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TND6032/D

Reduction of Switched Mode Power Supply Electro-Magnetic Emissions in Automotive Cockpit Applications

by Using of a Field Programmable Gate Array to Implement Pseudo Random Spread Spectrum Modulation

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TECHNICAL NOTE

Introduction

At the heart of automotive design is the requirement to pass Electro-Magnetic Compatibility (EMC) limits, by minimising conducted and radiated emissions and susceptibility. The use of Switched Mode Power Supplies (SMPS) is now common-place, yet a prime source of electro-magnetic emissions. Minimising these emissions is a key goal of SMPS design. Use of spread spectrum techniques is an increasingly common means of achieving this goal, and more complex techniques, such as pseudo-random spread spectrum modulation, can yield the greatest emissions improvements. While some SMPS Integrated Circuits (IC) have an integrated spread spectrum function, many don't. Implementation of spread spectrum techniques, can be achieved using Field Programmable Gate Arrays (FPGA), with a minimal burden on the FPGA's resources.

Many automotive audio and visual systems utilise an FPGA as a key part of the system. At the outset of deciding upon the overall system strategy the power supply design is often not of primary concern. However with some advance consideration of the power supply design and FPGA system resources, the FPGA can be used to help minimise power supply electro-magnetic emissions, thereby reducing counter measure costs, and time spent attempting to pass EMC limits. This approach requires a single FPGA I/O pin and a compatible SMPS IC with a synchronisation (SYNC) pin.

Switched Mode Power Supply

A "Buck" or "step-down" SMPS converts a higher voltage to a lower voltage, the ratio of the voltage at the input to that of the output termed the duty cycle, D. The aim is to regulate the output voltage at a fixed value; as the input voltage varies the duty cycle varies in proportion. The dc transfer condition (1) holds so long as the current through the inductor is continuous (continuous conduction mode).

$$V_{OUT} = V_{IN} \times D \qquad \textit{(eq. 1)}$$

Referring to Figure 1 the main switch, Q_1, when closed, provides a current path from the dc voltage source to charge the inductor, L. The inductor current increases linearly when a fixed dc voltage source is applied. When the output voltage reaches its target level then the main switch opens. The current through the inductor can't change instantaneously so the voltage across the inductor reverses. The diode, D_1, reversed biased, self-commutates and the inductor current flows through to ground. The capacitor, C_O, filters the inductor voltage so as to limit the ripple voltage. The ripple voltage is the peak-to-peak variation of the output voltage and is seen across the load, R_L.

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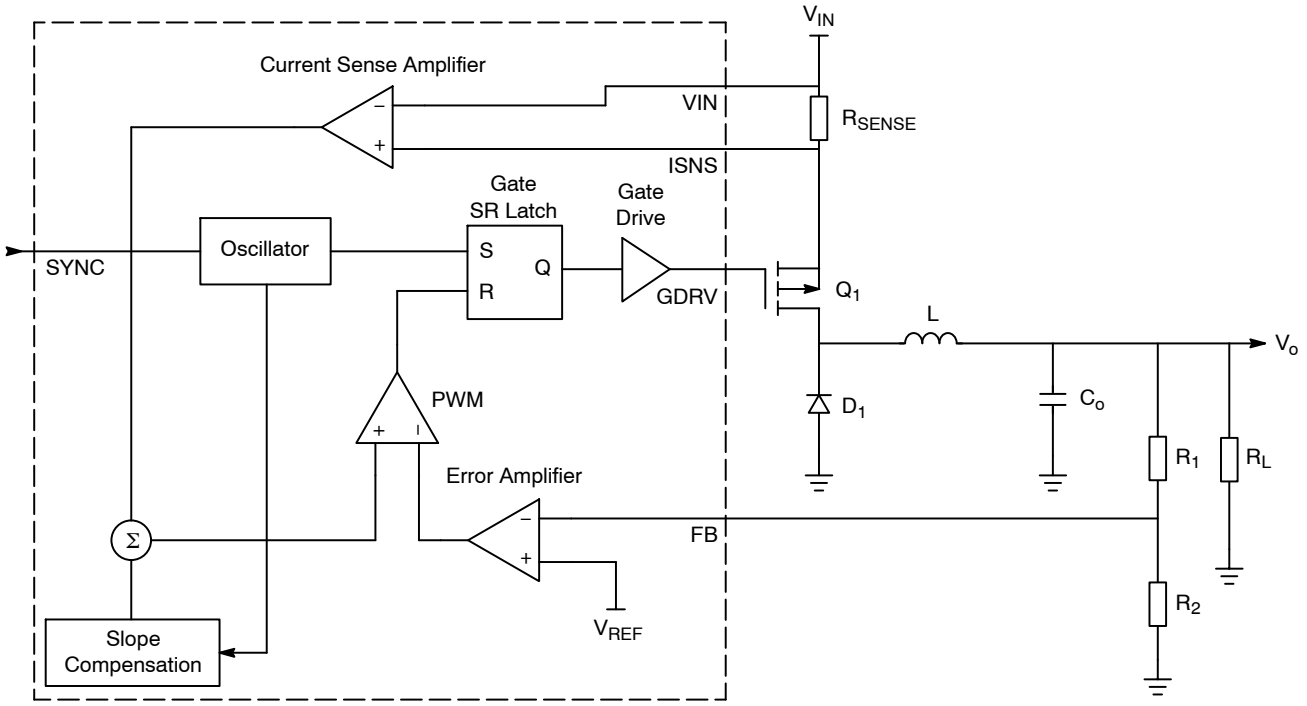


