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A Double-Hybrid Spread-Spectrum Technique for EMI Mitigation in DC-DC Switching Regulators

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Abstract

Randomizing the switching frequency (RSF) to reduce the electromagnetic interference (EMI) of switching power converters is a well-known technique that has been previously discussed. The randomized pulse position (RPP) technique, in which the switching frequency is kept fixed while the pulse position (the delay from the starting of the switching cycle to the turn-on instant within the cycle) is randomized, has been previously addressed in the literature for the same purpose. This paper presents a double-hybrid technique (DHB) for EMI reduction in dc-dc switching regulators. The proposed technique employed both the RSF and the RPP techniques. To effectively spread the conducted-noise frequency spectrum and at the same time attain a satisfactory output voltage quality, two parameters (switching frequency and pulse position) were randomized, and a third parameter (the duty ratio) was controlled by a digital compensator. Implementation was achieved using field programmable gate array (FPGA) technology, which is increasingly being adopted in industrial electronic applications. To evaluate the contribution of the proposed DHB technique, investigations were carried out for each basic PWM, RPP, RSF, and DHB technique. Then a comparison was made of the performances achieved. The experimentally investigated features include the effect of each technique on the common-mode, differential-mode, and total conducted-noise characteristics, and their influence on the converter's output ripple voltage.

Key Words: DC-DC power conversion, Electromagnetic compatibility, Electromagnetic interference, Field programmable gate arrays, Spread-Spectrum

I. INTRODUCTION

Telecommunication central offices, industrial automation, energy-efficient consumer appliances, photovoltaic installations, and mobile phones all rely on electronic power converters for operation [1].

The large markets for mobile phone handsets, laptop computers and personal digital assistants (PDAs) are becoming commodity-oriented. They are one of the major forces driving demand for the development of dc-dc converters.

Switching power converters (SPCs) generate considerable electromagnetic interference (EMI) because of the high dv/dt and di/dt during the switching instant of power devices. Several international standards (e.g., CISPR, FCC, and VDE) impose limits on the amount of EMI that a converter can inject into the utility supply [2],[3].

Many methods have been reported in the literature to mitigate the EMI problem. These techniques include common tools such as passive filters and shields [3]. However, such tools put increased pricing pressure on dc-dc converters.

The main source of EMI emissions in power converters comes from the switching of dc voltages following a constant scheme. The waveforms of interest are typically periodic functions of time. The EMI peaks are concentrated mainly on multiples of the switching frequency. However, in the case of spread-spectrum techniques, even though the energy of the harmonics is spread over a frequency belt, the peak of the harmonics drastically decreases [4]-[50]. Fig. 1 shows a frequency spectrum comparison of two switching signals: one is generated using basic PWM, and the other is generated using a spread spectrum modulation technique. It can be seen that the maximum amplitude of the modulated signal's spectrum is significantly lower than that of the original non-modulated signal.

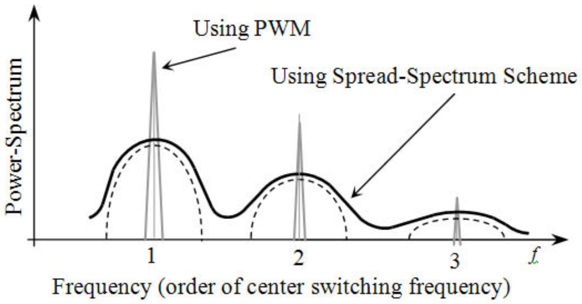

Fig. 1. Frequency spectrum comparison of two switching signals.

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This paper is organized in the following manner. A review of noise spectrum spreading in dc-dc power converters is addressed in section II. Section III presents the idea of the proposed double-hybrid spread-spectrum technique and the digital compensator design. The design and implementation of the proposed FPGA-based controller are addressed in section IV. Section V describes the details of the experimental work. The results and a discussion are provided in section VI. Finally, conclusions are presented in section VII.

II. REVIEW OF NOISE SPECTRUM SPREADING TECHNIQUES IN DC-DC POWER CONVERTERS

A number of active EMI mitigation techniques for SPCs have been described [4]-[50] as promising alternatives to expensive passive EMI suppression tools. By using these techniques, the noise generated by SPCs 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, as shown in Fig. 1. We present here a summary of these techniques.

