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# Triple-Hybrid Switching Strategy for Conducted-Noise Level Reduction in DC-DC Converters

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**Abstract:** A novel switching strategy for conducted-noise level reduction has been proposed in this paper. The proposed strategy uses three randomized parameters for generating the switching signals. These parameters are carrier frequency, duty-ratio, and the pulse position. This triple-hybrid switching strategy has been designed and implemented using field-programmable gate array (FPGA) technology. Moreover, the effect of using the proposed controller on common-mode and differential-mode noise, total conducted-noise, and radiated-noise characteristics of the dc-dc converter has been experimentally investigated. Furthermore, sweeping of the three randomization parameters has been carried-out for identifying the values which achieve the best conducted-noise level reduction. Numerous cases have been studied. All the studied cases have been designed, implemented and experimentally investigated. Then, the conducted-noise spectra have been compared. The experimental results show that using the proposed technique, with the identified randomization parameter values, significantly improves the conducted-noise spectrum and effectively reduces the noise peaks in both high- and low-frequency ranges. Moreover, the radiated-noise spectrum has been improved.

**Keywords:** Switched-mode power supply, EMC/EMI, Spread-spectrum, Noise reduction, Modulation strategy

## 1. Introduction

The omnipresent switch-mode power supplies (SMPSs) create a highly electromagnetically polluted environment in the office or factory space and on the utility grid. The source of pollution can be confidently traced to the on/off action of power converter switches and the resulting AC currents flowing in the switch and other power-processing components (rectifiers and inductors, in particular), [1].

In order to prevent “field problems” associated with electromagnetic interference (EMI), various stringent regulations on radiated and conducted electromagnetic emissions have been imposed. All electronic and electrical equipment ranging from hand drills to sophisticated computers were required to meet the emission limits of these standards, [2]. As a result, EMI has become a very important design aspect of the high-density power supplies.

A device is considered to be electromagnetically compatible only if it functions satisfactorily within its electromagnetic environment. This device, system, or equipment is assumed not only to be unaffected by external fields but also not to cause interference in sense of intolerable electromagnetic disturbances to a nearby system or anything in that environment, [3].

In order to fulfill the EMI regulations, additional EMI filters, normally both common mode (CM) and differential mode (DM), are needed at the input of the SMPSs to filter out the switching noise and eliminate electromagnetic interference to other equipment, [4]. Planar integrated passive EMI filters have been employed to achieve the necessary degree of ripple attenuation [5]. However, EMI filters have its limitations: size, weight, design complexity, efficiency, sometimes cost, etc. It lacks flexibility and practicality. It is often desirable to eradicate the source of the EMI [6].

Instead of that, modern modulation based EMI reduction techniques have been under an intensive research to overcome the problems faced in filter-solutions. With the help of spread spectrum modulation techniques, emissions of the switching power converter can be reduced. A review of such modern techniques has been discussed in the following section. The aim of this work is developing an improved spectrum spreading technique and investigating its use to minimize the EMI.

An overview of contributions and limits of FPGAs and several examples of relevant FPGA utilizations are presented in 7). These very promising control

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paradigms consist of predictive control, over sampling strategies, multiplan's control, etc. Although FPGA implementation is now widespread in a range of military, defense, and signal processing applications, it is much flexible than analog control, becoming lower cost, and applicable for power supply applications, $^{8)-9)}$. The implementation of the spread-spectrum technique has been accomplished by using an FPGA-based digital controller.

The paper is organized as follows: A brief review of noise spectrum spreading in switching power converters has been addressed in the following section. Then, the idea of the triple-hybrid spread-spectrum technique has been explained. After that, the design and implementation of the proposed FPGA-based controller which includes pseudorandom streams generator and digital pulse-width modulator have been described. The details of the experimental test circuit, results and discussions have been presented. Finally, conclusions have been addressed.

## 2. Brief Review of Noise Spectrum Spreading in Switching Power Converters

A number of active EMI mitigation techniques for SMPSs have been described $^{10)-19)}$ as promising alternatives to expensive passive EMI suppression tools. By using these techniques, the noise generated by the SMPSs can be spread across a well defined frequency band. As a result, the average spectral power density of the broadband noise can thus be drastically reduced. They can be summarized as follows:

In 10), two types of control circuits have been introduced; circuit I randomly alternated between two duty ratios. However, in circuit II the output of white noise generator is sampled and held with the signal from the saw-tooth wave generator. According to the sampled value, the switching frequency is randomized, keeping the duty ratio constant. The latter was more effective on reducing the level of switching noise spectrum.

