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Effects of Random Switching Schemes on the EMI Levels of Conventional and Interleaved Buck Converters for Mobile Devices

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Abstract: This study presents a comprehensive detailed analysis of the effect of five different random modulation switching schemes and their randomness levels on the elector magnetic interference (EMI) of designed simple and interleaved DC-DC buck converters for smartphone applications. The analyzed switching schemes are pulse width modulation (PWM), random pulse width modulation (RPWM), random pulse position modulation (RPPM), random carrier frequency modulation various duty (RCFMVD), and random carrier frequency modulation fixed duty (RCFMFD). The experimental analysis is performed for all aforementioned switching modulation schemes at the switching frequency of 20 kHz and different randomness levels (RL) (30% to 85%). For a fixed RL of 40%, the switching current harmonics/conducted emission (CE) levels are 5–10 dB/11 dBμV and 17 dB/14 dBμV lower for the RCFMVD case when compared to conventional PWM for both simple and interleaved buck-converters, respectively. The observed switching current harmonics and CE levels for interleaved schemes are around 23 dB and 12 dBμV lower when compared to the conventional simple buck converter scheme for the analyzed circuit configurations. The EMI levels decrease with the increase in the randomness levels from 30% to 85% with less variations in the output voltage level. The findings suggest that a interleaved buck converter circuit with the least-independent switching mechanisms and higher randomness is more appropriate for the reduction of both current spikes and CE levels with RCFMFD as the switching modulation scheme.

Keywords: buck converter; conducted emission (CE); interleaved buck converter; randomness level (RL); switching harmonics

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1. Introduction

A buck converter is a step-down DC-DC converter circuit that is widely used in switching mode power supply (SMPS), smartphone, laptop, and battery chargers [1–3]. In a buck converter, the output voltage level is controlled by the fast switching of the employed modulation scheme (usually pulse width modulation (PWM) [4,5]. The fast switching, particularly at a high frequency, produces high-frequency switching harmonics in the circuit and makes the circuit more susceptible to electromagnetic interference (EMI) [6]. The high-frequency switching spikes could also damage the functionality of the connected devices, such as smartphones or laptops, through the transfer of the conduction or radiated emissions [7–10].

The selection of buck converter schemes i.e., simple or interleaved; the randomness level of the switching schemes; and the inter-dependency of the switching mechanism for interleaved schemes could also affect the switching harmonics and emission levels [8,11–13]. Adequately designed charge pump circuits can be used as buck converters [14,15]. The literature lacks numerous simple and spread-spectrum-based modulation techniques on CE and peak-current harmonics levels for both conventional and interleaved buck converters.

A simple buck converter works well for low-voltage converter applications with a current up to around 25 A. However, power dissipation and efficiency begin to become an issue at higher currents [16]. An interleaved design of the buck converter is reported as a solution to high power dissipation and low efficiency as well as lower EMI levels as compared to a conventional buck converter [5,17–19]. Conventionally, the employed switching schemes in buck converters is pulse width modulation (PWM), which produces high switching current spikes [7,8].

The authors in [11] applied switching frequency modulation with variable delay (VDFM) for the reduction of amplitude of generated interference harmonics in parallel topology modular power supplies. Ferrazza et al. [12] employed artificial frequency modulation based on a spread spectrum approach for the reduction of EMI in a flyback power converter. The study of [13] discussed the impact of spread-spectrum based frequency-modulated PWM switching on the characterization of the quality of a power system. The authors in [20] suggested a dynamic resonant perturbation (DRP) technique to control the harmonic oscillation of a signal controlling the operation of a buck converter.

A chaotic triangular PWM signal for the active EMI reduction of a buck converter was reported in [21]. Along with conventional approaches, increasing the number of phases in a buck converter also helped to decrease the conducted emission profile as reported in [10]. Recent studies of [6,22] proposed that controlling the operation of a buck converter with a spread-spectrum modulated signal reduced the amplitude of the spectral contents of produced EMI noise. The literature lacks a comprehensive analysis of the impact of various switching modulation techniques on the current and CE profile of both interleaved and non-interleaved buck converter typologies.

