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Spread Spectrum Techniques to Reduce EMI in SMPS Devices

Prepared by Matthew Majeika
ON Semiconductor

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APPLICATION NOTE

Introduction

Electromagnetic compatibility (EMC) is a very important consideration in modern electronic design. With critical information being transmitted, received, stored and acted upon, accurate communication within and between such devices must be assured. Alongside the continuously increasing power levels and frequencies, engineers must design with EMC in mind, especially in the case of high-density layouts.

Switch-mode power supplies (SMPS) are critical power management components in many automotive applications.

The purpose of this document is to investigate a radiated emission reduction technique called *spread spectrum* with specific regard to SMPS applications.

EMC Background

Electromagnetic compatibility (EMC) is the capability of a particular electronic component to function properly under its normal operating conditions without disturbing the operation of any other components or devices. More specifically, electromagnetic susceptibility (EMS) is the level of tolerance of an electronic component or device to various forms of electromagnetic radiation. Electromagnetic interference (EMI) is the level of electromagnetic radiation that is emitted from the device in operation.

There is a set of accepted standards that regulates the amount of radiation a device must be able to withstand as well as the amount that it is allowed to emit. Under a strict method of EMC testing, the final revision of a component must meet these requirements in order to optimize its performance.

Three standards are commonly used for EMC applications: IEC62132-4 (*Direct Power Injection, DPI*) is used for EMS, while IEC61967-2 (*Measurement of radiated emissions - TEM cell and wideband TEM cell method*) and IEC61967-4 (*Measurement of conducted emissions – 1 Ω / 150Ω direct coupling method*) are used for EMI.

Sources of Noise

Many circuits designed today must withstand certain levels of radio frequency (RF) noise. RF generators, electrostatic discharge, high-frequency switching, and mains all play a part in electromagnetic interference. Noise can easily be transferred to any device through EM waves, inductive/capacitive coupling, conduction, or any combination of these. One of the main roles of EMC testing in SMPS is to allow designers to optimize their design by severely limiting these interferences.

Architecture of SMPS

SMPS circuits are commonly used to translate voltage levels in many automotive applications where high-efficiency is a paramount consideration.

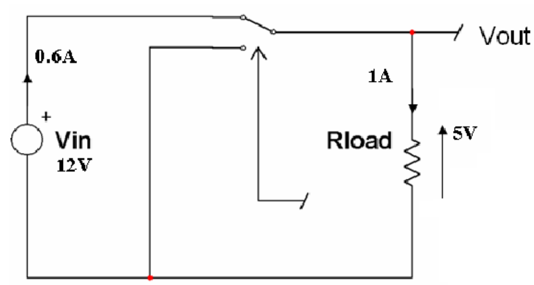


Figure 1. Switch-mode Power Supply

Unlike linear power supplies, SMPS circuits have the ability to step up (boost), step down (buck), or invert their input voltage. Figure 1 shows a basic diagram of an SMPS operation. Notice that the circuit does not constantly provide power from V_{in} to the load, which markedly increases its efficiency. A well-designed SMPS circuit can achieve an efficiency of more than 80%.

Buck converters allow for large fluctuations in input voltage while maintaining a constant output voltage.

Figure 2 depicts a single-pole double-throw switch attached to a load resistor.

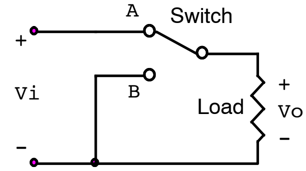


Figure 2. Switched Resistor

In position A, current is allowed to pass through the resistor. In position B, the current is cut off from the resistor, demonstrated in Figure 3.