In [4], two types of control circuits were introduced. Circuit I randomly alternated between two duty ratios. In circuit II, the output of a white noise generator was sampled and held with the signal from a saw-tooth wave generator. According to the sampled value, the switching frequency was randomized, keeping the duty ratio constant. The latter was more effective in reducing the level of the switching noise spectrum. In [5], the authors concluded that: much higher harmonics are spread by small deviations in the switching frequency (F_s), a wider deviation in F_s gives a more effective reduction of the noise-spectrum level, and the variance of the F_s distribution affects noise reduction.

The analysis presented in [6],[7] showed that the region where the noise spectrum is sufficiently reduced can be expressed with the standard deviation of the switching interval. For experimental confirmation of the theoretical results, they used a series of pulses as switching noise instead of actual noise.

The authors in [8] showed experimentally that random switching using the M-sequence depends on both the switching interval deviation and the noise frequency, while the length of the M-sequence has little effect on noise reduction. However, in [9],[10], 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 even more effective in reducing peak spectral density.

The study in [11] was carried-out by calculating the spectrum of computer generated switching signals modulated with various sequences. The modulation sequence for the frequency-hopping spread-spectrum (FHSS) is stored in an EPROM, and the conducted EMI is then measured. Attention has been drawn to both the effects of practical measurements and to the implications of frequency deviation on the physical characteristics of a switching mode power converter. In [12], the authors concluded that fixing the duty ratio can have additional benefits: the implementation would be simpler and cheaper.

An approach to simulate EMI emissions comparable to EMC standards was presented in [13]. They concluded that the use of a zero-intermediate-frequency approach or a homodyne receiver model turned out to be extremely effective, resulting in accurate predictions without extra computational overhead.

In [14], the authors presented a low power step-down DC-DC converter prototype with a hybrid delay line-based digital pulse-width-modulator. The switching frequency of the buck converter was varied using a pseudo-random 512 cycle pattern. Unlike analog controllers, the compensator pole and the zero locations were shifted due to the variable frequency operation. They recommended that the resulting effect on the phase margin be carefully analyzed to avoid stability problems. In addition, good notations have been presented in [15] concerning the design considerations and the compensator design guidelines.

In [16]-[21], the authors devoted their research to issues in the analysis and synthesis of randomized modulation schemes based on finite Markov chains. The main advantage of their suggested schemes is the availability of an explicit control of the time domain performance, in addition to the possibility of shaping the power spectra of the signals of interest. They presented numerical (Monte Carlo) and experimental verifications for their power spectral formulas. They concluded that randomized modulation is very effective in satisfying narrow-band constraints, but has limited effectiveness in meeting wide-band signal power constraints.

In [22],[23], the authors presented an analysis and the experimental results for the random pulse-width modulation (RPWM) and the random pulse-position modulation (RPPM) methods for dc-dc converters. The theoretical relationships between the discrete harmonics, the continuous noise, and the output voltage ripple of the RPWM and RPPM schemes were established and compared with those of a standard deterministic pulse-width modulation (PWM) scheme in a buck converter. The theory developed in their papers showed that randomized schemes, due to the presence of continuous noise, have an inherent noise induced low-frequency voltage ripple problem when compared with the deterministic PWM method. The main reason for this problem is the continuous noise spectrum within the pass-band of the low-pass filter, which causes extra fluctuation in the converter output voltage.

In [24], the authors presented an analysis and the spectral characteristics of a random carrier-frequency (RCF) technique for suppressing conducted EMI in an offline switched-mode power supply. They compared the RCF scheme for a dc-dc converter with the standard PWM scheme and the frequency modulation (FM) scheme. They concluded that the RCF scheme offered a simple solution to reduce the conducted EMI in power converters and that it is better than the FM scheme. In [25]-[27], investigations into the effects of the randomness level on spreading the dominating frequencies that normally exist in constant-frequency PWM schemes were extended. The chaotic carrier-frequency modulation scheme (CCF), as described in [28], introduces less low-frequency harmonics at the output than the RCF scheme.

In [29],[30], the authors outlined a methodology that ensures a fair comparison of the calculated and estimated power spectral density of random pulse-width modulation (PWM) techniques. They derived analytical expressions to aid in understanding the frequency domain characteristics and to overcome the problems originating from the digital signal processing techniques that make the comparison difficult.

In [31], the authors presented a simplified simulation method for the calculation of conducted EMI caused by SPCs. Their method was based on a "*source-propagation-path-derived disturbance*" simulation process and was specially designed to simplify the computation problems due to the complex geometry and the wide range of time constants involved in EMI simulation in real SPCs. In [29], they presented a wavelet-based analysis of the effectiveness of conducted EMI reduction in power converters.