In this work, we analyze the performance of a conventional as well as interleaved buck converter in terms of the switching current harmonics and conducted emission (CE) levels for the five different kinds of switching modulation schemes, i.e., pulse width modulation (PWM), random pulse width modulation (RPWM), random pulse position modulation (RPPM), random carrier frequency modulation various duty (RCFMVD), and random carrier frequency modulation fixed duty (RCFMFD).

Separate typologies of conventional and interleaved buck converters are designed and fabricated. Experimental analysis is performed for all aforementioned switching modulation schemes at the switching frequency of 20 kHz and different randomness levels.The switching frequency of 20 kHz is generated by the Arduino Due board. Analysis is conducted for both the simple and interleaved buck converter schemes as illustrated in Figure 1. For the interleaved scheme, the effect of the switching dependency (correlation) on the output voltage, current harmonics and CE levels is also analyzed.

To the best of our knowledge, this is the first such study that presents a detailed experimental EMI analysis of interleaved and non-interleaved buck converters as per the analysis strategy of Figure 1.

The rest of the work is organized as follows. Section 2 describes the basic simple and interleaved buck converter circuits. The details of the employed random switching modulation schemes and their generation are given in Section 3. The analysis of the switching current harmonics and conducted emission results for both converter circuits is presented in Sections 4 and 5, respectively. Section 6 describes the comparison of the current harmonics and CE levels for both buck converter schemes. The dependency of the harmonics spikes on the switching mechanism of the interleaved circuit is detailed in Section 7, while the impact of the randomness levels on the harmonics is described in Section 8. Section 9 concludes this work.

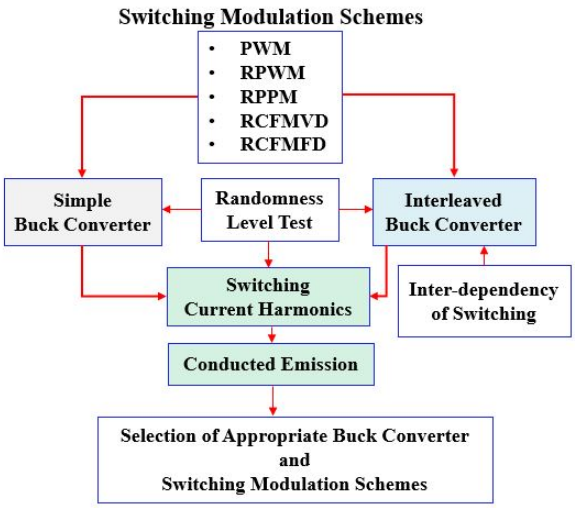

Figure 1. Analysis strategy for the selection of an appropriate buck converter and switching modulation schemes.

2. Buck Converter Circuits

2.1. Simple Buck Converter

A schematic of the analyzed simple buck converter for 6 V–3 V DC conversion is shown in Figure 2. An N-type MOSFET was used for the purpose of switching (on/off). The switching signal (V_{switch}) of 20 kHz with different employed random modulation schemes is fed by the commercially available Arduino Due board. The input supply source (V_s) was 6 V, and the buck converter was designed to operate at 20 kHz. The values of the lumped components (inductor (L) and capacitor (C)) were calculated using Equations (1) and (2) with the duty ratio (D) of 50%. The value of the output voltage fluctuation ($\Delta V_0/V_0$) was set to 25% for calculations [23].

$$L = \frac{(1-D)R_0}{2f} \tag{1}$$

$$C = \frac{(1-D)}{8If(\Delta V_0/V_0)} \tag{2}$$

The output of the Arduino board was amplified for the MOSFET switching operation. The capacitor (C) was aimed to reduce the ripples of output voltages (V_0). Switching current harmonics (i_{switch}) were measured at the source terminal of N-MOSFET using a current probe in the fabricated experimental setup.

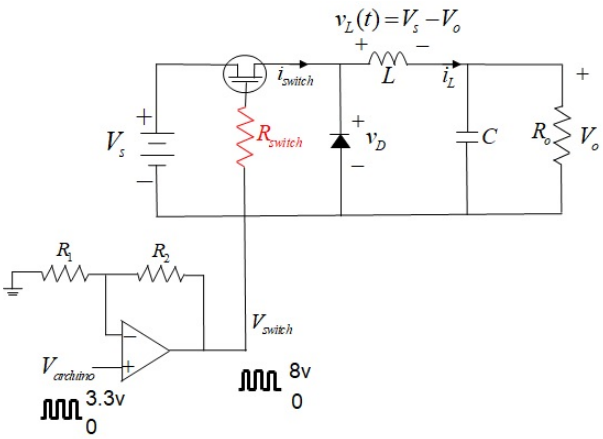

Figure 2. Schematic of simple buck converter for switching the current harmonics analysis.