The effect of randomizing the switching frequency on noise reduction in DC-DC boost-converter and switching mode rectifier has been experimentally investigated in 11). The authors randomized the switching frequency from 80 to 120 kHz; in this range they concluded that: 1. much higher harmonics are spread by little deviation of switching frequency. 2. Wider deviation of switching frequency gives more effective reduction of the noise-spectrum level. 3. Variance of switching frequency distribution affects the noise reduction.

In 12)-13), the authors analyzed the noise spectrum, generated by random switching technique, in a general approach including a noise-generation model and a switching function with random process. They showed that the region where the noise spectrum is reduced enough can be expressed with the standard deviation of switching interval. For experimental confirmation of the theoretical results, instead of the actual one, they used a series of pulses as switching noise.

The authors in 14) showed experimentally that the random switching using M-sequence depends on both the switching interval deviation and noise frequency, while the length of M-sequence has a little effect on noise reduction. However, in 15) the authors theoretically applied the programmed and randomized PWM techniques for the reduction of unwanted spectral components in power converter waveforms. They also suggested that a combination of these two approaches may prove most effective in reducing peak spectral density.

The study in 16), was carried-out by taking the spectrum of computer generated switching signals modulated with various sequences. The modulation sequence for the frequency-hopping spread-spectrum is stored in an EPROM and then the conducted EMI was measured. Attention has been drawn to both the effect of practical measurements and implications of frequency deviation on the physical characteristics of the switching mode power converter.

An approach to simulate the EMI emissions comparable to electromagnetic compatibility (EMC) standards was presented in 17). They concluded that the use of zero-intermediate-frequency approach or a homodyne receiver model turned out to be extremely effective resulting in accurate predictions without extra computing overhead.

In 18), the authors presented a low power step-down DC-DC converter prototype with hybrid delayline-based digital pulse-width-modulator. The switching frequency of the buck converter is varied from 1.74 MHz to 2.84 MHz in 128 steps using a pseudo-random 512 cycle pattern. Unlike analog controllers, the compensator pole and zero locations are shifted due to the variable frequency operation. They recommended that the resulting effect on the phase margin must be carefully analyzed to avoid stability problems. In addition, good notations have been addressed in 19) concerning the design considerations and compensator design guidelines.

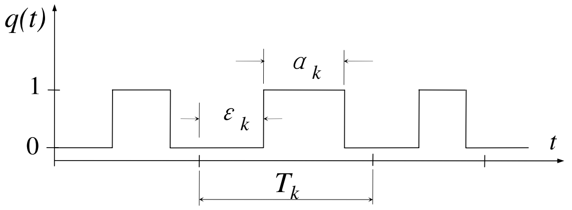


**Fig. 1** Randomization parameters in the switching signal.

# 3. Triple-Hybrid Switching Strategy

## 3.1 The Basic Idea

According to **Fig. 1**, $T_k$ is the duration of the kth cycle, $a_k$ is the duration of the on-state within this cycle, and $e_k$ is the delay from the starting of the switching cycle to the turn-on within the cycle. Note that the duty ratio is $d_k = a_k/T_k$ and the switching frequency $F_k = 1/T_k$. The switching function $q(t)$ consists of a series of such switching cycles. In order to spread the frequency spectrum of the switching noise, $F_k$, $d_k$, and/or $e_k$ can be randomized.

Due to hardware limitations and the complexity of the control circuit, only one or two parameters could be randomized in the addressed techniques for power electronics applications, $^{10)-25)}$. However, with the flexibility and programmability of the FPGA technology, all the three parameters have been randomized for generating the switching signal. This new hybrid switching strategy has been designed, implemented and addressed in this paper.

## 3.2 FPGA-Based Implementation

### 3.2.1 Pseudorandom Streams Generator

In order to spread the noise spectrum, $F_k$, $d_k$, and $e_k$ are randomized. Hence three random number generators are required to realize the proposed strategy.

A pseudorandom streams generator has been constructed for this purpose. As shown in **Fig. 2**, the proposed construction uses several maximum length linear feedback shift registers (m-LFSRs) in parallel. For different m-LFSRs output bits, different initial contents of m-LFSRs (seeds) have been used. The taps are XOR'd sequentially with the output and then fed back into the leftmost bit.

