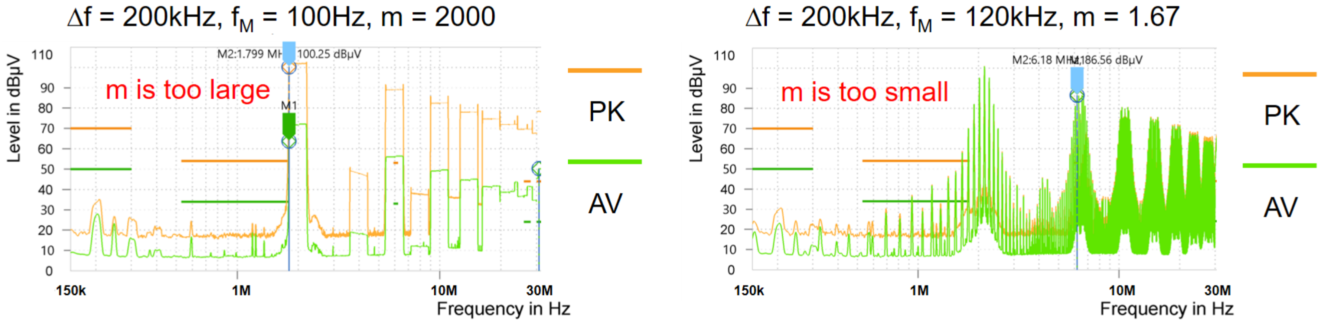


Figure 12: EMI Spectrum for Various Modulation Frequencies

To analyze the noise reduction effect of varying *m*, consider two cases with a very large *m* (see Figure 13(a)) and a very small *m* (see Figure 13(b)).


Δf = 200kHz, f_M = 100Hz, m = 2000

Δf = 200kHz, f_M = 120kHz, m = 1.67

Figure 13: EMI Spectrum of a 2MHz Square Waveform with a Very Large *m* (a) and a Very Small *m* (b)

The results are based on the EMI spectrum of a 2MHz square waveform with different frequency spread spectrum modulations, generated by a signal generator and analyzed by an EMI receiver. If *m* is very large, it means that f_{SW} is almost constant during the interval when the EMI receiver captures the data related to RBW. As a result, the frequency is not spread at all. On the other hand, if *m* is too small, there are only a few steps of f_{SW}. The energy is concentrated on these steps and cannot be evenly distributed across the span.

For different RBW settings, the optimal *m* is different. Based on CISPR regulation, for band B (150kHz to 30MHz), RBW is equal to 9kHz; for band C and D (30MHz to 1GHz), RBW is equal to 120kHz. There is a tradeoff for f_M selection: At f_M = 9kHz, the EMI performance of the low-frequency band is optimized, while at f_M = 120kHz, the high-frequency band's EMI is optimized (see Figure 14).

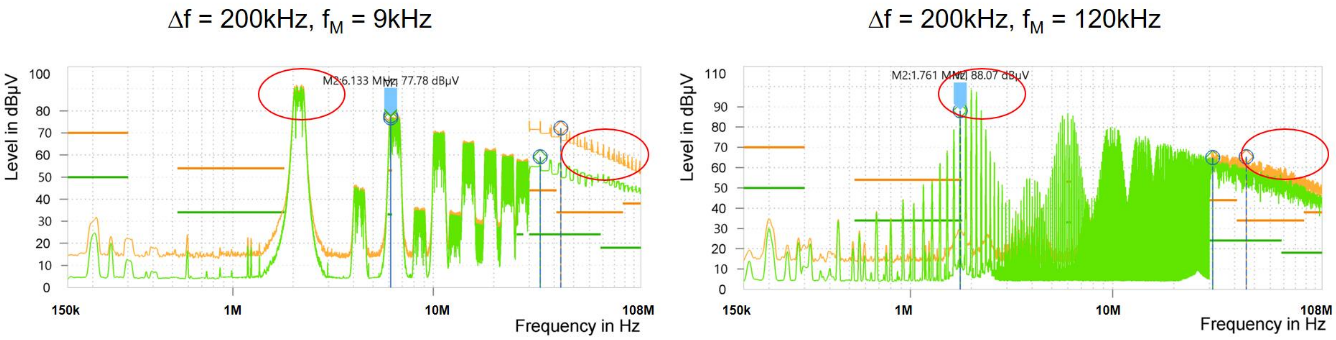


Figure 14: EMI Spectrum of a 2MHz Square Waveform with f_M = 9kHz (a) and f_M = 120kHz (b)

EMI Detectors

To pass EMI tests, both the peak and average EMI noise must meet the corresponding regulation. Similar to peak noise, the impact of the FSS parameters on average EMI noise can also be examined using a signal generator and EMI receiver. Table 1 shows a comparison of the results of noise reduction performance with various FSS parameters and noise detectors.

