Application Report

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EMI Reduction Technique, Dual Random Spread Spectrum

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ABSTRACT

Spread spectrum techniques are commonplace in switch mode controllers and converters, and serve the purpose of reducing the effect of electromagnetic interference (EMI) that switchers generate. There are many ways to implement spread spectrum, and each of these will typically perform better at either low frequencies or high frequencies, due to the multiple resolution bandwidths (RBW) used in industry standard tests. Dual Random Spread Spectrum (DRSS) uses a digital algorithm specifically designed to spread spectral emissions in multiple frequency bands, without trading off performance between them.

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1 Introduction

Spread spectrum techniques (or “dithering”) have been used for many years in a variety of applications, with a history of use in radio and wired communications. In the context of switching regulators, spread spectrum can be used to reduce the effects of EMI generated by fixed frequency switching, at both the fundamental switching frequency and its harmonics [1]. This EMI can manifest itself in the form of radiated and conducted emissions, both of which are important to address. For this application note, the focus will be on optimizing spread spectrum for automotive applications, where the primary frequencies of interest are governed by CISPR-25 conduction EMI test standards [2]. However, the methods described herein can be applied to other test standards as well.

One of the biggest challenges when optimizing spread spectrum is finding solutions that work well in multiple frequency bands, as most modulation schemes will perform best in one band, but have shortcomings in others [1]. This is due to the fact that industry standard EMI tests require different spectrum analyzer RBW settings for different frequency bands, and the RBW has a significant impact on dithering performance [3]. This application note will introduce a novel digital spread spectrum scheme, DRSS, which performs well at both the high (120 kHz) and low (9 kHz) CISPR-25 RBWs that are used for automotive conducted EMI tests [4]. This scheme is used in both the LM5156x(-Q1) and LM5157x(-Q1), which are a current mode, programmable frequency, non-synchronous, boost/SEPIC/Flyback controller and converter, respectively.

The tradeoffs that are faced when optimizing spread spectrum will be reviewed, using common spread spectrum design parameters such as f_C, Δf_C, f_m, and m, as well as a discussion of the time domain implications of the RBW filter. The majority of the application note focuses on reviewing current techniques and spread spectrum theory. This is purposeful, as the value of DRSS is most readily seen through the lens of a thorough understanding of the tradeoffs that need to be balanced.

(1)

2 Spread Spectrum Review

2.1 Purpose of Spread Spectrum

The basic principle behind spread spectrum is to reduce the effect of EMI by converting a narrowband signal into a wideband signal, which will spread energy across multiple frequencies. For a switching regulator, this can be done by manipulating the oscillator that sets the switching frequency, and can be done for most switch mode power supply topologies (buck, boost, and so forth). Conservation of energy requires the total energy to remain constant, but by spreading this energy across multiple frequency bands, peak energy is minimized. As a result, nearby sensitive circuits (hereafter referred to as victims) will be less perturbed by the interference. Figure 1 illustrates how manipulating the clock frequency over time has the effect of spreading energy generated by a switcher.

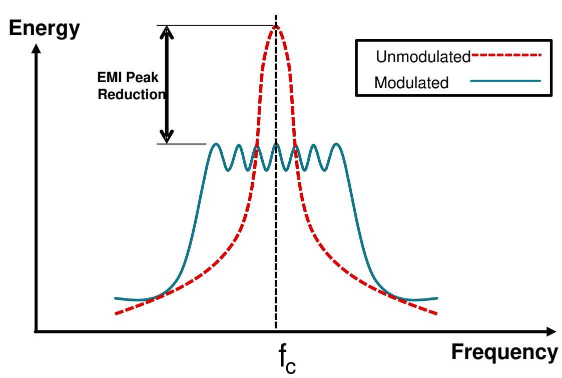

Figure 1. EMI Reduction by Spread Spectrum, Frequency Modulation

2.2 Definitions

The use of frequency modulation to achieve spread spectrum is similar to FM radio transmission, whereby a signal is transferred via the modulation of a carrier frequency. Although there is no signal being transmitted in spread spectrum, there is a shared terminology between the two.