In [33]-[38], the authors investigated the influence of frequency modulation on EMI reduction using three periodic modulation profiles: sinusoidal, triangular, and exponential modulation. They concluded that the maximum reduction of the whole envelop of the EMI spectrum is obtained with a triangular profile and high switching frequencies. They also determined that the overlap of the bands fades this effect and that the choice of the most convenient profile depends on the target. The authors recommended that the use of switching frequency modulation as an EMI suppression technique be considered, especially in converters where the duty cycle remains nearly constant.

In [39],[40], the authors investigated the side effects of using frequency modulation techniques on the converter performance in terms of the output voltage and its ripple. They concluded that the average output voltage is slightly affected when real components are considered in a buck converter, mainly due to the difference between the turn-on and -off times corresponding to the transistor. In addition, the output voltage ripple is affected by the modulation process in such a way that its amplitude varies according to the modulating frequency. This influence cannot be avoided by means of a closed-loop control, and it can only be attenuated by a convenient selection and design of the output filter. As pointed out in [41], this feature may prohibit the use of randomized modulation in dc-dc converters, which require tight voltage regulation.

In [42], the authors presented a modulation scheme to reduce the conducted EMI generated by power converters with a parallel topology. The proposed scheme was based on a combination of interleaving and switching frequency modulation techniques. Their objective was to cancel certain harmonics of EMI and to reduce the amplitude of the remaining harmonics. They showed that a significant EMI reduction was achieved with their proposed scheme when compared to just applying the interleaving and switching frequency modulation schemes separately.

In [43], the authors investigated several sigma-delta modulation switching schemes to reduce the harmonic spikes in the power spectrum of the PWM control signals. The switching frequency was spread by a random dither generator placed at the input or the output parts. In [44], the authors proposed a random switching strategy to reduce the harmonics spectra of single phase switched reluctance motors. This method combined the random turn-on/off angle technique and the random pulse width modulation technique. The experimental results show that the harmonic intensity of the output voltage for the proposed method was better than that for conventional methods.

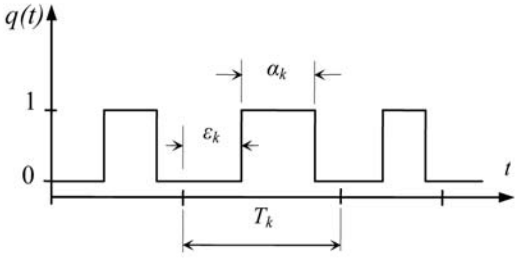


Fig. 2. Characteristic parameters in the switching signal.

In [45]-[49], the authors reported many investigations related to the use of digital controllers for conducted-noise peak reduction in DC-DC converters. The authors of [50] concluded that increasing the FPGA clock speed improved the conducted-noise spectrum of the converter. They also determined that the feedback controller slightly attenuates the noise reduction and that the randomization ratio shouldn't be more than one third of the central switching frequency to avoid overlapping and increased low-frequency noise.

III. DOUBLE-HYBRID SPREAD-SPECTRUM TECHNIQUE

A. Basic Idea

The concept of the switching function $q(t)$ is shown in Fig. 2, where T_k is the duration of the kth cycle, α_k is the duration of the on-state within this cycle, and ε_k is the delay from the starting of the switching cycle to the turn-on within the cycle. Note that the duty ratio is $d_k = \alpha_k/T_k$, and that the switching frequency is $F_k = 1/T_k$. The switching function consists of a series of such switching cycles.

There are two fairly well-known techniques for reducing the electromagnetic interference (EMI) of switching power converters that have been previously discussed:

1) Random Pulse Position Technique (RPP): The RPP technique is similar to a traditional PWM method with a constant switching frequency. However, the turn-on pulse position is randomized within each switching period instead of always starting at the beginning of each period [22]. In other words, each switching cycle has the same length T, and the pulse in each cycle has the same duration α, but an independent random variation is allowed in the position ε_k of the pulse in the kth cycle [20].

RPP: T_k fixed ($T_k = T$); α_k fixed ($\alpha_k = \alpha$); $\varepsilon_k$randomized.

It has been pointed out that the RPP technique produces a small noise-induced voltage ripple. However, it does not significantly reduce the noise spectrum in both the low- and high-frequency ranges [22].