2.2. Interleaved Buck Converter

As with the simple buck converter of Figure 2, the interleaved buck converter was also designed for 6 V to 3 V DC-DC conversion. The schematic of the designed parallel or interleaved buck converter is shown in Figure 3. The values of inductors (L_1) and (L_2) were calculated using Equations (1) and (3). The capacitor (C) value was determined using Equation (4) with the duty ratio (D) of 25% and output voltage fluctuation ($\Delta V_0/V_0$) of 25% [18].

$$L_1 = L_2 = L/2 \tag{3}$$

$$C = \frac{(1-D)}{8L(If_s)^2(\Delta V_0/V_0)} \tag{4}$$

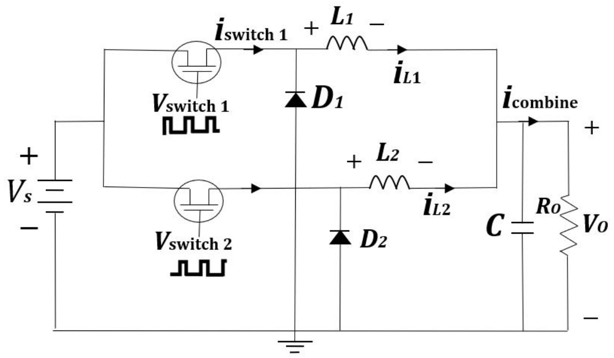

Figure 3. Schematic of an interleaved buck converter for switching current harmonics analysis.

3. Random Modulation Switching Schemes

3.1. Switching Modulation Schemes for Simple Buck Converter

The conventional pulse width modulation (PWM) has a constant switching frequency and duty cycle. Figure 4a illustrates the typical waveform of a conventional PWM. In the Figure 4 waveforms, T_k and α_k refer to the kth cycle time period and pulse width, respectively. The ratio of pulse width and time period ($d_k = \alpha_k/T_k$) is termed as the duty cycle of the waveform, which remains constant for PWM waveforms.

Figure 4b shows a typical random pulse-width modulation (RPWM) waveform. For such signals, the switching frequency (time period) remains constant. However, the pulse width (α_k) varies in the range of α_{max} to α_{min}, which makes the duty ratio random for such waveforms. The randomness level (RL) for each modulation scheme can be defined based on its changing modulation parameters. For the RPWM signal of Figure 4b, the ratio of the change in the gate pulse width (α_k) and nominal switching period (T_k) defines the randomness level [1] as depicted in (5). In (5), α_{min} and α_{max} are the minimum and maximum pulse widths of each duty cycle.

$$RL_{RPWM} = \frac{(\alpha_{max} - \alpha_{min})}{T_k} \tag{5}$$

The signal representing the characteristics of random pulse-position modulation (RPPM) is depicted in Figure 4c. For such a modulating waveform, duty cycle (d_k) and the switching frequency remain constant. However, the pulse position changes for each time period and is controlled by the delay time of the pulse defined by parameter ϵ_k. The shown parameters of ϵ_{max} and ϵ_{min} in Figure 4c refer to the maximum and minimum limits of the pulse position. For the RPPM case, randomness level (RL) becomes the ratio of the change in the pulse position (ϵ_k) and T_k as depicted in (6) [1].

$$RL_{RPPM} = \frac{(\epsilon_{max} - \epsilon_{min})}{T_k} \tag{6}$$

A random carrier-frequency modulation fixed duty (RCFMFD) typical signal is shown in Figure 4d. In this modulation topology, the switching carrier frequency is randomized through variations in the pulse width. The duty ratio did not change for this case. The variations in the pulse width (α_k) bring a change in the time period of that cycle. The maximum and minimum values of the cycle time period i.e., T_{max} and T_{min} depend on the corresponding maximum and minimum values of the pulse width i.e., α_{max} and α_{min}, respectively.