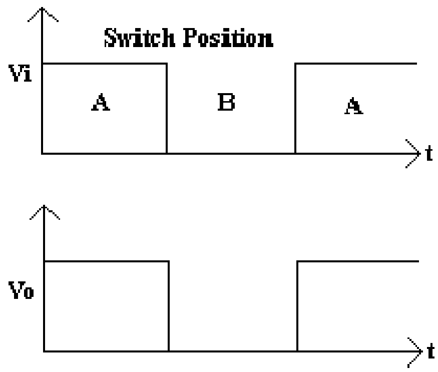


Figure 3. Output voltage versus Input Voltage

Given that a constant output voltage is required, an inductor can be added to smooth out the output voltage, shown in Figure 4.

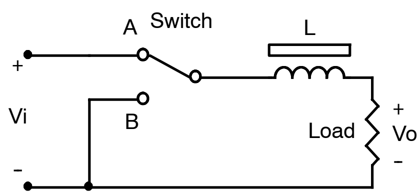


Figure 4. Inductance

Since the inductor is in series with the load resistance, the current through the two components is equal. Therefore, the inductor limits the fluctuations in current through the load, making the output voltage much more consistent. In Figure 5, the output voltage is shown to be rising and falling around an average voltage. When the switch is in position A, the current starts flowing through the circuit and charges the inductor. The inductor stores power according to:

$$P = \frac{1}{2}LI^2 \qquad \text{(eq. 1)}$$

When the switch is in position B, the voltage supply is disconnected and the current in the inductor decreases, releasing the stored energy through the circuit.

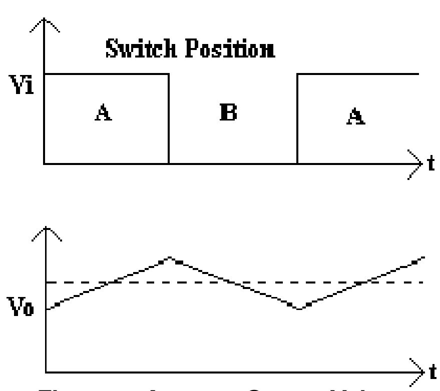


Figure 5. Average Output Voltage

A capacitor can also be added in parallel with the load to diminish fluctuations in the output voltage, as shown in Figure 6.

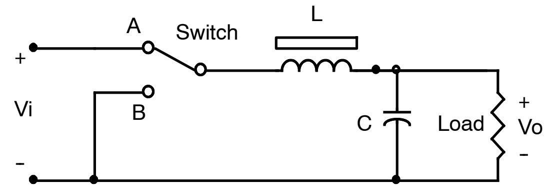


Figure 6. Capacitance

Although power can be lost through the internal resistance of the capacitor, selecting capacitors with a low effective series resistance (ESR) can minimize this concern. Power is stored in the capacitor according to:

$$P = \frac{1}{2}CV^2 \qquad \text{(eq. 2)}$$

The LC filter that is created limits fluctuations in the current through the load as well as the voltage across the load. The result is a well controlled output voltage generated from a wide range of input voltages.

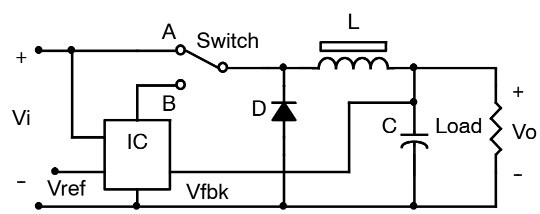


Figure 7. Buck Converter

Figure 7 shows a buck converter applied to step down a variable input voltage to a regulated output voltage. A diode is added to provide a current path during the 'discharge' period. To optimize efficiency, a Schottky diode is preferred. An integrated circuit (IC) is utilized to regulate the output voltage while a transistor is inserted as the switch itself.

One main drawback of SMPS is that the rapid switching creates noise, which can lead to electromagnetic interference with other devices. The frequency at which the device switches can lead to a large spike in the emission profile. The next sections discuss the testing procedures for measuring radiated interference and a specific way to minimize it.