Figure 1. Current Mode Control "Buck" Switched Mode Power Supply

The SMPS IC SYNC pin allows an external signal to control the internal oscillator typically by bypassing the internal oscillator, with an internally level-shifted signal, which has the same frequency as the applied signal. The IC manufacturer places limits on the signal waveform in terms of its shape, frequency, duty and voltage amplitude. Use of the SYNC pin ensures that the next period will only change at the end of the last period, ensuring accurate duty cycle control and limiting output voltage ripple.

Spread Spectrum

Frequency Modulation (FM) can be described as the process of varying the frequency of a carrier signal in proportion to a modulating signal.

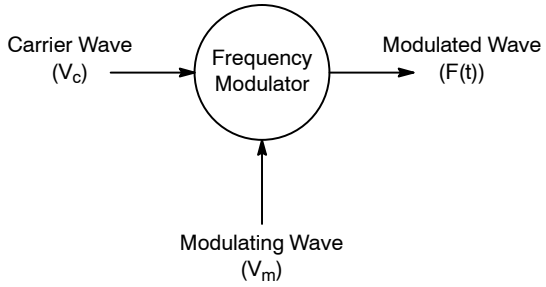


Figure 2. The Frequency Modulation Plant

A modulator creates an output signal whose instantaneous frequency is directly proportional to the constant frequency of the carrier wave and a time-varying component that is proportional to the amplitude of the modulating wave. An expression for a sinusoidal waveform is shown in (2).

$$F(t) = A \sin(\omega.t + \phi) \qquad \textit{(eq. 2)}$$

where,

A = Amplitude

ω = Angular frequency

t = Time

ϕ = Phase angle

Spectral Spreading

Power Spectral Density (PSD) is a measure of signal power as a function of frequency. What can be observed, by comparing the PSD of the un−modulated sinusoidal waveform, to that of the frequency modulated sinusoidal waveform (Figure 3), is that frequency modulation yields a reduction in peak amplitude of the fundamental frequency and that the narrow band energy of the carrier signal is converted into the broadband energy of the frequency modulated signal. The carrier signal contains just the fundamental frequency (unique to a sinusoidal waveform), whereas the frequency modulated waveform contains a multitude of harmonic side bands. This result demonstrates the fundamental benefit of frequency modulation. The peak amplitudes of the emissions are suppressed and spread across broader spectra. This is termed spread spectrum.

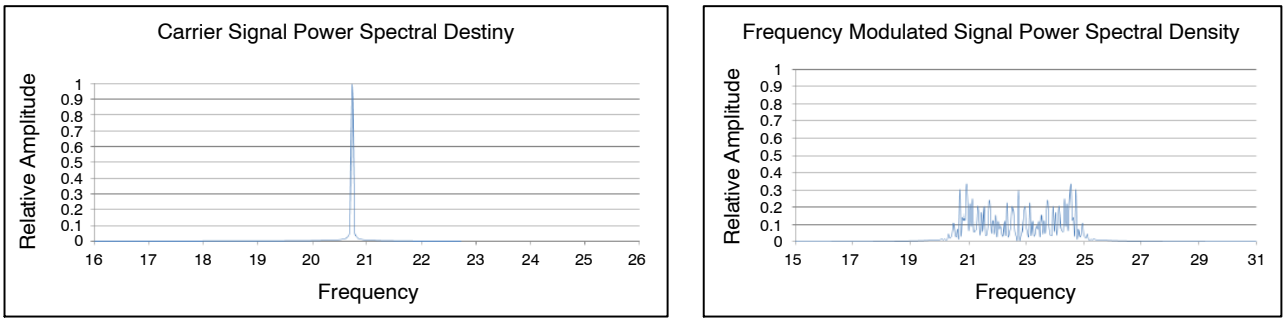


Figure 3. The Affect of Spectral Spreading on Power Spectral Density

The modulation index, β, is a ratio metric measure that can be used to determine the peak deviation of the carrier frequency from the modulating wave:

$$\beta = \frac{\Delta_{f_c}}{f_m} \qquad \textit{(eq. 3)}$$

where,

Δf_C = Peak frequency deviation

f_m = Modulating frequency

Utilising the Bessel function Figure 4 shows the relationship between the carrier signal (J0) and the modulated signal (>J0), showing the harmonic side bands of the latter, up to the 11th order (the first harmonic is J1). As the modulation index is increased the fundamental amplitude decreases.