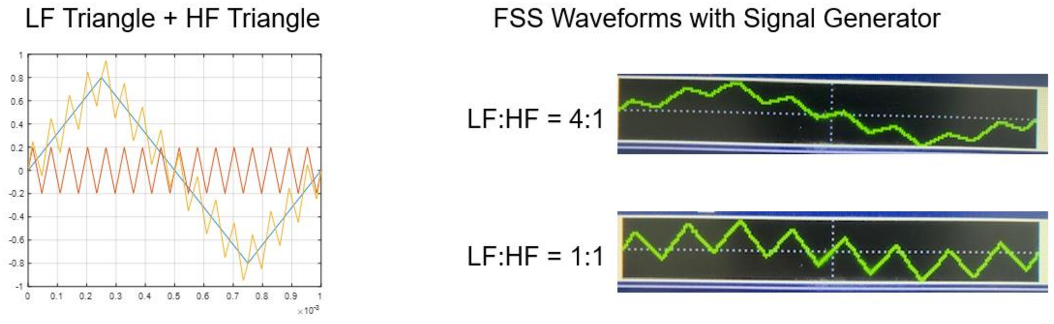
Table 1: Noise Reduction Performance with Various FSS Parameters and Noise Detectors

FSS Parameters	CISPR PK Detector		CISPR AV Detector	
	LF (2.2MHz)	HF (108MHz)	LF (2.2MHz)	HF (108MHz)
No FSS, baseline	0dB	0dB	0dB	0dB
Triangle, f_M = 100Hz	0dB	+2dB	-28.5dB	-27.5dB
Triangle, f_M = 1kHz	-5dB	+1.5dB	-23dB	-23.5dB
Triangle, f_M = 9kHz	-11dB	-3dB	-12dB	-15.5dB
Triangle, f_M = 120kHz	-2dB	-7.5dB	-2dB	-14.5dB

Unlike with peak noise, the attenuation of average EMI noise is better with a larger *m* due to the significantly higher data acquisition interval for the average detector compared to the peak detector. Even with a large *m*, the energy remains evenly spread across the FSS span. When selecting the FSS parameters, it is more critical to select a proper f_M based on its impact on peak EMI noise.

Dual-Modulation FSS

As previously established, if the modulation frequency is close to RBW, optimal frequency spread spectrum performance is achieved in the frequency band where RBW is applied. Figure 15a shows a modulation waveform with dual frequency components that is proposed to reach a balance between high-frequency and low-frequency performance. Figure 15b shows that the waveforms with different high-/low-frequency component ratios can be imported into a signal generator to be further processed by the EMI receiver.



(a) (b)

Figure 15: Modulation Waveform for Dual-Modulation FSS (a) and Applying Different Ratios with a Signal Generator (b)

Table 2 shows the performance of dual-modulation frequency spread spectrum.

Table 2: Performance of Dual-Modulation FSS

FSS Parameters	CISPR Peak Detector	
	LF (2.2MHz)	HF (108MHz)
Triangle, 15kHz, baseline	0dB	0dB
Triangle, 15kHz:120kHz = 4:1	+0.5dB	1.5dB
Triangle, 15kHz:120kHz = 1:1	+1dB	4dB

Compared to FSS with single-modulation frequency, the dual-modulation technique helps improve the high-frequency band EMI performance, while the low-frequency EMI becomes degraded.

As power converters with increasingly higher switching frequencies are developed today, the high-frequency EMI poses notable challenges. Dual modulation FSS improves the high-frequency EMI noise attenuation, and has been applied in several MPS power ICs, such as the MPQ4371-AEC1.

FSS Considerations for Various Applications

Some applications, such as radar sensors and Class-D audio amplifiers, have their own sensitive frequency bands. The FSS technique must not induce extra noise on these bands. The RF rails of a radar sensor are sensitive to power supply ripple and noise in the baseband (10kHz to several MHz) because these supplies feed blocks, such as the phase-locked loop (PLL) circuit, baseband analog-to-digital converter (ADC), and synthesizers (see Figure 16).