Transverse Electromagnetic Mode

Per IEC requirements, all SMPS devices are tested under the TEM cell method (IEC61967-2). This method measures the radiated emissions from the DUT at short distances. To perform this test, the IC is mounted on the bottom of a 10 cm x 10 cm four-layer PCB with all traces and other components on the other three layers, as shown in Figure 8.

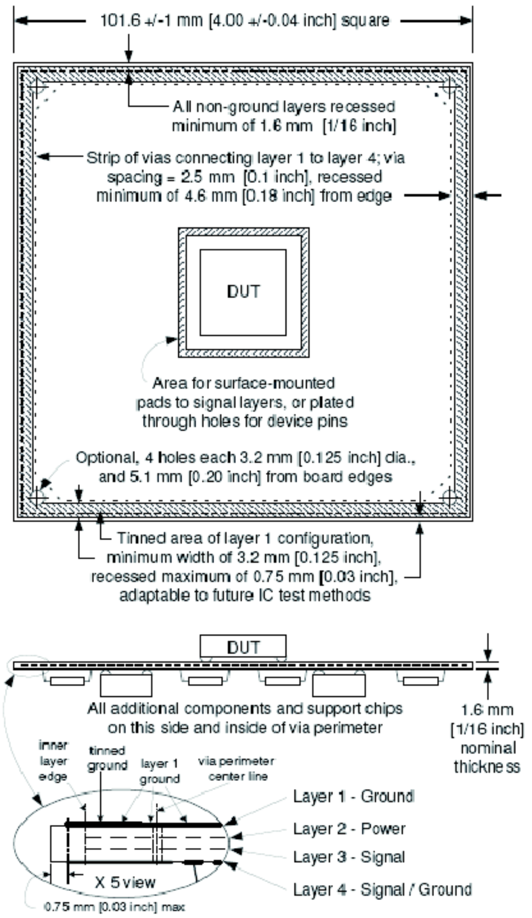


Figure 8. PCB Setup

This assures that the measured electromagnetic radiation is due solely to the IC. The PCB is then mounted to the TEM cell device with the IC on the inside and connections made as shown in Figure 9. The system ground layer is exposed on the edge of the PCB so that it makes a connection with the opening in the TEM cell. This creates a ‘sealed,’ or continuous, environment within which the device can be tested.

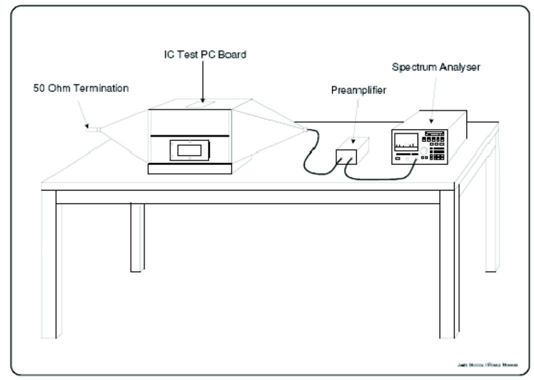


Figure 9. TEM Cell Setup

The TEM cell is connected to a spectrum analyzer via a 50 Ω cable, to make the impedance uniform, and the device is measured for radiated emission. The test is then repeated with the PCB rotated 90° from its original orientation. All four orientations must be tested. The orientation with the greatest emission should be considered for design improvements.

EMC Testing for SMPS: TEM Cell

Typical reference levels for TEM emission are shown in Figure 10.

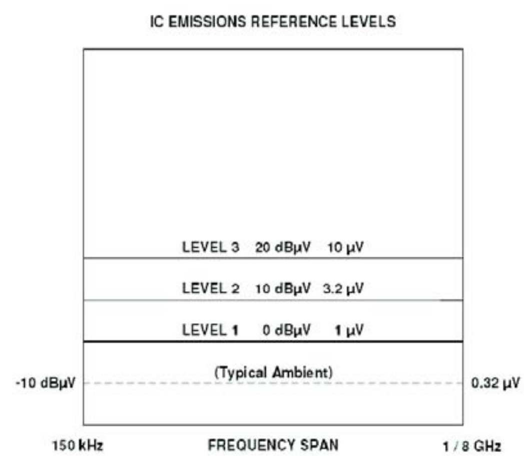


Figure 10. Reference Levels

For TEM cell testing, there are no individual pin considerations because we are only concerned directly with the overall IC radiated emission. Figure 11 shows a typical configuration for a TEM cell test.