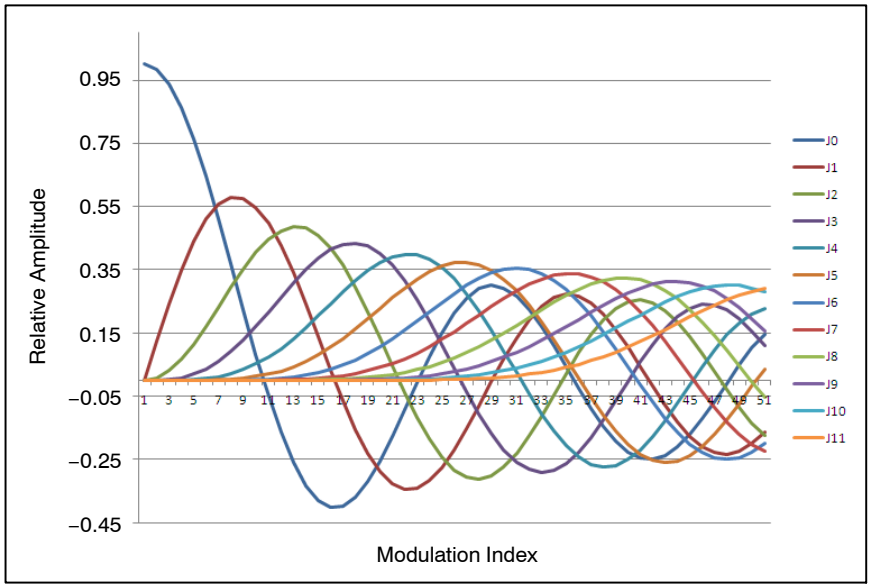


Figure 4. Plots of the Bessel Function at Different Modulation Indices

The effect of increasing the modulation index can be more readily observed, for specific values of modulation index, by reproducing the results of Figure 5 in the form of symmetrical bar graphs, centred on the fundamental frequency. Figure 5 shows the relative amplitude (indexed to 1.0 for modulation index = 0) along the y-axis and the fundamental at the centre of the x-axis surrounded by the sidebands created by the modulation. A modulation index equal to zero implies no modulation.

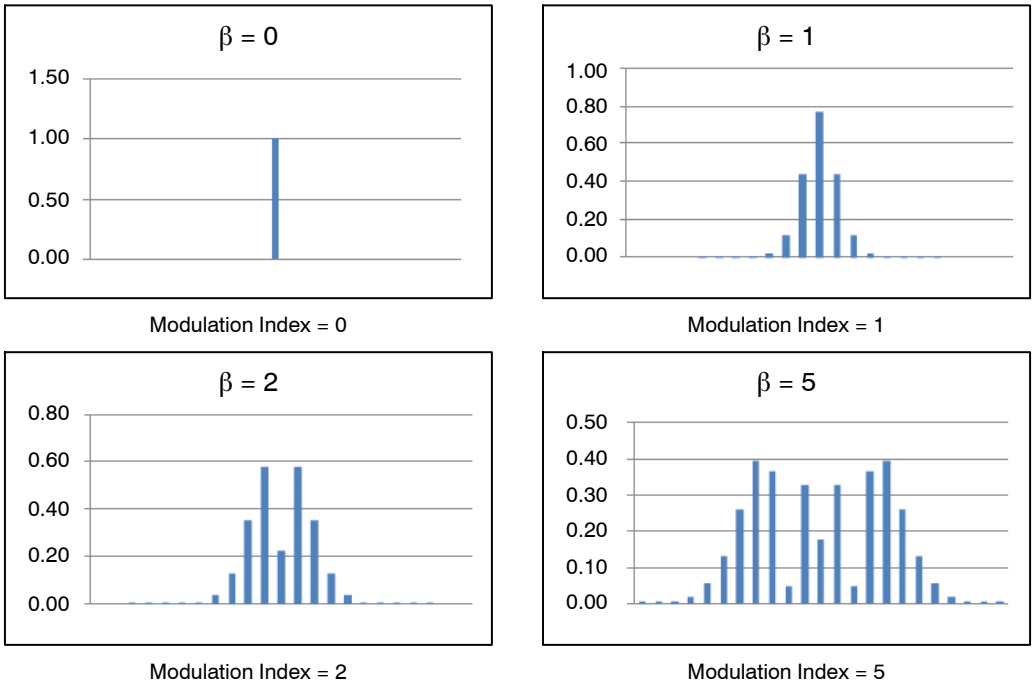


Figure 5. The Affect of Adjusting the Modulation Index on Spectral Spreading

When the modulation index is zero there are no sidebands. As the modulation index is increased the amplitude of the fundamental decreases and the number of harmonic sidebands increases, increasing the spreading effect. However the amount of energy in the spectra remains the same.