The switching frequency and duty cycle were randomized in the last analyzed switching modulation scheme in this study i.e., random carrier-frequency modulation variable duty (RCFMVD). Figure 4e shows the RCFMVD waveform in which α_k did not change. The RL of both RCFMFD and RCFMVD is defined by (7)

$$RL_{RCFMFD} = RL_{RCFMVD} = \frac{(T_{max} - T_{min})}{T_k} \quad (7)$$

The conventional scheme of PWM generates large spiked harmonics due to its periodic on and off time. When the pulse characteristics are changed randomly in terms of the duty cycle, pulse width, pulse position, and carrier frequency as in Figure 4, this may have an impact on the generated switching harmonics due to the change (spreading) in the power spectral density of the used modulation technique. The level of randomness of the aforementioned parameters of Figure 4 waveforms could also impact the switching harmonics and conducted emission profiles.

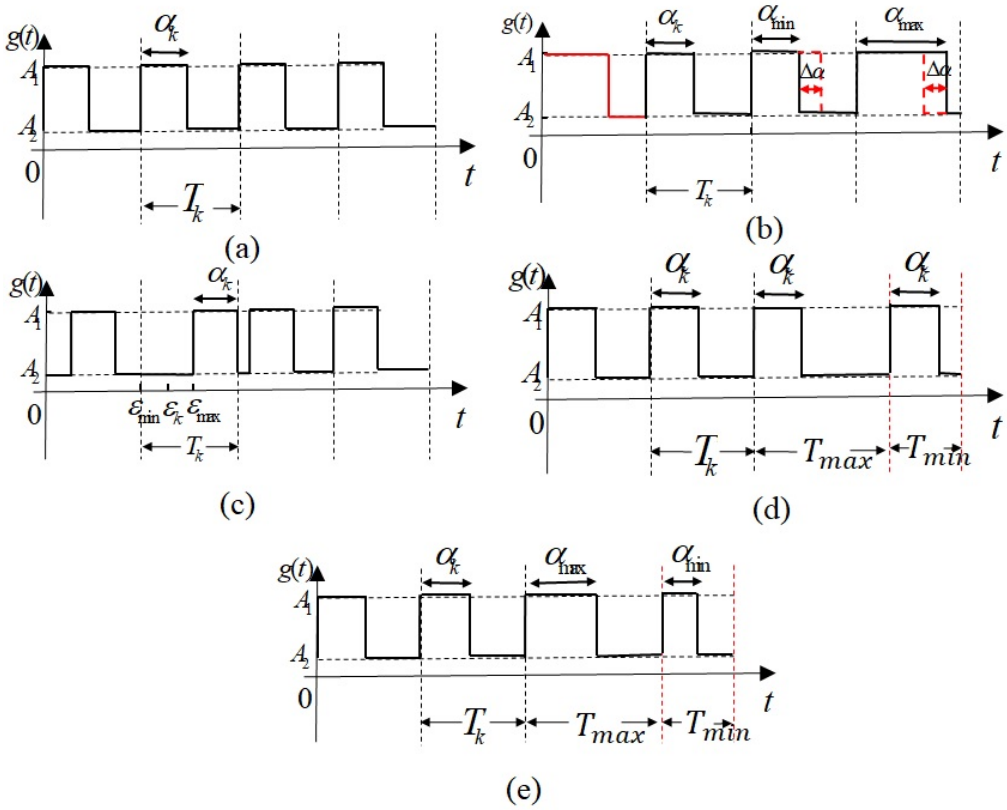

Figure 4. Typical pulse modulation random switching signals: (**a**) PWM, (**b**) RPWM, (**c**) RPPM, (**d**) RCFMVD, and (**e**) RCFMFD.

The switching modulation signals for different schemes of Table 1 and Figure 4 were generated using the Arduino Due board for 20 kHz (T = 50 µs). Figure 5 shows the waveform of the real-time generated switching modulation signals. All switching signals of Figure 5b–e were produced for the fixed randomness level (RL) of 40%.

Table 1. Summary characteristics of different switching schemes [1].