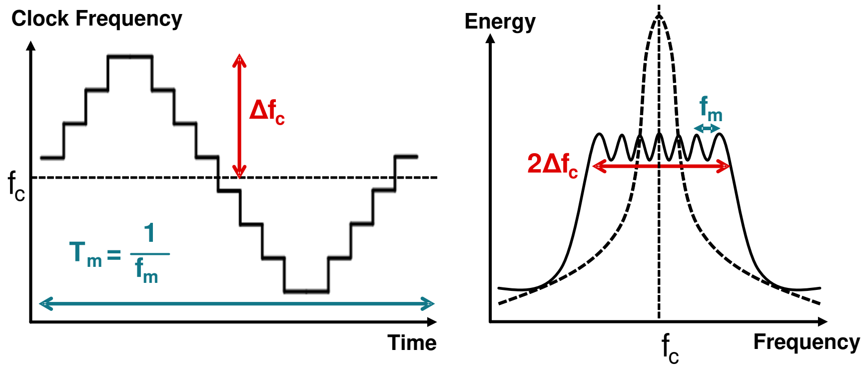

Figure 2. Triangular Modulation in the Time (Left) and Frequency Domain (Right)

Figure 2 (Left) shows an example of triangular type spread spectrum, where the clock frequency is plotted as a function of time, along with the resulting spectral plot of the fundamental in Figure 2 (Right). The time domain shows one cycle of the modulation waveform, where f_C is the unmodulated oscillator (carrier) frequency, f_m is the modulation frequency, and Δf_C is the distance that the switching frequency deviates from f_C. Note that although the waveform shown in Figure 2 (Left) is discretized, this does not necessarily mean that this is digital dithering. Because the clock frequency of a switching regulator can only be updated once per switching cycle, the frequency versus time waveform must be discrete, regardless of the modulation method. Although a triangular modulation profile is just one of many analog dither profiles, it is quite common due to the ease of generation as well as its performance [1]. For that reason, other types of analog dither profiles will not be analyzed for this application note.

2.3 Optimization and Tradeoffs

When optimizing spread spectrum, the most important factor is the modulation index, m, which is defined as $\Delta f_C/f_m$ [3]. In general, the larger this number is, the better the energy reduction at the fundamental frequency will be. Increasing Δf_C spreads the energy across additional frequencies, and decreasing f_m reduces the energy at the fundamental by providing additional frequency components within Carson's bandwidth, $2\Delta f_C$ [1]. However, there are limitations for both Δf_C and f_m. For Δf_C, there are constraints in both the time and frequency domain. In the time domain, large Δf_C can increase output ripple, and also leads to large variations in inductor current ripple. In the frequency domain, if Δf_C is too large it can start spreading energy into bands where it is not desired.

From a mathematical perspective, reducing f_m should always lead to a reduction of energy. However, there is an additional constraint due to the time-based effects of the RBW filter. The RBW filter has a settling time that is reciprocal to the bandwidth of the filter [3]. If this filter is allowed to settle, the peak detector of the spectrum analyzer will detect energy equal to an unmodulated signal. On the other hand, modulating very fast with respect to the settling time of the RBW filter does not give it a chance to respond, and the peak energy is not allowed to decay. In other words, not enough time is spent outside of the bandwidth of the filter for the modulation to be useful. Figure 3 illustrates this concept, and shows the finite settling time that exists both entering and leaving the RBW filter. Because of this constraint, f_m is typically chosen to be approximately equal to the RBW, despite the fact that from a theoretical perspective a smaller f_m is preferred. Analyzing modulation frequency from both a theoretical perspective and a time-based filter perspective is the key to optimizing spread spectrum.

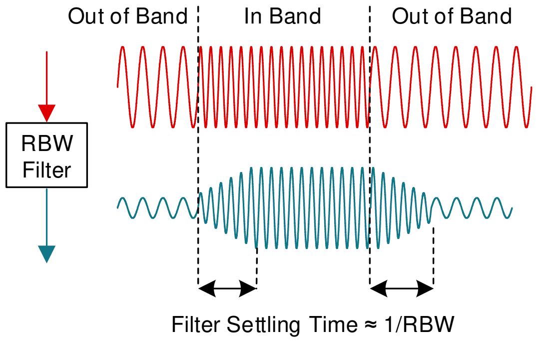

Figure 3. Settling Time Effects of the RBW Filter

It is important to note that the best performance that can be achieved by spread spectrum/dithering is reduced as the system frequency (f_C) decreases. This is simply because at low frequency, Δf_C is limited by system constraints, and spread spectrum peak reduction can be no better than $10\log(RBW/2\Delta f_C)$ [3].