2) Random Switching Frequency Technique (RSF): In this technique, also known as asynchronous dc-dc randomized

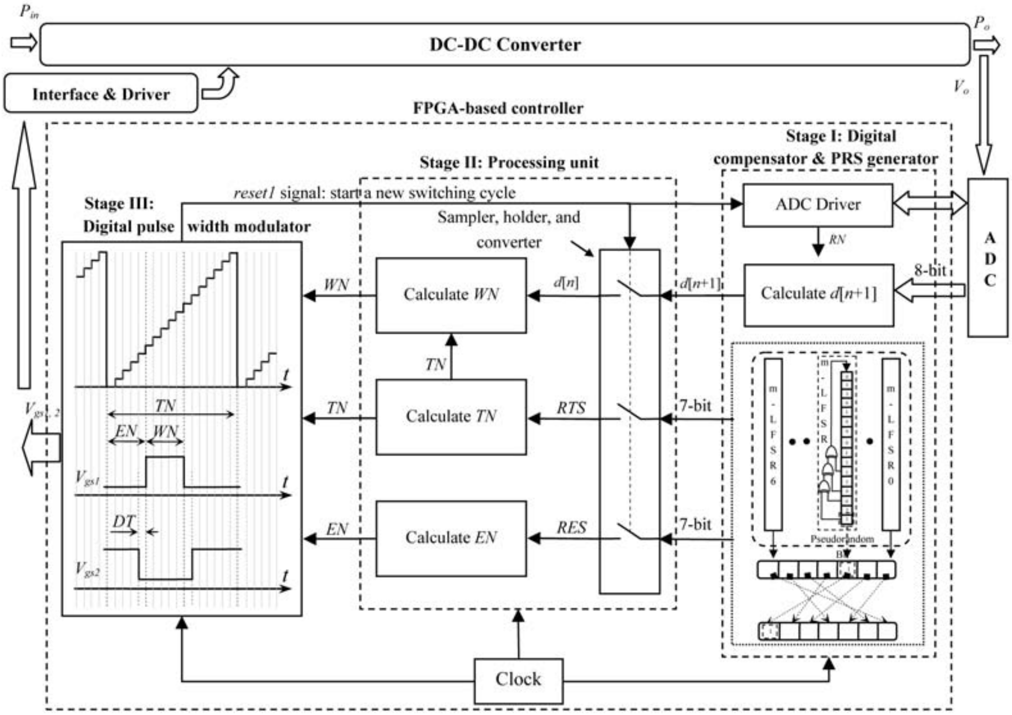


Fig. 3. The proposed digital controller's drive synthesis flowchart.

modulation, the lengths of the successive cycles T_k are randomized, while the duty ratio is kept fixed at its nominal value [4],[22].

RSF: $\varepsilon_k = 0; T_k$ randomized.

α_k = changes synchronously: d_k fixed ($d_k = \alpha_k/T_k = d$).

An attractive feature of this technique is that it inherently ensures constant duty cycle operation in a dc-dc converter. The variation of the output voltage is not as significant as it is in the RPP scheme and therefore it allows for a simple feedback control design [24].

The power spectral density of the RSF technique contains the continuous spectrum only because the switching frequency is randomized. Thus, it is effective in conducted EMI suppression [22]. However, the continuous noise spectrum, produced within the pass band of a low-pass filter, results in a noise-induced low-frequency ripple in the converter's output voltage [41].

As a summary of the merits and demerits of both the RPP and RSF techniques, the RSF technique gives better EMI performance than the RPP technique. However, the RSF technique introduces higher low-frequency harmonics than the RPP technique at the converter output voltage.

3) The Proposed Double-Hybrid Technique (DHB: This study proposed and investigated the use of both of the above mentioned techniques (RPP and RSF) for spreading the frequency spectrum of the switching noise and attaining a satisfactory output voltage quality at the same time. Two parameters, F_k, ε_k, were randomized, and the third parameter; d_k was controlled by a digital compensator.

Randomness levels are defined in [26] by the following equation:

$$R\varepsilon = \frac{\varepsilon_u - \varepsilon_l}{T} \tag{1}$$

where the delay time $\varepsilon_k \in [\varepsilon_l, \varepsilon_u]$. $\varepsilon_l, \varepsilon_u$, and T denote the lower and upper limits of the pulse delay time in each cycle, and the nominal switching time period, respectively.

$$RT = \frac{T_u - T_l}{T} \tag{2}$$

where the time period $T_k \in [T_l, T_u]$. T_l, and T_u denote the lower and upper limits of time period in each cycle, respectively.