Modulatiton	T_k	α_k	ϵ_k	$d_k = \alpha_k/T_k$
PWM	constant	constant	zero	constant
RPWM	constant	random	zero	random
RPPM	constant	constant	random	constant
RCFMVD	random	constant	zero	random
RCFMFD	random	random	zero	constant

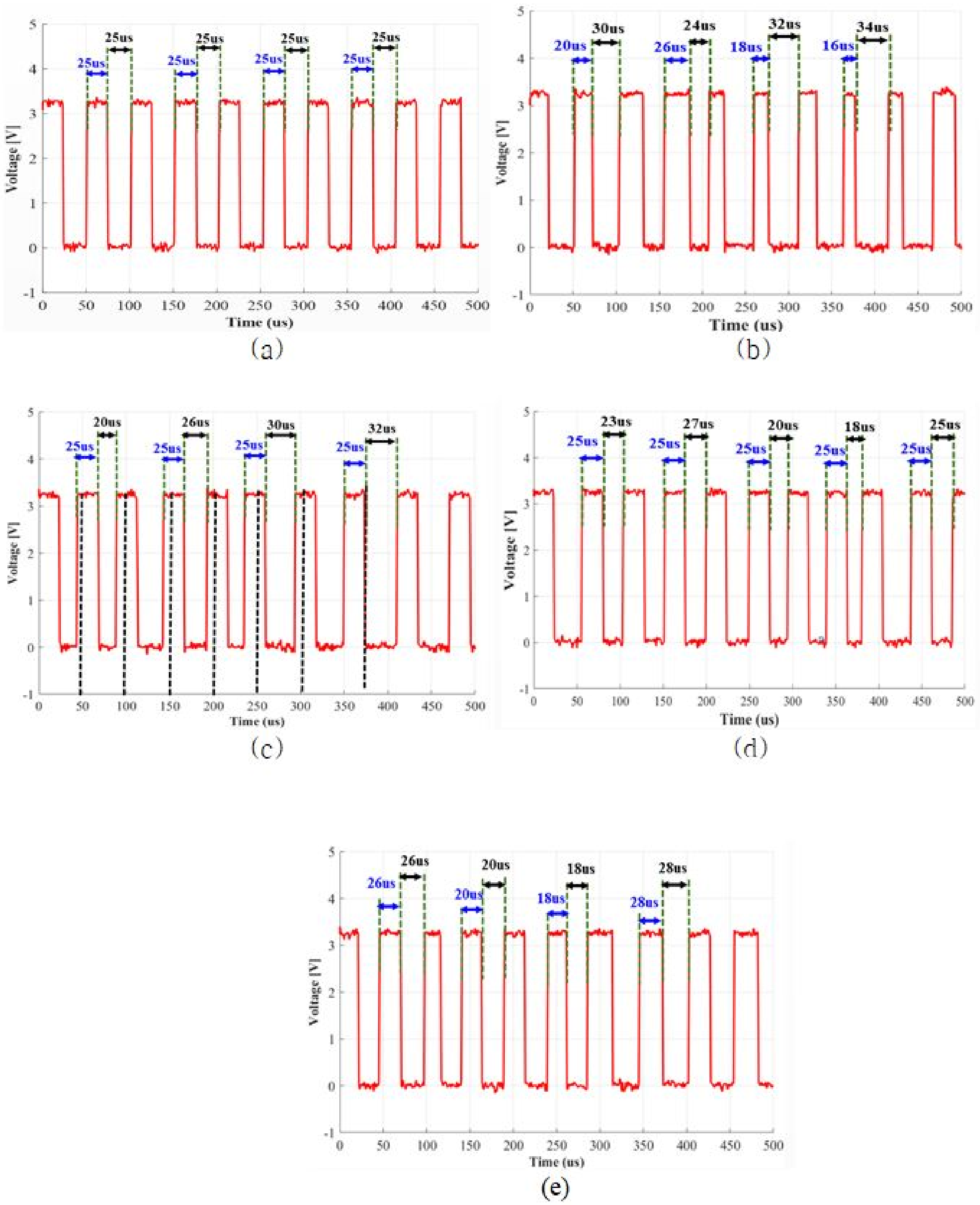

Figure 5. Switching modulation signals from Arduino for a simple buck converter operation: (**a**) PWM, (**b**) RPWM, (**c**) RPPM, (**d**) RCFMVD, and (**e**) RCFMFD.