Method:	TEM Cell Method close to the IEC 61967-2
DC input voltage:	12 V
Spectrum Analyzer Parameters:	
Frequency bandwidth:	150 kHz to 1 GHz
RBW:	10 kHz
VBW:	30 kHz
Reference Level:	107 dBμV
Attenuation:	10 dB
Load Resistance:	250 Ω

Figure 11. Typical Test Conditions

The following parameters will be used for a more precise analysis of spread spectrum techniques:

Method:	TEM Cell Method close to the IEC 61967-2
DC input voltage:	12 V
Spectrum Analyzer Parameters:	
Frequency bandwidth:	100 kHz to 1MHz 1 MHz to 2 MHz 2 MHz to 3 MHz 3 MHz to 4 MHz 4 MHz to 5 MHz 5 MHz to 6 MHz 6 MHz to 7 MHz 7 MHz to 8 MHz 8 MHz to 9 MHz 9 MHz to 10 MHz
RBW:	9 kHz
VBW:	10Hz
Reference Level:	107dBμV
Attenuation:	10dB

Figure 12. Spread Spectrum Test Conditions

A common TEM cell setup for an SMPS printed circuit board is shown below:

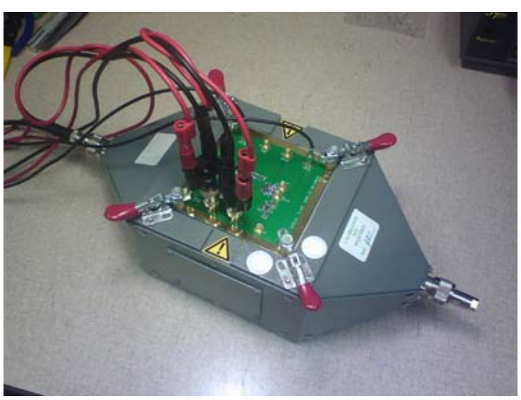


Figure 13. Sample TEM Test Configuration

The ambient system noise must be at least 6 dB below the intended reference level to receive an accurate measurement. The background noise can be measured by replacing the PCB with a metal plate to completely enclose the TEM cell, shown in Figure 14.

Figure 14. Sealed TEM Cell

Spread Spectrum

Spread spectrum involves spreading the peak emission values over a larger frequency range.

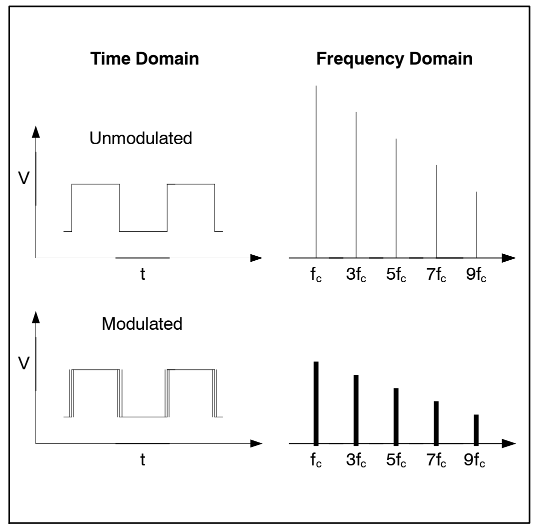


Figure 15. Modulation in Frequency Domain

The effect is a reduction in critical peak values from spreading overall energy in the frequency domain. The most drastic effects are seen in the fundamental frequency, the third, and the fifth harmonics.