B. Digital Compensator Design

The converter was designed to generate a regulated output voltage at 3.3 V with an output current of 5 A from an input voltage of 12 V. For the case study, using a 3.3 V computer processor power supply, the voltage must not be allowed to overshoot to 5 or 6 volts when the supply is turned on. Such an overshoot may destroy the integrated circuits in the computer motherboard. Thus, the Q-factor must be sufficiently low, i.e., 0.5 or less [51].

A controller was designed in [52] to fulfill the above conditions. The coefficients were determined based on the poles-zeros cancellation approach. The controller zeros were selected to (approximately) cancel the poles of the discrete transfer function. The gain of the controller was found using the root locus method (with the help of the MATLAB rltool [53]). The obtained discrete-time control law is given by:

$$U[n]=U[n-1]+0.5565E[n]-E[n-1] \\ +0.4736E[n-2] \tag{3}$$

where U is the control output, E is the error voltage, the quantities with (n) denote the sampled values for the current sampling cycle, the quantities with $(n-1)$ denote the values of the previous sampling cycle and so on. The sampling frequency was taken as a tenth of the switching frequency (200/10 = 20 kHz).

IV. FPGA-BASED DIGITAL IMPLEMENTATION

Fig. 3 shows the proposed digital controller's drive synthesis flowchart. It contains three stages that can be briefly explained as follows:

Stage I: Digital Compensator and Pseudorandom Stream Generator. The ADC's driver and the digital compensator were designed and implemented inside a FPGA. The converter output voltage was sampled, converted into a digital signal, and processed by the digital compensator. During the current sample, the digital compensator computed the duty ratio ($d[n+1]$) for all of the switching cycles within the sampling time period. Moreover, two random number generators to randomize both F_k and ε_k were required to realize the proposed technique. As shown in Fig. 3, a pseudorandom stream (PRS) generator was constructed for this purpose. The proposed construction used several maximum length linear feedback shift registers (m-LFSRs) [54] in parallel. It delivered two different random 7-bit streams. The streams were composed of the output bits of the m-LFSRs with different arrangements. For a detailed description of the generator, the reader is referred to [49],[50].

The operation of the proposed PRS generator digitally simulated the classical analog white-noise source as well as the sample and hold circuit. The output bits were converted into integer numbers (RFS and RES) at the beginning of each switching cycle and processed at the processing unit.

Stage II: Processing Unit. At the beginning of each switching cycle, this unit achieved the following assignments:

1) Converting the pseudorandom streams into integer numbers (RFS and RES).
2) Calculating the randomization parameters for the started switching cycle and the number of steps needed to fulfill the switching frequency, duty ratio, and pulse position (TN, WN, and EN respectively) according to the following equations:

$$TN = T_L + RTS \tag{4}$$

$$WN = TN \times d(n) \tag{5}$$

$$EN = E_L + RES \tag{6}$$

where:

TN : Needed number of steps to fulfill the switching frequency*

T_L : Lower time period limit*

RTS and RES : Pseudorandom output streams converted into integer numbers

WN : Needed number of steps to fulfill the duty ratio

EN : Needed number of steps to fulfill the pulse position*

E_L : Lower pulse position limit*

* For the case study DHB, ($R\varepsilon = RT = 0.4$, at an FPGA clock speed 66 MHz: TN = 267 394 clks, EN = 24 151 clks).

Stage III: Digital Pulse Width Modulator (DPWM). To generate gate signals ($V_{gs1,2}$) with the identified randomization parameters, the DPWM counted up to TN and then reset at the end of every switching cycle (see the *reset1* signal in Fig. 3 and Fig. 4). $V_{gs1,2}$ were generated in the following way:

- *To generate* V_{gs1}: When the counter value was between the reference values $EN, EN+WN$, the controller kept the PWM output state high; otherwise, it remained low.
- *To generate* V_{gs2}: DT denotes the required number of clock steps to fulfill the dead time. When the counter value was between the reference values $EN-DT, EN+WN+DT$, the controller kept the PWM output state low; otherwise, it remained high.

The proposed hybrid technique was designed in VHDL (VHSIC hardware description language; VHSIC: very-high-speed integrated circuit). It was analyzed and synthesized using Quartus II web edition software. A sample of the simulations is shown in Fig. 4. Then, it was implemented inside an Altera Cyclone EP1C6T144C8 FPGA.