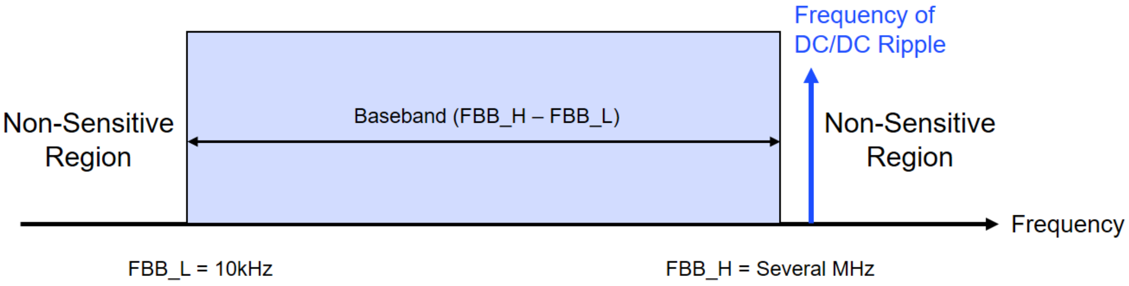


Figure 16: Baseband of Radar Sensors

Figure 17a shows a waveform for dual FM frequency spread spectrum, an approach to reducing the impact of baseband noise performance by modulating f_M. The frequency spectrum of dual FM FSS is compared with a single FSS in Figure 17b, where the frequency spectrum of a square waveform is modulated with a fixed f_M. A significant component occurs at f_M and its harmonics, which can influence the baseband noise performance. The peak value around f_M is greatly reduced and benefits the radar sensor's noise performance.

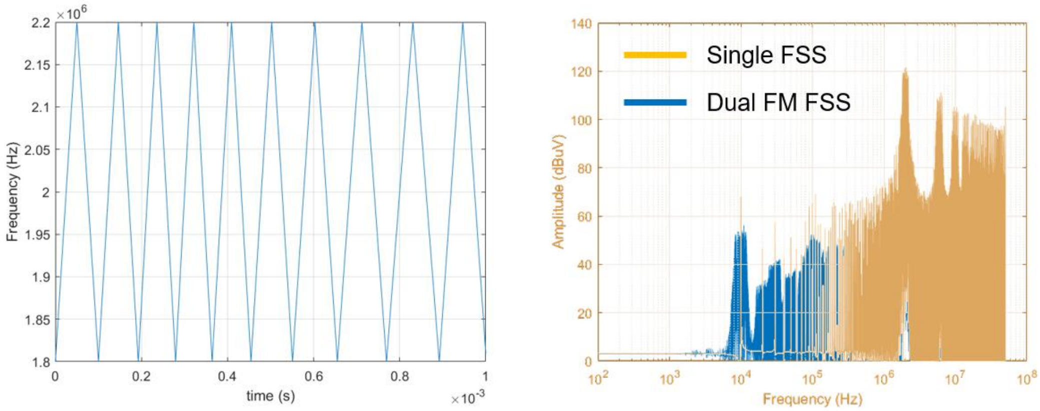


Figure 17: Dual FM FSS Modulation Waveform (a) Spectrum of Single FSS and Dual FM FSS (b)

Since the audio band for Class-D amplifier applications (20Hz to 20kHz for the normal audio range, or 20Hz to 40kHz for the high-resolution audio range) are sensitive to power supply noise, the FSS technique does not influence noise. This band is not very wide, and a straightforward method to reduce the impact of baseband noise performance is to set f_M beyond the audio band. f_M can typically be implemented between 35kHz and 50kHz for the 20kHz band, or between 70kHz and 100kHz for the 40kHz band.

Conclusion

Frequency spread spectrum for EMI noise reduction is an effective method. This article introduced the parameters of FSS techniques and provided a guide for selecting the proper FSS parameters. Methods including simulation, evaluation using ICs, and using a signal generator were introduced to evaluate FSS performance. In some noise-sensitive applications (e.g. radar sensors and Class-D audio amplifiers), FSS parameters require special consideration to prevent degrading normal operation.

Learn more about MPS's AEC-Q100 grade switching converters and controllers.

References

[1] F. Pareschi, R. Rovatti and G. Setti, "EMI Reduction via Spread Spectrum in DC/DC Converters: State of the Art, Optimization, and Tradeoffs," in IEEE Access, vol. 3, pp. 2857-2874, 2015.

[2] L. Yang, S. Wang, H. Zhao and Y. Zhi, "Prediction and Analysis of EMI Spectrum Based on the Operating Principle of EMC Spectrum Analyzers," in IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 263-275, Jan. 2020.