In the frequency domain, a sine wave is represented by a single pulse. A square wave, however, is a much more complex signal consisting of multiple frequencies and related harmonics. A sharper transition edge on a square wave signal includes significantly more high-frequency content (harmonics). Spread spectrum techniques can distribute this high energy level over a larger frequency range, thereby reducing EMI.

Spread spectrum is accomplished by modulating the offending signal and is measured as a percentage. The frequency of modulation is typically in the kHz range. A 100 MHz signal with 0.5% modulation is swept between 99.5 MHz and 100.5 MHz at a rate of 30 kHz, for example. This means that the 100 MHz signal no longer spends all of its time at 100 MHz, but has been spread between 99.5 MHz and 100.5 MHz. This reduces a lot of the peak energy at 100 MHz and distributes it between 99.5 and 100.5 MHz.

The example above demonstrates a "center spread" modulation of 0.5%. Modulation takes place above and below the center frequency of 100 MHz. "Down spread" modulation can be used when there are strict limits maximum value of the nominal frequency. For example, a 100 MHz signal with -0.5% modulation is swept between 99.5 and 100 MHz at a rate of 30 kHz. This would be equivalent to a center spread modulation of 0.25% with a 99.75 MHz center frequency.

Spread Spectrum for SMPS

In SMPS devices, switching translates to higher efficiency. Unfortunately, the switching leads to a much noisier EMI profile. We can greatly decrease some of the radiated emissions with some spread spectrum techniques.

The switching frequency for the SMPS device tested is set by the R_{OSC} pin which connects to GND through a resistor. The resistor value is determined by:

$$R_{OSC} = \frac{8687000}{F_{SW}} \qquad \text{(eq. 3)}$$

F_{SW} is the switching frequency (Hz) and R_{OSC} is the pin resistance (kΩ). The formula is accurate to within 3% from 150 to 450 kHz. Below is the schematic representation for our spread spectrum circuit:

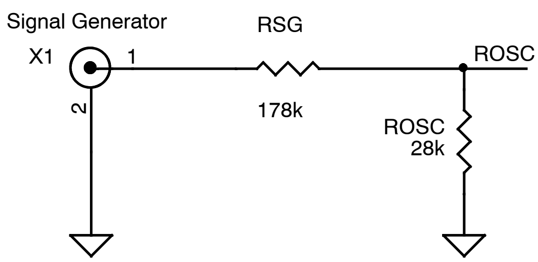


Figure 16. Spread Spectrum Circuit

Adding the 178 kΩ resistor allows us to modulate the current at the R_{OSC} pin, which in turn varies the switching frequency. The current through the pin determines the switching frequency. The current is set up by a voltage source at 0.5 V provided on that pin. Modulation of the switching frequency can be achieved by a linear sweep (triangle wave) between 0 V and 1 V through the 178 kΩ resistor on the R_{OSC} pin.

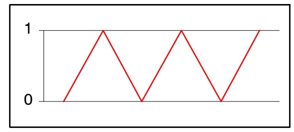
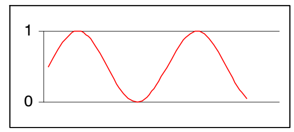
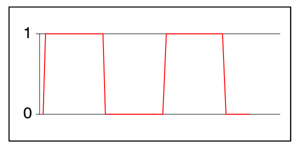
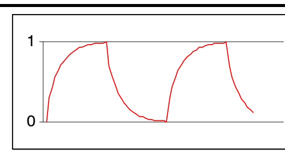
Table 1. SWITCHING FREQUENCY MODULATION

Voltage (V)	0	0.5	1
R_{OSC} (kΩ)	24.19	28.00	33.23
F_{SW} (kHz)	359.05	310.25	261.45

Table 1 describes how the effective resistance changes at the R_{OSC} pin due to the triangle wave on the signal generator, thereby modulating the switching frequency. The voltages shown represent the signal at X1 in Figure 16.