The designed pseudorandom streams generator delivers three different random streams; (16-bit, 12-bit, and 10-bit streams). The streams are composed of the output bits of the m-LFSRs with different arrangements. The m-LFSRs are clocked regularly; i.e., the movement of the data in all the m-LFSRs is controlled by the same clock.

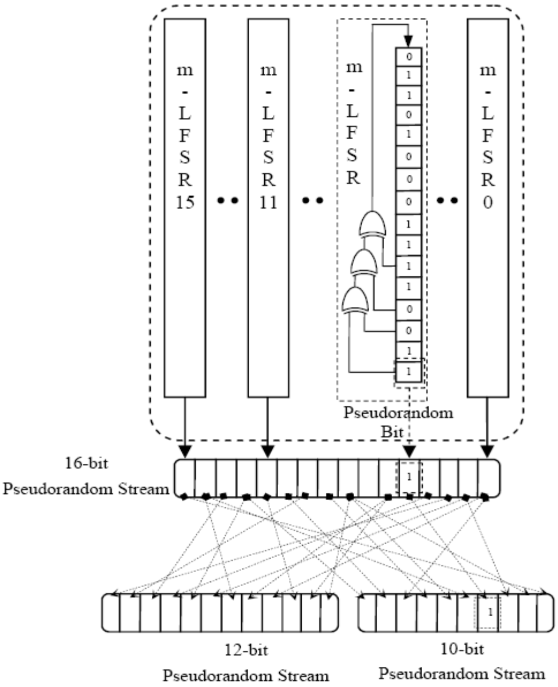


**Fig. 2** The proposed pseudorandom streams generator.

Only at the beginning of every switching cycle, the random output bits are converted into an integer numbers and used in the digital pulse-width modulator (DPWM). However, the other generated random output bits are discarded.

### 3.2.2 Digital Pulse-Width Modulator

At the beginning of every switching cycle, the DPWM achieves the following assignments:

1. Converting the pseudorandom streams into integer numbers.
2. Calculating randomization parameters for the started switching cycle and the needed number of steps to fulfill switching frequency, duty-ratio, and pulse position ($T_N$, $W_N$, and $E_N$ respectively as shown in **Fig. 3**).
3. Generating the digital pulse-width modulated waveforms ($V_{gs1,2}$) with the commanded randomization parameters. As shown in **Fig. 3**, the designed DPWM uses a clocked-counter that increments and resets at the end of every switching cycle of the PWM (see reset1 signal). When the counter value lies between the reference values $E_N$, $E_N + W_N$, the controller keeps the PWM output state high, else low. In this way, the digital pulse-width modulated waveforms ($V_{gs1,2}$) are generated with the commanded randomization parameters.

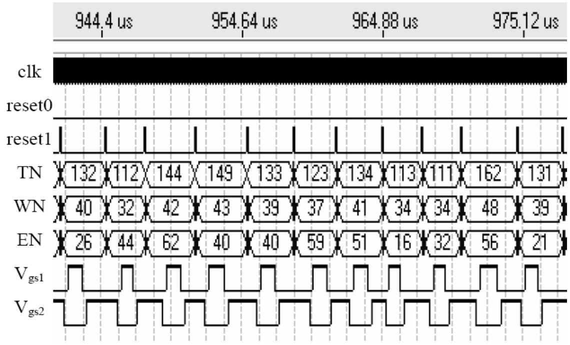
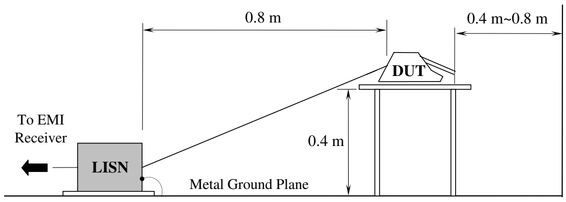
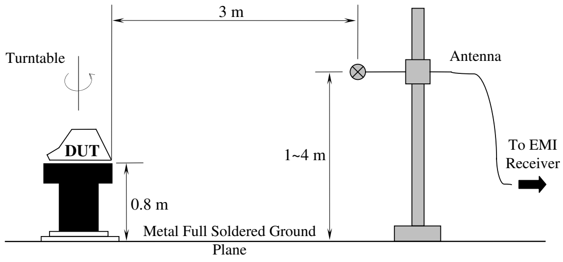