Fourier analysis reveals infinite sidebands, however as the order of the harmonics ascends, their amplitudes, as a whole, reduce towards the limit of zero, rendering higher order harmonics, beyond a certain level, negligible for the purposes of analysis.

Random Modulation

There are different methods of SMPS switch control of which Pulse Width Modulation (PWM) is the most common. A PWM Buck SMPS maintains its output voltage, at a regulated steady state level, by adjusting the on−time of the switch according to the input voltage level, and the load current placed upon the output. By adjusting the duty cycle ratio the output voltage can be regulated.

Simplifying the SMPS PWM waveform as a rectangular wave (Figure 6) the relevant waveform parameters are: Period, T_K; Switch on-time, a_K; Switch on-time delay, ε_K

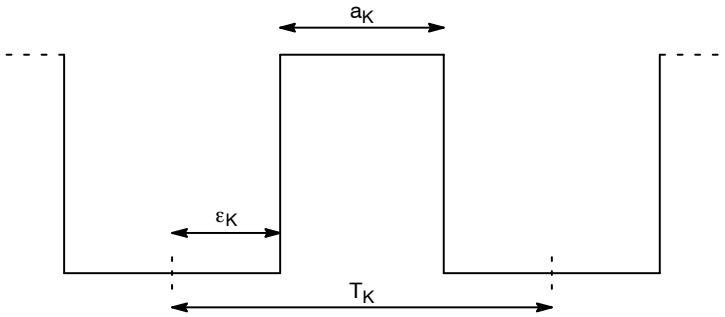


Figure 6. Pulse Width Modulation

Standard PWM will maintain a fixed frequency, with no switch on-time delay but the switch on-time will be adjusted accordingly. So PWM can be shown to be a waveform where T_K is fixed, a_K is variable and ε_K is fixed at zero.

Random modulation of a parameter will be limited by boundary conditions, resulting in the term pseudo-random modulation. Pseudo-random modulation is statistically random modulation of a parameter created by a deterministic process.

Analysis of the PWM waveform reveals the possible modulation schemes. The parameters of the modulation schemes can be tabulated:

Table 1. MODULATION SCHEMES AND THEIR PARAMETERS

Modulation Schemes	T_K	a_K	ε_K	$d_K = a_K / T_K$
Pulse Width Modulation	Fixed	Fixed	Zero	Fixed
Pseudo Random Pulse Position Modulation	Fixed	Fixed	Random	Fixed
Pseudo Random Pulse Width Modulation	Fixed	Random	Zero	Random
Pseudo Random Frequency Modulation Fixed Duty	Random	Random	Zero	Fixed
Pseudo Random Frequency Modulation Variable Duty	Random	Fixed	Zero	Random

Pseudo Random Frequency Modulation Fixed Duty (PRFMFD) has been found to yield optimal results with its PSD results exhibiting a continuous noise spectrum. It also exhibits a variable period and switch on-time and therefore maintains a fixed duty cycle per cycle. Those schemes that don't exhibit a fixed duty per cycle suffer from increased output voltage ripple, which manifests itself as poor output voltage regulation and as low frequency noise. Furthermore it presents an issue to loop stability – the lower the ripple the simpler the feedback loop design.

Circuit Implementation

Implementation requires two key design blocks: a randomisation block and a modulation block. A decoder block is required to interface the two.

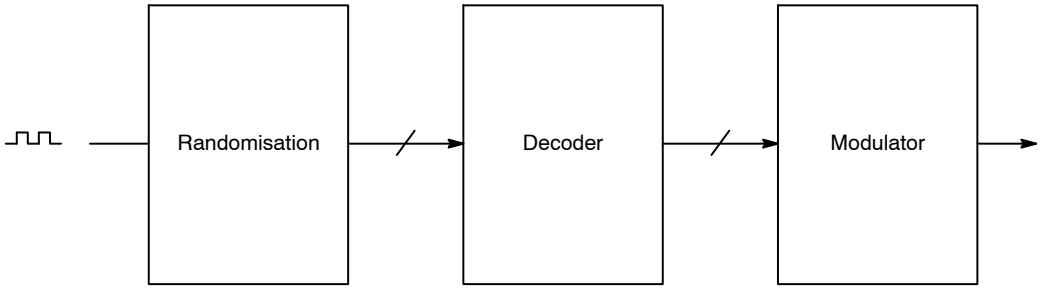


Figure 7. Top Level Entity Block Diagram

Randomisation

Various randomisation schemes could be considered, however the Linear Feedback Shift Register (LFSR) is used in this case as the most appropriate for digital implementation.