3 Analog and Pseudo-random Techniques

Triangular analog dither is a common approach that offers good performance in CISPR-25 bands within the 150-kHz to 30-MHz range, which have a 9-kHz RBW requirement [4]. It performs well here as it is easy to achieve a wide Δf_C, and f_m can be set to approximately equal the RBW. Unfortunately, this frequency exists in the audible range, and care must be taken to ensure that the analog dithering is inaudible. Performance in bands within the higher 30-MHz to 108-MHz range, which have a 120-kHz RBW requirement, is not optimal if the modulation frequency is kept at 9 kHz. For the higher frequency bands with a 120-kHz RBW requirement [4], a common solution is to use pseudorandom spread spectrum (PRSS) [1]. In this modulation scheme, the frequency is changed pseudorandomly at every switching cycle to generate a fast modulation that is closer to the 120-kHz RBW. Because the pseudorandom sequence repeats very infrequently, the f_m from a theoretical perspective is significantly reduced, improving both EMI and audible performance. Although PRSS works quite well for high RBWs, there is a penalty to be paid at lower RBW due to the fast modulation that does not leave the RBW filter for a long enough duration. Secondly, Δf_C must be kept small due to concerns related to output ripple. This can be mitigated with step size limiting, but the change in the random distribution will degrade performance.

3.1 Adaptive Random Spread Spectrum

A recent advancement in digital spread spectrum technology is a technique known as adaptive random spread spectrum (ARSS). The basic principle behind ARSS is to take the modulation frequency, f_m, and randomly change it at the conclusion of every ramp. The purpose of this is to reduce the audible tone that accompanies dithering with a fixed frequency. Figure 4 shows how the 10-kHz tone is reduced and spread when looking at conducted emissions on a spectrum analyzer. The audible reduction was observed qualitatively in the lab, but has not been measured quantitatively. Performance at the fundamental frequency is comparable to analog dither. Although the tones that are not at the RBW reduce performance from a RBW perspective, this is counteracted by the improvement to the theoretical performance that arises from the very low period of the pseudorandom sequence.

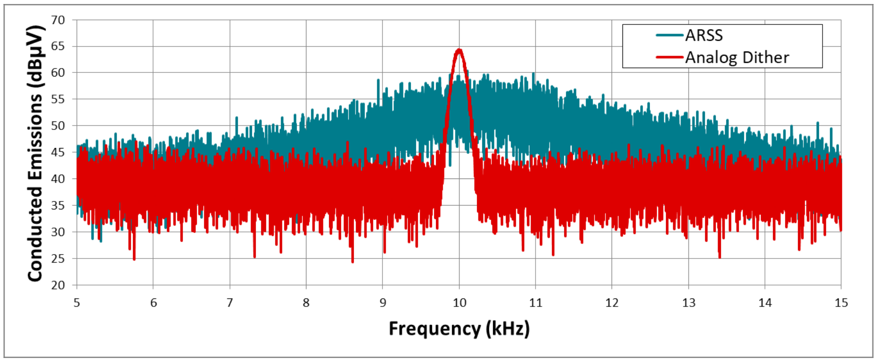

Figure 4. ARSS Improves Audible Noise by Spreading the 10-kHz Tone

Unfortunately, with any digital triangular modulation scheme with finite step size, there is a price to be paid at high frequency. Because the changes to the oscillator frequency are implemented digitally, the switcher can operate at the same frequency for many cycles. At high RBW, this has the time-based effect of a slow moving modulation, spreading the frequency across multiple bands, but without reducing the peak energy, which is counter to the goals of spread spectrum.