3.2. Switching Modulation Schemes for an Interleaved Buck Converter

The interleaved buck converter circuit of Figure 3 can be operated in two modes: continuous conduction mode (CCM) and discontinuous conduction mode (DCM) [9]. In order to keep the whole system of interleaved in CCM the same as with a simple buck converter, the inductor and capacitor values are crucial. In addition, the duty ratio (D) should be 25%, and both switches of the interleaved circuit (see Figure 3) are operated 180 degrees out of phase [18].

The two switches of the interleaved circuit are operated in parallel to each other. When switch 1 is operating in the 'on state' (Mode 1), switch 2 is in the 'off-state' and vice versa for switch 2 operation. Figure 6 shows the generated switching signals of different modulation schemes for the CCM operation of the interleaved buck converter of Figure 3.

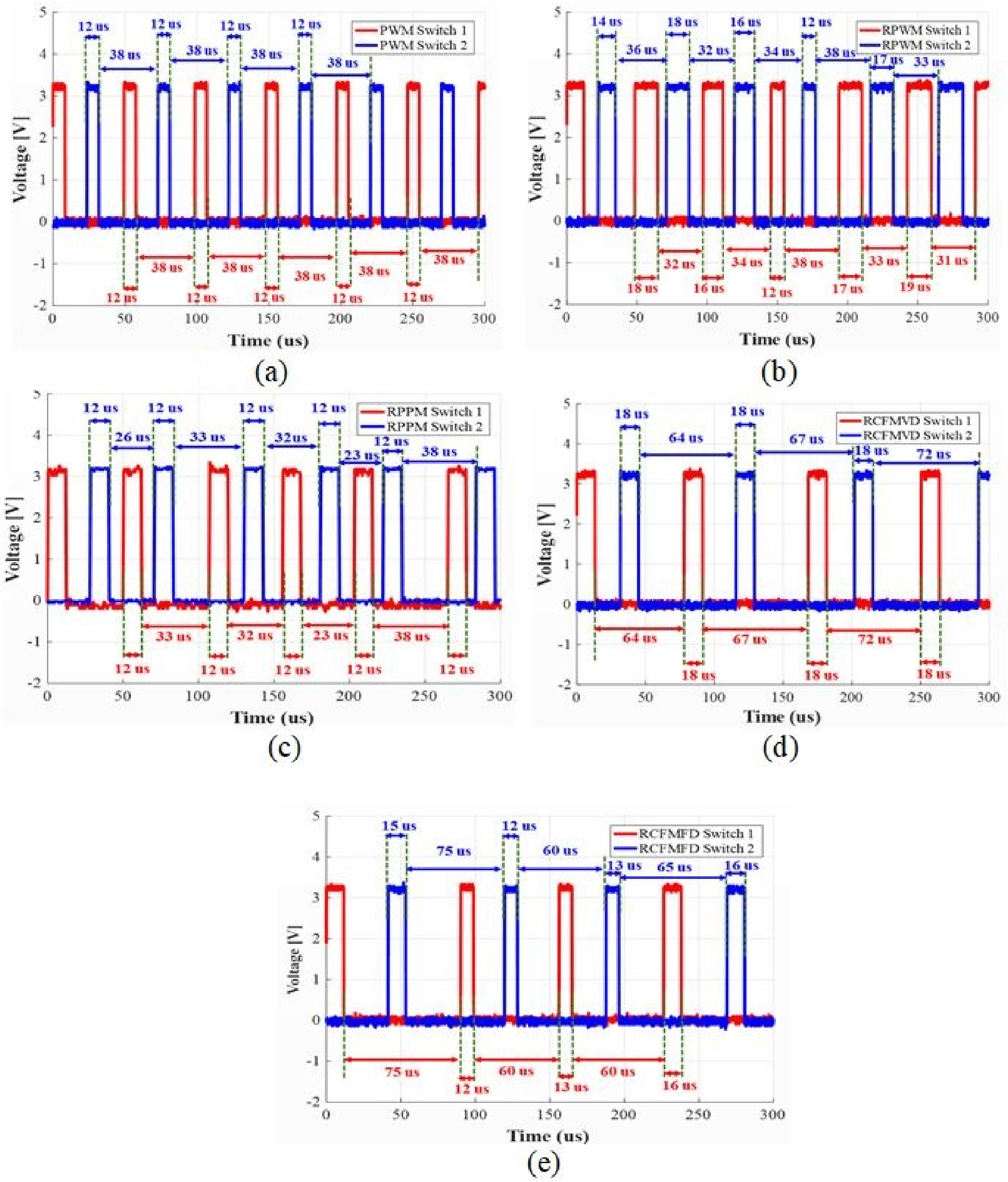

Figure 6. Switching modulation signals from Arduino for the interleaved buck converter operation: (**a**) PWM, (**b**) RPWM, (**c**) RPPM, (**d**) RCFMVD, and (**e**) RCFMFD.