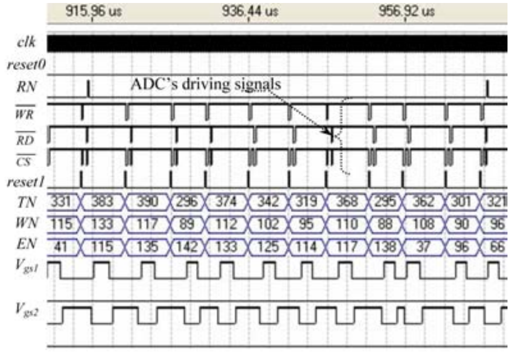


Fig. 4. VHDL simulation of the proposed FPGA-based controller with the double-hybrid technique for the following signals:

clk : FPGA clock, 66 MHz.
reset0 : Reset signal, for resetting the m-LFSRs once at the turn on instant.
reset1 : Reset signal, for resetting the PWM counter at the end of the switching cycle and for starting a new switching cycle.
$\overline{WR}$: Write control input signal.
$\overline{RD}$: Read input signal.
$\overline{CS}$: Chip-select input signal, which must be low for the ADC to recognize the $\overline{WR}$ and $\overline{RD}$ input signals.
RN : Read now signal, orders the compensator to read the converted 8-bits.
V_{gs1} : Gate signal for the Q1 switch (shown in Fig. 6).
V_{gs2} : Gate signal for the Q2 switch (shown in Fig. 6).

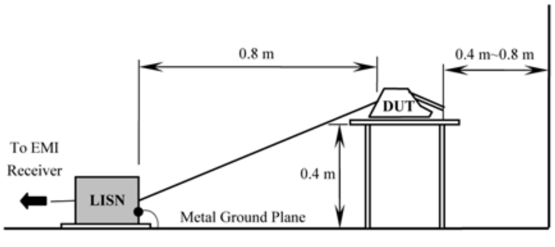


Fig. 5. Conducted-noise measurement system.

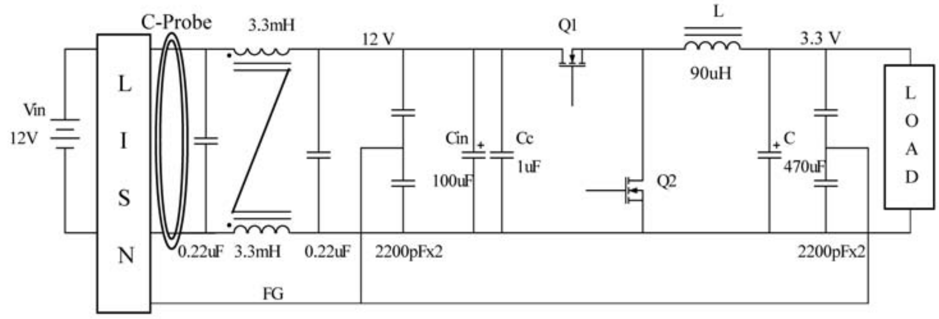


Fig. 6. Experimental converter circuit configuration.

V. EXPERIMENTAL VERIFICATION

The size of the output inductor and capacitor of the selected buck converter were chosen such that the converter operates in the continuous conduction mode with a low output current ripple.

Fig. 5 shows a typical setup for conducted-noise measurement, which exactly follows the defined regulations for conducted EMI measurements in [3]. A line impedance stabilization network (LISN: ESH2-Z5 type) was used to standardize the input impedance seen from the input of the device under test (DUT), while ensuring a high degree of isolation over the spectral measurement range. The LISN sensed the conducted-noise, and a high-frequency current probe (C-Probe: EZ-17 type) sensed both the common-mode and the differential-mode noise currents. The EMI receiver (ESCI type) provided a 50 Ω termination for the LISN/C-Probe measurement port. This setup guaranteed a fixed or calibrated relationship between the conducted EMI current and the resulting voltage at the input of the measurement apparatus. Fig. 6 presents the experimental converter circuit configuration.

Noise measurements were taken at $V_{in} = 12V, V_o = 3.3V$, and $I_o = 5$ A with a center switching frequency f_{csw}= 200 kHz and a resolution band width of the spectrum analyzer RBW = 9 kHz.

The following constraints were considered when setting the randomization parameters:

1) The randomized switching frequency must have the same average as the center switching frequency [15].
2) The lowest frequency harmonic in the PWM waveform must be well above the bandwidth of the control loop. Otherwise, the control loop will modify the PWM waveform, even in the steady state [4], [12].
3) To avoid increased low-frequency noise and overlapping between successive frequency spectrum ranges, the frequency randomization ratio (ΔF_k) was set to be less than ± one third of the central switching frequency [50].
4) The pulse position (ε_k) must be less than ($T_k - \alpha_k$), which limits the upper bound of ($\Delta\varepsilon_k$).