There are 4 types of modulation used in this experiment, shown in Table 2, all ranging from 0 V to 1 V:

Table 2. MODULATION SIGNALS

Waveform	Signal Generator
Linear (Triangle Wave)	
Sine Wave	
Square Wave	
RC Filtered Square Wave	

Each of these waveforms was used to modulate the current at the R_{OSC} pin through the 178 kΩ resistor. The RC-filtered square wave was created by filtering the square wave with a 2 kΩ, 10 nF filter.

The baseline emission in the TEM cell was tested with the Signal Generator pin, X1, shorted to GND, which translates to a 359 kHz switching frequency. This will represent a "down spread" modulation method. The triangle wave frequency was varied from 10 kHz to 50 kHz in 10 kHz steps. Each of the other waveforms was tested at 10 kHz.

Results: Frequency Depth

First, the board was analyzed with the TEM cell without any spread spectrum techniques to achieve a baseline, as shown in Figures 17 and 18.

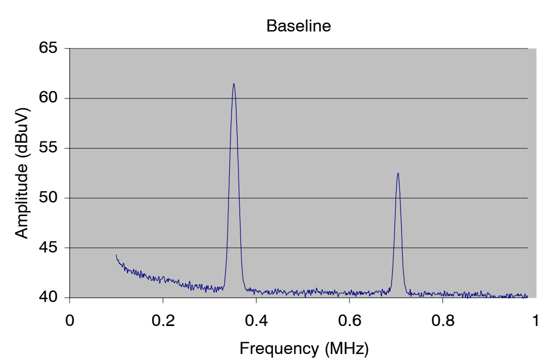


Figure 17. Baseline Emission 0.1 – 1 MHz

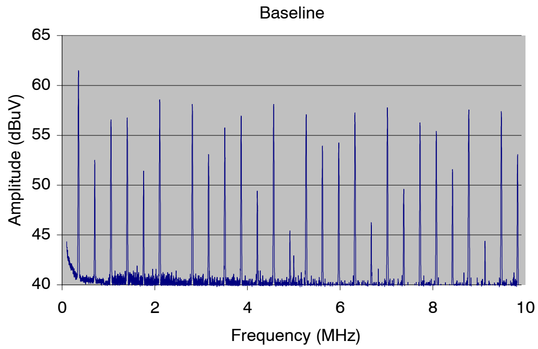


Figure 18. Baseline Emission 0.1 – 10 MHz

The fundamental frequency and nearest harmonic will be given the most consideration. Triangle wave modulation leads to the following comparisons:

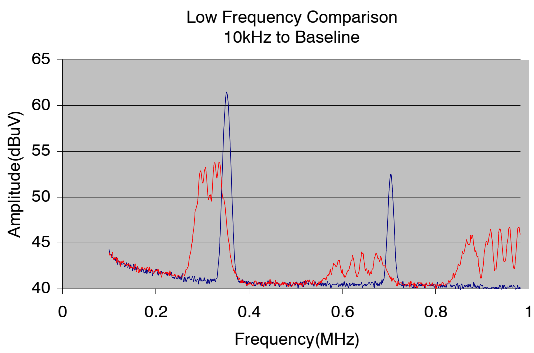


Figure 19. Emission with 10 kHz Triangle Wave

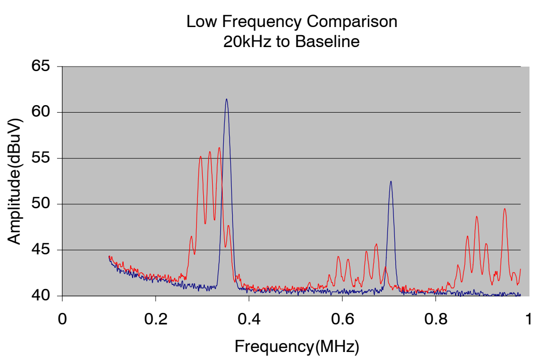


Figure 20. Emission with a 20 kHz Triangle Wave

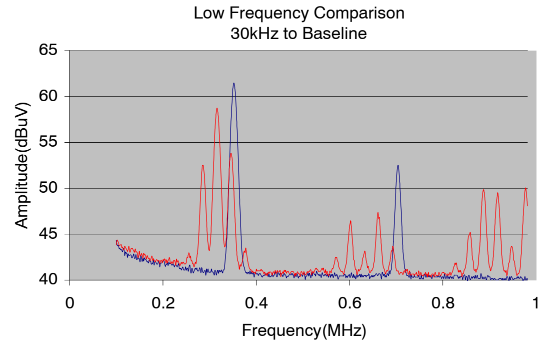


Figure 21. Emission with a 30 kHz Triangle Wave

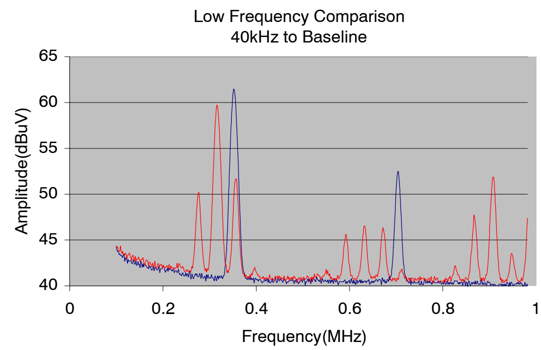


Figure 22. Emission with a 40 kHz Triangle Wave

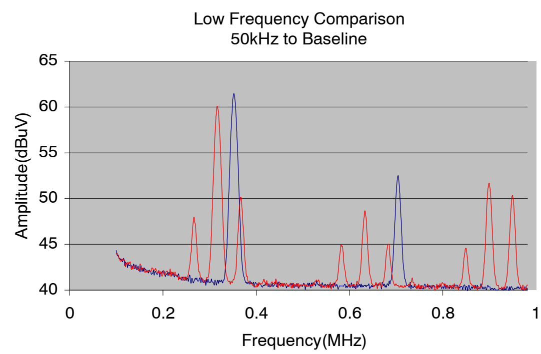


Figure 23. Emission with a 50 kHz Triangle Wave

As the frequency depth increases (up to 50 kHz), the peaks become more spread out. The triangle wave at 10 kHz from 0 V to 1 V, Figure 19, produces the largest reduction, 8 dBuV at the fundamental frequency, in radiated emission. Below is a chart of the expanded emission with triangle wave modulation:

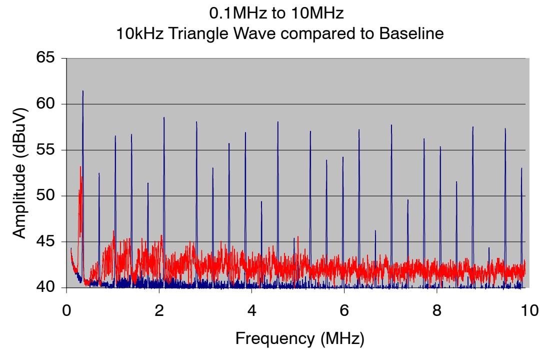


Figure 24. Emission with 10 kHz Triangle Wave

Notice in Figure 24 that the related harmonic emissions are reduced as well as the emission at the fundamental frequency.