The LFSR is a synchronous circuit making use of D-type Flip-Flops, connected in series, as a shift register. The shift register is of "m" bits in length, clocked by a periodic clock which will produce a pseudo-random bit sequence (PRBS). Feedback is provided by XOR'ing the output at one or more "tap" points, the m^{th} and n^{th} bits respectively, to the input of the register. The register will cycle through a set of deterministic states, repeating the sequence every "K" cycles. The maximum number of cycles is termed maximal-length:

$$K = 2^m - 1 \qquad \textit{(eq. 4)}$$

The "−1" term is introduced as an all zero register state would result in a zero being fed back to the input, which ultimately results in register lock−up, due to n a perpetual all zero state. The aim then is to determine, for a register of a given length, the maximal state; that is the tap point for the XOR feedback that ensures that the all zero state doesn't occur. The tap sequence to achieve maximal length is a polynomial mod2:

$$1 + x^n + x^m \qquad \textit{(eq. 5)}$$

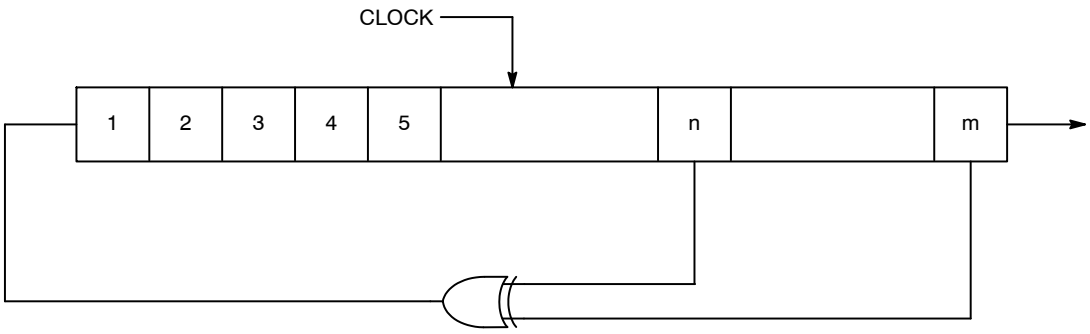


Figure 8. Linear Feedback Shift Register

The LFSR therefore does not produce a random sequence but a pseudo random sequence, as it is a sequence that will repeat itself at the end of the cycle. However, the sequence length can be made to be such a length that its repeat rate or frequency is low and can therefore, for most practical purposes, be considered statistically random.

The length of the LFSR, m, is a key parameter enabling control of the modulating frequency and other key control parameters. The modulating frequency, or the register frequency, has to be set so as to avoid audible frequencies. The human audible range is between approximately 20 Hz and 20 kHz.

Different register lengths require different tap points; the m^{th} and the n^{th} terms XOR'd together. For most values of "m" a single tap point, "n", is required, however for some values of "m" multiple tap points are required. While additional XOR operators can be included in the design, the circuit can be simplified somewhat by avoiding values of "m" that require more than a single tap point.

The LFSR cycle sequence is deterministic. The registers as a result should be started in a known state for validation of correct operation. For this reason a reset is used so that the registers are "seeded" at reset both to ensure a known state is initialised and to ensure that register lock−up does not occur.

Decoder

The decoder interfaces the LFSR word to the Modulator word, interpreting the LFSR outcome to a specific period. It can be designed as an asynchronous block, with the intent that the decoding process should occur in a time period of less than the LFSR clock period, so as not compromise statistical randomness.

The implemented design samples the first 4 bits of the LFSR. These are then decoded to a maximum of 16 possible frequency outcomes.

Modulator

An entirely digital interface can be developed to produce a rectangular waveform. In practice this limits the interface to driving the SMPS SYNC pin only, however this approach lends itself to FPGA implementation.

The LFSR provides a parallel output signal to the decoder which decodes the LFSR number to a number that corresponds to a period that the modulator can interpret and reproduce at the output.

The Modulator is a synchronous circuit receiving data from the Decoder and interpreting this as a fixed period, driving its output signal appropriately. The output transmits a rectangular wave with a fixed 50% duty.