Corresponding to these constraints, four cases were investigated. These cases were as follows:

1) Basic pulse width modulation (PWM), ($R\varepsilon = RT = 0$).
2) Random pulse position technique (RPP), ($R\varepsilon = 0.4, andRT = 0$).
3) Random switching frequency technique (RSF), ($R\varepsilon = 0, andRT = 0.4$).
4) The proposed double-hybrid technique (DHB), ($R\varepsilon = RT = 0.4$).

All of the studied cases were designed, implemented, and experimentally investigated. The conducted-noise spectra were then compared.

VI. RESULTS AND DISCUSSION

Fig. 7 shows a comparison between of the measured conducted-noise spectra and their envelopes (the line that connects the amplitudes of the spectral components [3]) for each of the investigated modulation techniques. It is clear that the noise peaks were concentrated in two regions. The first region is in the low-frequency range (0.15-1 MHz) around the center switching frequency and the other region is in the high-frequency range (1-30 MHz). For a better illustration, the measured conducted-noise spectrum envelopes were redrawn together in Fig. 8. It is obvious that randomizing one parameter only (i.e., random pulse position (RPP) or random switching frequency (RSF)) does not significantly improve the conducted-noise spectrum. However, the proposed DHB technique attained the best EMI performance (i.e., the highest level of noise level reduction) in both the low- and high-frequency ranges.

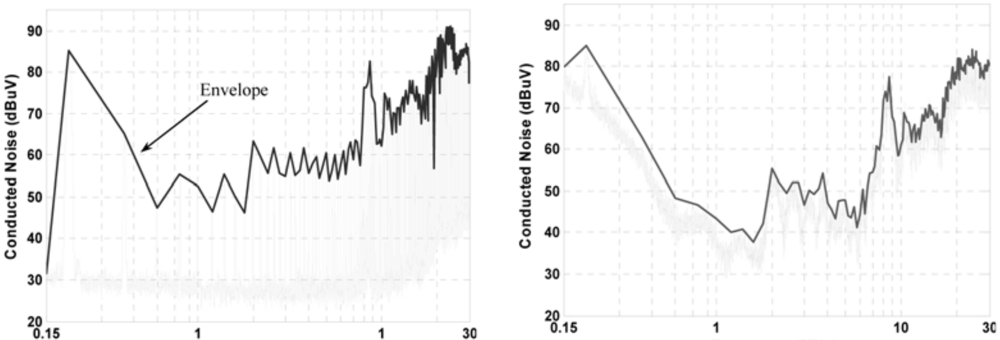
On the other hand, the common-mode noise was not significantly affected by any of the investigated techniques.

The measured differential-mode current spectrum envelopes are presented in Fig. 9. The proposed DHB technique significantly improved the differential-mode current spectrum in both the low- and high-frequency ranges.

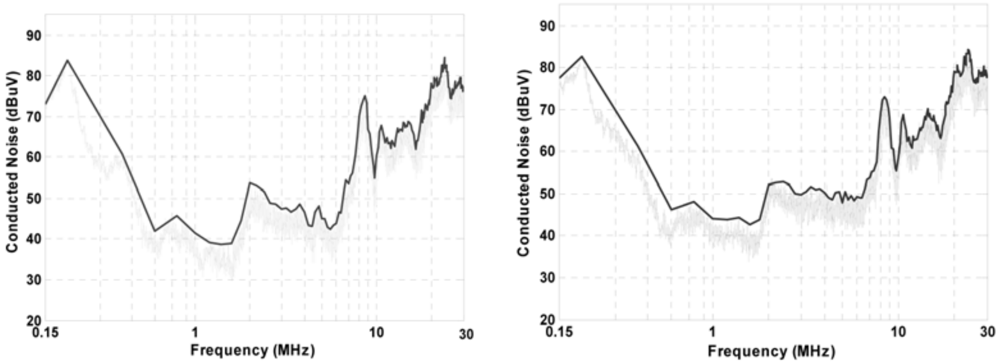
To investigate the influence of using the proposed technique on the converter's normal operation (i.e. dc-dc conversion with an acceptable output voltage quality), the effect of using all the studied techniques on the converter's output voltage ripple was investigated and compared (see Fig. 10). It is clear that the converter's output voltage ripple was not deteriorated by using the proposed technique.