3.2 Dual Random Spread Spectrum

The solution to the problem that ARSS has at high RBW is to add pseudorandom cycle-by-cycle dithering on top of the triangular profile. This pseudorandom modulation improves high frequency performance, as it provides a fast enough modulation for the 120-kHz RBW. At low frequency and low RBW, the envelope of the triangle modulation can still provide the low f_m benefits of ARSS. The tradeoffs between low and high RBW are eliminated by addressing both simultaneously. Figure 5 shows how this is implemented in the time domain. The RBW is represented as a windowing function in the time domain, which aligns with Discrete Fourier Transform theory, where the frequency bin size is set by the window size.

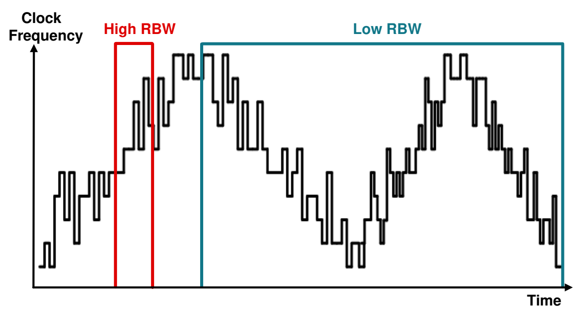

Figure 5. Time Domain Implementation of DRSS

Figure 6 shows the conducted emissions of the non-synchronous boost converter using the LM5156 device, operating at 2.2 MHz, before and after enabling DRSS. The discontinuity at 30 MHz is due to the RBW change from 9 kHz to 120 kHz. In the CISPR-25 low frequency band, DRSS shows a peak reduction of 10–15 dB. In the CISPR-25 high frequency band, DRSS shows a peak reduction of 5–7 dB.

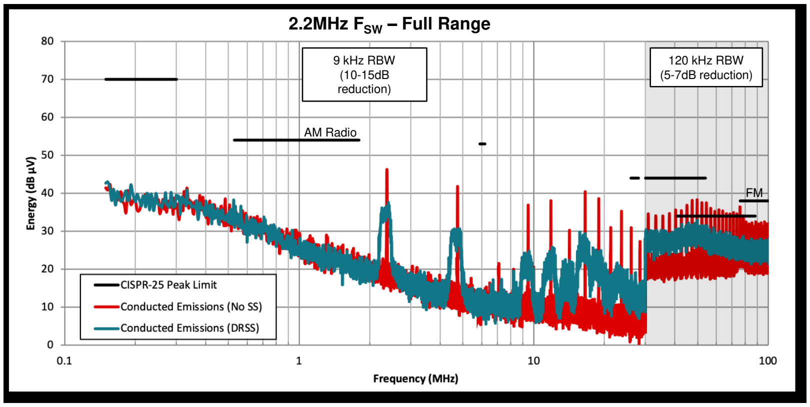

Figure 6. Conduction EMI Reduction by DRSS (LM5156, Switching at 2.2 MHz)

In the LM5156, DRSS is implemented with a Δf_C of $f_C \times 5.5\%$, a Δf_{PRSS} of $f_C \times 2.3\%$, and an f_m randomized between 10 kHz and 16 kHz. These values were chosen to provide a good balance between peak EMI reduction and regulator performance in the time domain. Because output ripple is an important concern for switching regulators, care must be taken when implementing any spread spectrum method, including DRSS. In a current mode regulator, output ripple can be significantly improved by modulating the slope compensation ramp in a way that is inversely proportional to the oscillator frequency. This has the effect of maintaining the average inductor current, despite spread spectrum modulation that is manipulating the time at which the inductor begins energizing.

4 Summary

A study of spread spectrum theory, techniques, and tradeoffs was presented in this application note, along with a new digital approach for improving spread spectrum performance of switching regulators at multiple frequency bands of varying resolution bandwidths. A new digital spread spectrum scheme, DRSS, effectively minimizes peak EMI in multiple frequency bands by adding pseudorandom cycle-by-cycle dithering on top of the randomly changing triangular profile.

5 References

- [1] Rice, John, Dirk Gehrke, and Mike Segal. “Understanding Noise-Spreading Techniques and their Effects in SwitchMode Power Applications” TI Power Supply Design Seminar SEM1800, 2008.
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