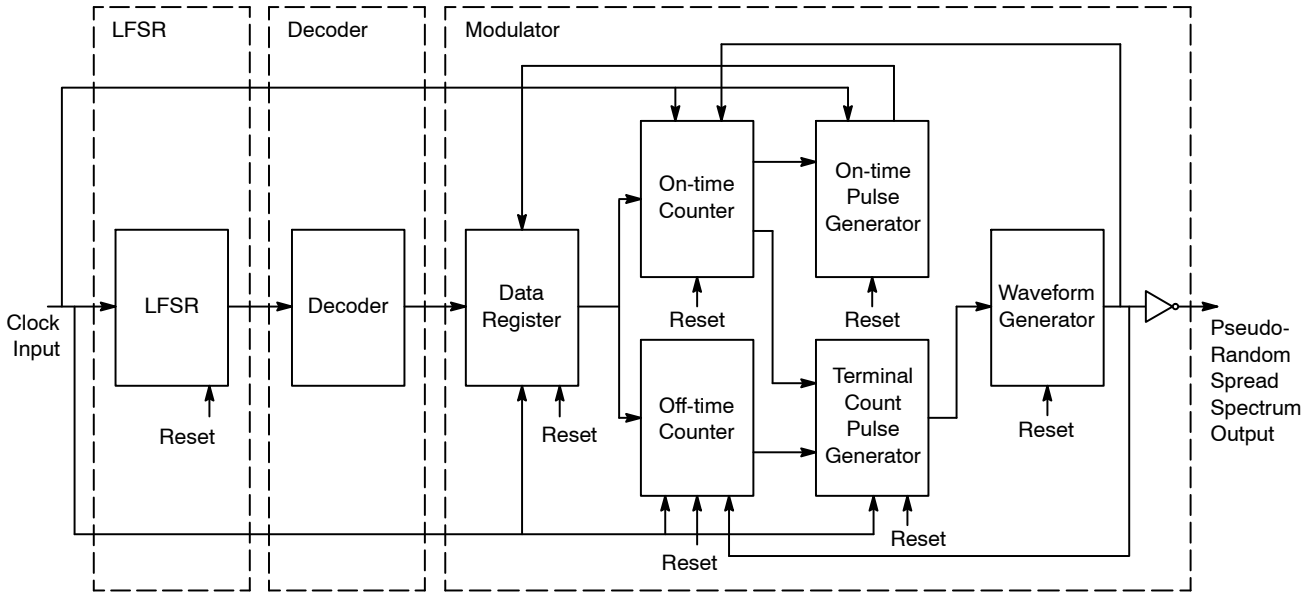


Figure 9. Pseudo Random Spread Spectrum Clock Generator Block Diagram

A key consideration is to create a design that controls an SMPS IC suitable for automotive cockpit applications. However implicit within this is the need to minimise any EMC impact that the design may have on other systems within the automotive cockpit and specifically with the highly susceptible radio receiver. As a result the frequency of operation of the design, and consequently the switching frequency of the SMPS IC it is controlling, is an important consideration. While most consumer listening of analogue audio frequencies is of stations broadcasting in the FM band, FM's higher signal to noise ratio means that FM interference is of a lesser concern compared to that of AM interference. Trying to avoid a fundamental frequency, or one of its harmonics, that conflicts with a tuned radio band is an important aim, so as to minimise interference with audio reception of the radio receiver. While it is difficult to avoid harmonics in the broadcast bands a nominal frequency can be selected that minimises conflicts. The higher the switching frequency the lower the probability of harmonic conflict within a broadcast band.

Results

The circuit was implemented using an Altera Cyclone 2 2C20 FPGA. 63 logic elements were used to implement the design, representing just 0.3% of available resources. A single pin provides the spread spectrum output. For test purposes a hard wired toggle switch is used to switch enable/disable the output.

The spread spectrum output of the FPGA was applied to two different ON Semiconductor automotive "buck" SMPS ICs: NCV8851F, a 0.5 MHz NMOS synchronous controller and NCV890201, a 2 MHz NMOS non-synchronous converter. Two different nominal frequency settings and bandwidths were used, depending upon the SYNC frequency range of the SMPS IC: 32 frequencies between 219 kHz to 481 kHz or 4 different frequencies between 1.92 MHz to 2.5 MHz.