VII. CONCLUSIONS

A hybrid technique was designed and implemented for conducted-noise reduction in dc-dc converters. The effect of using the proposed controller on the common-mode, the



(a) PWM, $(R_\varepsilon = RT = 0)$. (b) RPP, $(R_\varepsilon = 0.4, RT = 0)$.



(c) RSF, $(R_\varepsilon = 0, RT = 0.4)$. (d) DHB, $(R_\varepsilon = RT = 0.4)$.

Fig. 7. Comparison of the measured conducted-noise spectra and their envelopes for the investigated modulation techniques.

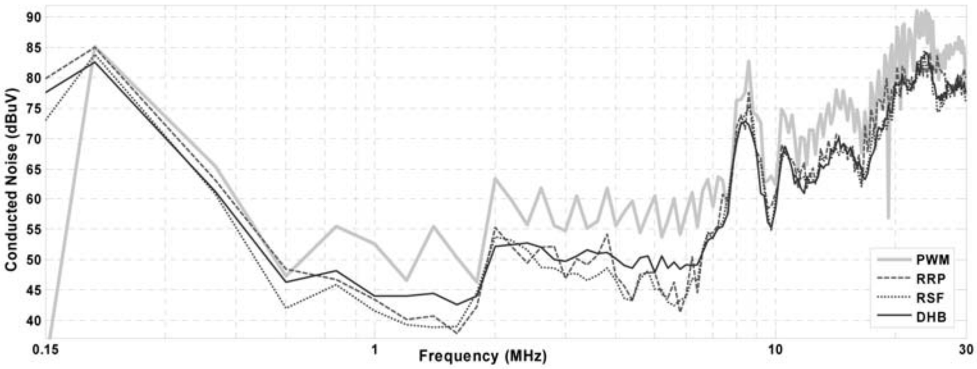


Fig. 8. Comparison of the measured conducted-noise spectrum envelopes for the investigated modulation techniques.

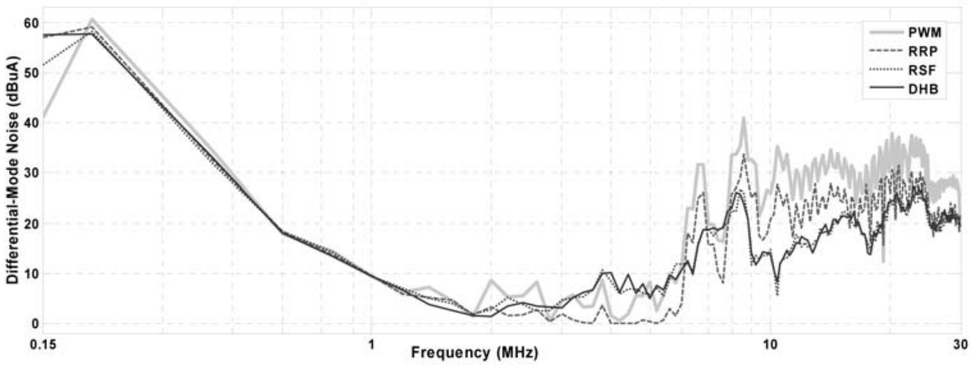


Fig. 9. Comparison of the measured differential-mode noise current spectrum envelopes for the investigated modulation techniques.

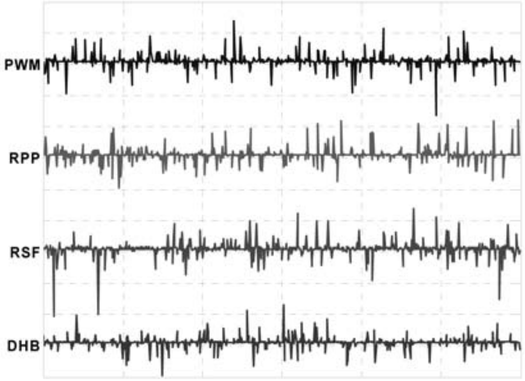


Fig. 10. The measured converter's output voltage ripple for the investigated modulation techniques (vertical: 0.5 V/div, horizontal: 0.5 s/div).

differential-mode, and the total conducted-noise characteristics of the converter was experimentally investigated. To investigate the influence of using the proposed technique on the converter's normal operation, the effect of using the proposed techniques on the converter's output voltage ripple was investigated. To evaluate the contribution of the proposed DHB technique, the investigations included basic PWM, RPP, RSF, and DHB techniques. A comparison of the performances of the various techniques was then made. The experimental results proved that the proposed double-hybrid technique demonstrated the merits of both the RPP and RSF techniques: good EMI performance and a rather quiet output voltage.

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