**Fig. 3** VHDL simulation of the proposed FPGA-based controller for the proposed technique.



(a) Conducted-noise test setup



(b) Radiated-noise test setup

**Fig. 4** Noise measurement system.

## 4. Experimental Investigation and Results

As described in **Fig. 4a** and **Fig. 5**, the line impedance stabilization network (LISN) is used to standardize the input impedance seen from the converter input and sense the conducted-noise. A high-frequency current probe (C-Probe) is used to sense both the common-mode and differential-mode noise currents which are measured by an EMI receiver, 2). The radiated-noise has been measured in a semi-anechoic chamber (SAC), as shown in **Fig. 4b**. The SAC is a shielded room having radio-frequency absorber material on the sides and at the top of the room to prevent reflections and simulate free space, 2). The randomly switched converter has been designed and implemented using an Altera FPGA. A synchronous buck converter topology has been selected in order to improve efficiency and reduce heat loss. **Fig. 5** illustrates the converter circuit configuration.

Noise measurements have been taken at: $V_{in} = 12$ V, $V_o = 3.3$ V, $I_o = 5$ A, center switching frequency ($f_{csw} = 300$ kHz), center duty-ratio ($d_{cdr} = 0.275$), and the resolution band width (RBW) of the measuring instrument in all cases was 9 kHz.

Sweeping of the three randomization parameters has been carried-out for reaching the values which achieve the best conducted-noise spectrum spreading, as follows:

1. The switching frequency randomization ratio ($\Delta F_k$), (0, 10.92, 21.85, and 32.77 % of $f_{csw}$ have been used).
2. The duty-ratio randomization ratio ($\Delta d_k$), (0, 4.25, 8.52, and 17.05 % of $d_{cdr}$ have been used).
3. The pulse position randomization ratio ($\Delta e_k$), (0, 0.25 ˜ 0.35, 0.2 ˜ 0.4, and 0.1 ˜ 0.51 of $T_k$ have been used).

All the 64 studied cases have been designed, implemented and experimentally investigated. Then, the conducted-noise spectrums have been compared.

A comparison has been carried-out between all the studied cases for identifying the case which achieves the best conducted-noise spectrum spreading. Case 40, with the randomized parameters ($\Delta F_k = 21.85\%$ of $f_{csw}$, $\Delta d_k = 4.25\%$ of $d_{cdr}$, and $\Delta e_k = 0.1$ ˜ 0.51 of $T_k$), attains the best performance. It provides the highest conducted-noise peak reduction in the high- and the low- frequency ranges. As shown in **Fig. 6a** and **Fig. 7**, the conducted-noise spectrum and its components have been significantly improved and the noise level has been effectively reduced. Moreover, the radiated-noise spectrum has been slightly improved by three decibels, as revealed in **Fig. 6b**.

## 5. Conclusions

A novel switching strategy has been designed and implemented for conducted-noise level reduction in DC-DC converters. Furthermore, the effect of using the proposed controller on both the conducted-noise and radiated-noise characteristics of the converter has been experimentally investigated. Finally, experimental results show that using the proposed switching strategy, the conducted-noise spectrum has been significantly improved and the noise level has been effectively reduced at both high- and