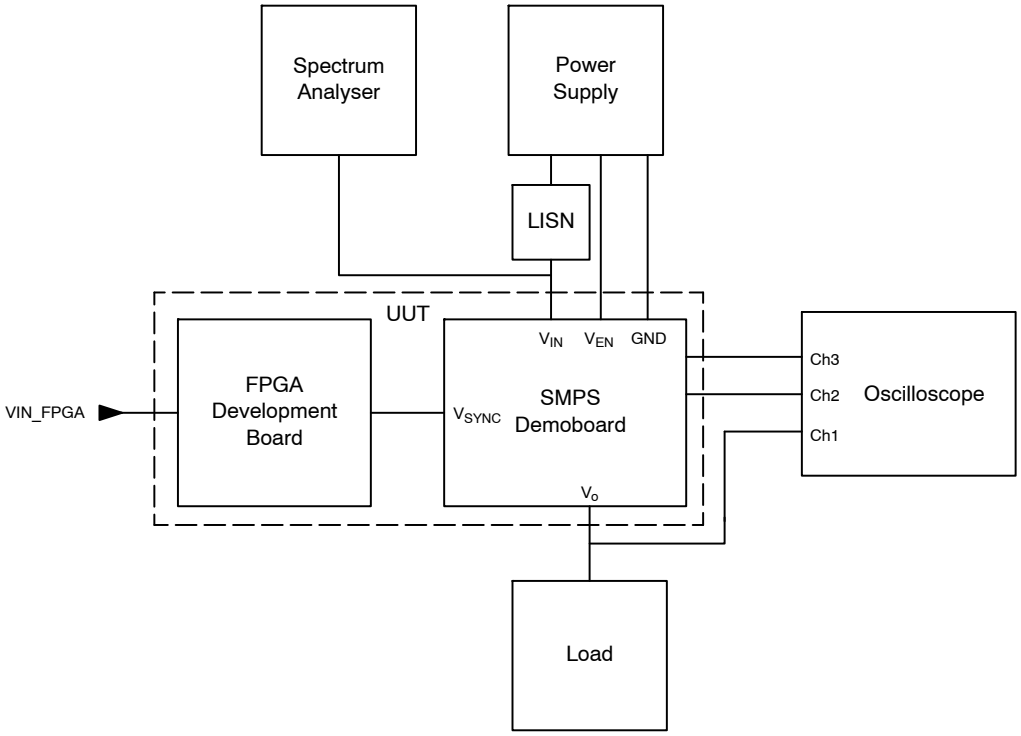


Figure 10. Evaluation Set−up

Measuring Conducted Emissions (CE) in the Class B band, of 0.15 MHz to 30 MHz, with a peak detector the following results were achieved:

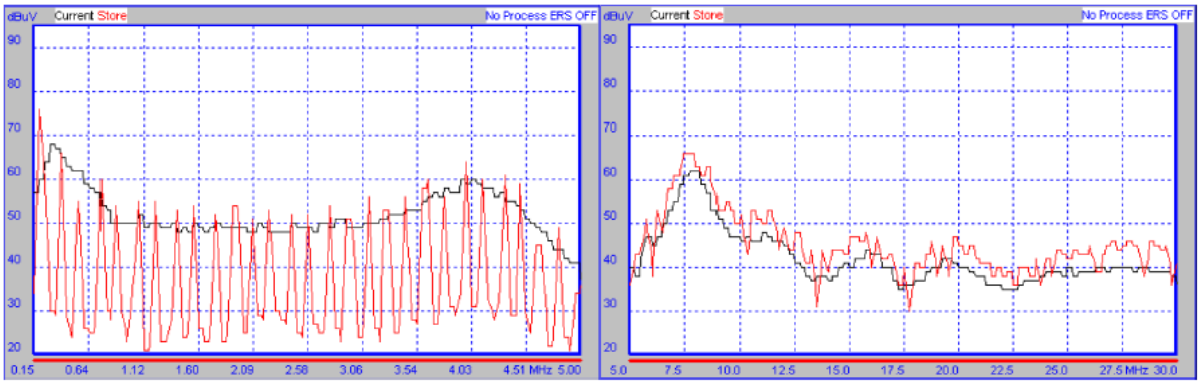


Figure 11. NCV8851F (F_{SW}=170 KHz) CE Results 0.15 MHz to 30 MHz

(Red Trace – Fixed Frequency Operation; Black trace Pseudo Random Spread Spectrum Operation)