Results: Modulation Shape

Modulating with a sine wave at 10 kHz produces the following emission profile:

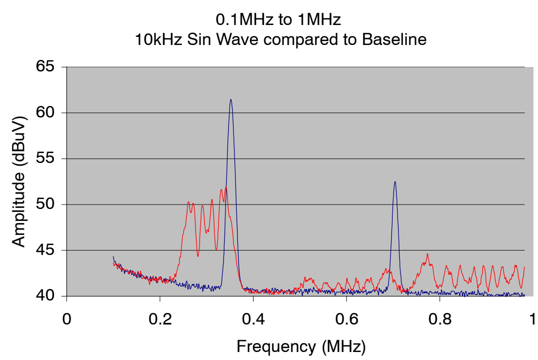


Figure 25. Emission with 10 kHz Sine Wave

Modulating the switching frequency with a square waveform produces the following emission:

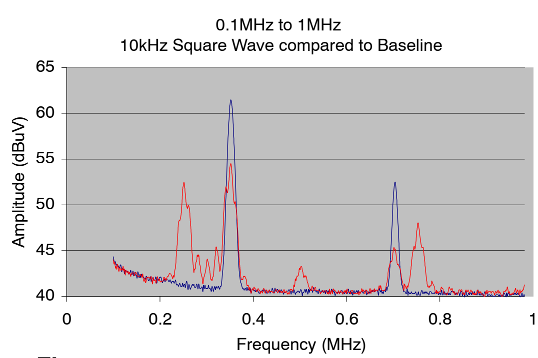


Figure 26. Emission with 10 kHz Square Wave

Modulation with an RC-filtered square wave results in the following emission:

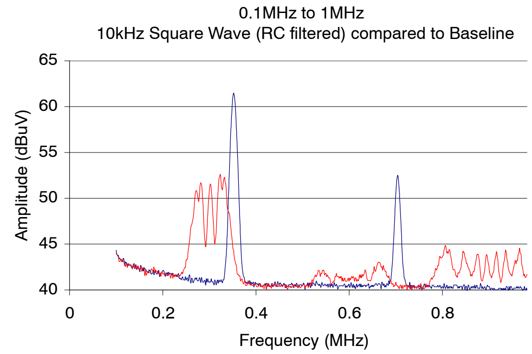


Figure 27. Emission with 10 kHz RC filtered Square Wave

The sine wave at 10 kHz modulating between 0 V and 1 V, shown in Figure 25, produced the greatest overall reduction, 10 dBuV at the fundamental frequency, in radiated emission. Below in Figure 28 is a chart of the expanded emission with sine wave modulation:

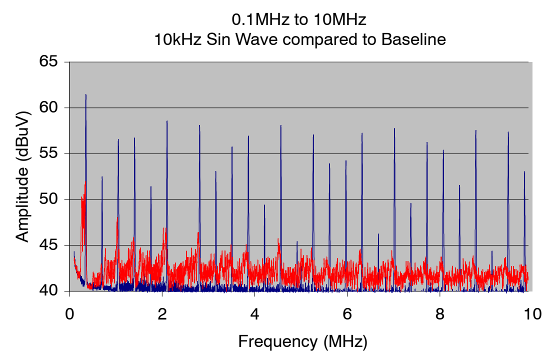


Figure 28. Emission with 10 kHz Sine Wave

Summary

Electromagnetic compatibility is becoming an increasingly important consideration with today's faster and smaller devices. The ability of each device to function properly under its normal operating conditions without disturbing the operation of any other devices is crucial. Devices must be able to withstand disturbances (EMS) from radio frequency noise such as mains voltages or electrostatic discharges. Electromagnetic susceptibility can be tested through the direct power injection method (IEC 62132-4). They must also, at the same time, minimize their own interference (EMI) with other devices from high-frequency switching, for example. Electromagnetic interference, or emission, can be tested through the differential conducted emission method (IEC 61967-4) as well as the transverse electromagnetic cell method (IEC 61967-2).

Switch-mode power supply devices are critical power management components in many automotive applications.

With their ability to step up, step down, or invert their input voltages, SMPS circuits generate a lot of unwanted noise.

Conclusion

Spread spectrum methods have the unique ability to reduce the noise at the switching frequency of an SMPS device. Through modulation at the R_{OSC} pin, the switching frequency can be spread to nearby frequencies, thereby reducing the peak emission levels at the fundamental frequency and the related harmonics.

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