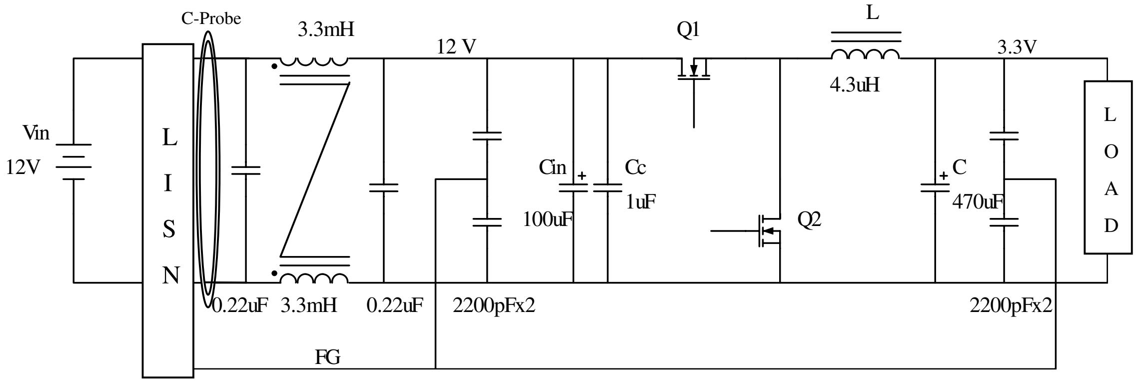
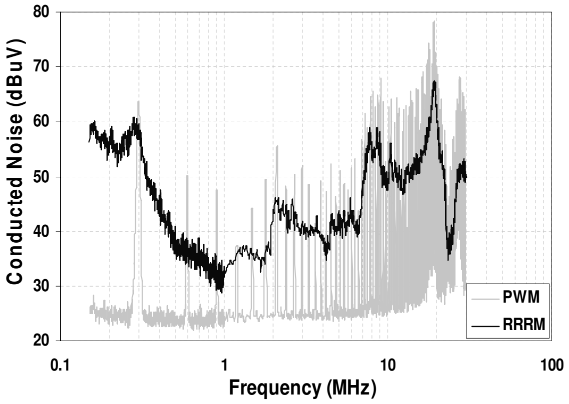
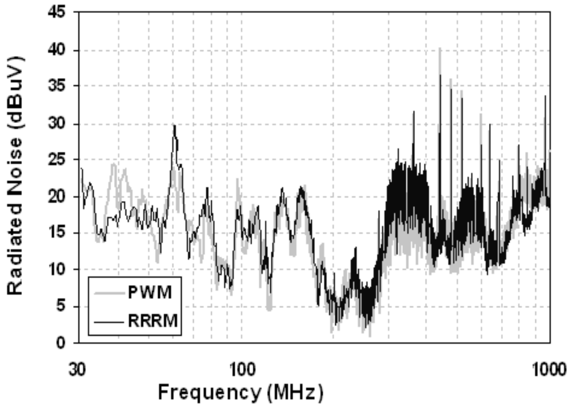


**Fig. 5** Experimental converter circuit configuration.

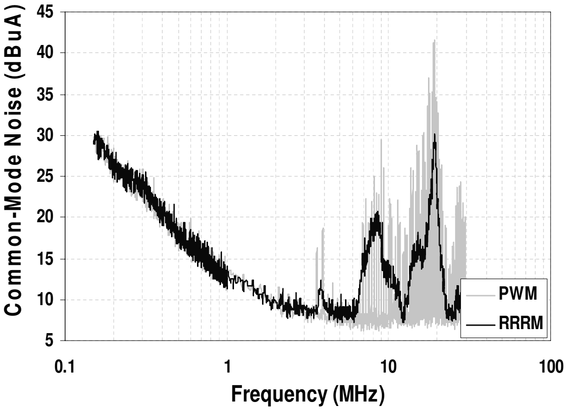


(a) The measured conducted-noise spectrum

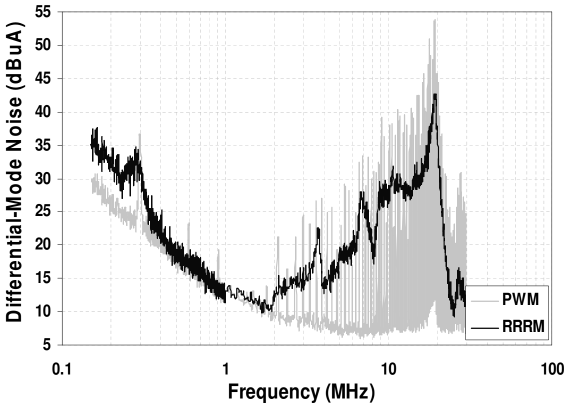


(b) The measured radiated-noise spectrum with horizontal polarization

**Fig. 6** Comparison between the noise spectrum with the basic pulse-width modulation (PWM) and that with randomized parameters (RRRM, $\Delta F_k$ = 21.85% of $f_{csw}$, $\Delta d_k$ = 4.25% of $d_{cdr}$, and $\Delta e_k$ = 0.1 ˜ 0.51 of $T_k$) at RBW of spectrum analyzer = 9 kHz.



(a) Spectrum of common-mode noise current



(b) Spectrum of differential-mode noise current

**Fig. 7** Comparison between spectra of the conducted-noise components with the basic pulse-width modulation (PWM) and that with randomized parameters (RRRM, $\Delta F_k$ = 21.85% of $f_{csw}$, $\Delta d_k$ = 4.25% of $d_{cdr}$, and $\Delta e_k$ =0.1 ˜ 0.51 of $T_k$) at RBW of spectrum analyzer = 9 kHz.

low- frequency ranges. Moreover, the radiated-noise spectrum has been improved.

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