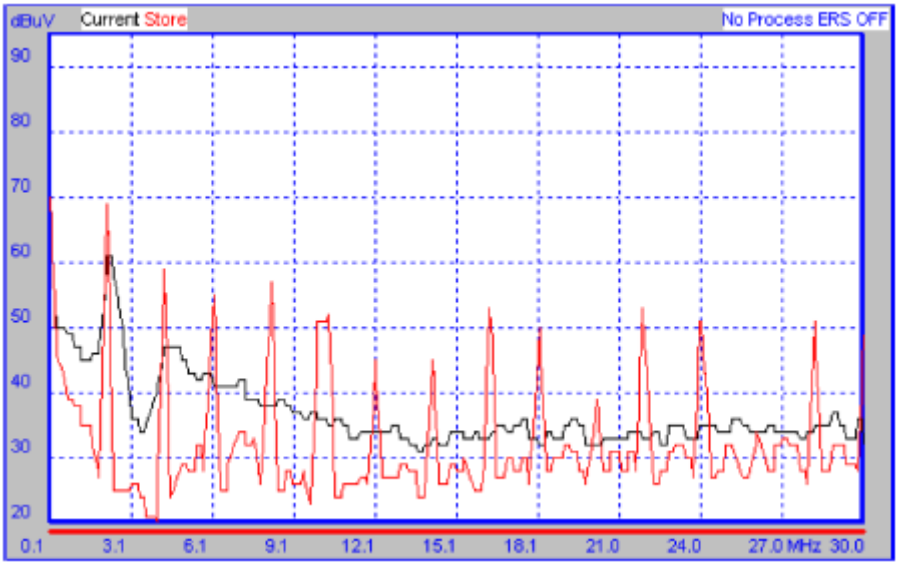
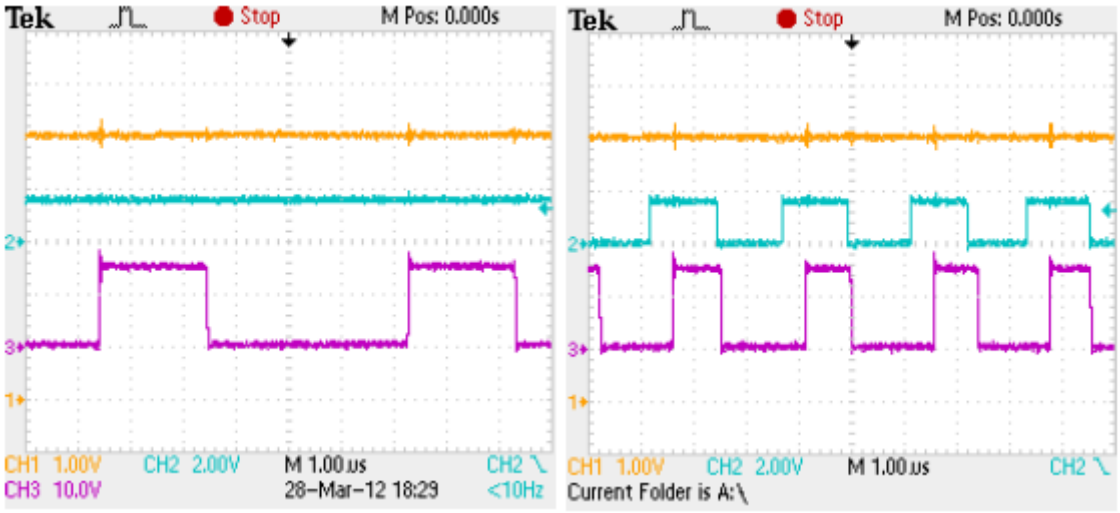


Figure 12. NCV890201 (F_{SW}=2MHz) CE Results 0.15 MHz to 30 MHz

(Red Trace – Fixed Frequency Operation; Black trace Pseudo Random Spread Spectrum Operation)

While performance varies across the spectrum, the results can be summarised. Pseudo random modulation of the NCV8851F yielded a 10 dB/uV improvement of the 170 kHz fundamental and approximately 5 dB/uV across the spectrum. Pseudo random modulation of the NCV890201 yielded an 8 dB/uV improvement of the 2 MHz fundamental and approximately 10 dB/uV to 18 dB/uV across the spectrum.

Low levels of output voltage ripple were recorded (Figure 13). A correlation between the length of the LFSR m-parameter and output voltage ripple was also observed. However, it was noted that the difference between the lower and upper limits of peak-to-peak output voltage measured in different experiments was only 240 mV, and the worst case ripple was 800 mV. This compared to a worst case peak-to-peak output voltage for fixed frequency operation of 720 mV. The increase in ripple, due to pseudo random spread spectrum operation, could not be considered significant as a result.



(a) (b)

Figure 13. NCV8851F Output Voltage Ripple (CH1=VOUT, CH2=SYNC, CH3=VSW): (a) 170 KHz Fixed Frequency Operation, (b) Pseudo Random Spread Spectrum Operation

Conclusion

Pseudo random spread spectrum modulation, in automotive cockpit applications, can be implemented with spare FPGA system resource and SMPS ICs such as the ON Semiconductor NCV8851F and NCV890201. The solution utilises minimal FPGA system resources, and I/O, and can substantially reduce spectral emissions in automotive cockpit applications, while not sacrificing output voltage ripple.

References

[1] K. McDonald, *A Pseudo Random Spread Spectrum Clock Generator to Reduce Electro-Magnetic Emissions in Automotive Cockpit Switched Mode Power Supply Applications*. University of Bolton, 2012.

[2] http://www.onsemi.com/pub_link/Collateral/NCV8851F−D.PDF

[3] http://www.onsemi.com/pub_link/Collateral/NCV890131−D.PDF

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