4. Switching Current Harmonics Analysis

4.1. Switching Current Harmonic Results for Simple Buck Converter

Figure 7 show the comparison of the measured switching current harmonics for the random modulation switching signals of Figure 5 for the simple buck converter. The results of Figure 7a show that the levels of the current harmonics were the highest for the PWM case and were the minimum for the RCFMFD and RCFMVD cases.

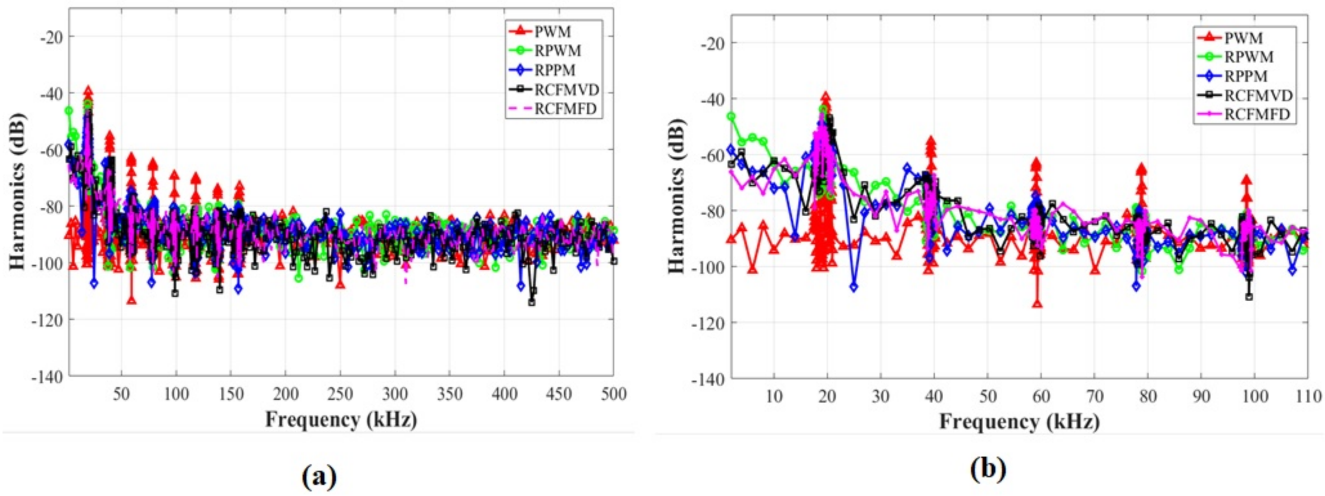

Figure 7. Comparison results for a simple buck converter for different modulation schemes: (**a**) switching current harmonics and (**b**) switching current harmonics up to the fifth harmonic.

Table 2 summarizes the peak values of switching current harmonics (up to the fifth harmonic) of Figure 7b for all analyzed modulation schemes. We notice that the harmonic spike levels reduce when we move towards the RCFMFD switching scheme. In this case, the switching current harmonics are around 5–15 dB lower as compared to the conventional PWM case, and the output voltage value is near to the desired voltage level of 3 V.

For the RCFMFD switching modulation case, the current harmonics levels touch the −80 dB limit from the fourth harmonic, while for other schemes (PWM, RPPM, and RFFMVD) this occurs from the fifth or higher harmonics as depicted in Table 2. The first harmonic spike value for RPWM cases is higher than for the RPPM, RCFMVD, and RCFMFD cases. However, higher harmonic component values for this case are lower than the RPPM, RCFMVD, and RCFMFD modulation schemes. The fundamental spectrum component value for RPPM is lower than for RCFMFD. However, for further spectral harmonic components, the performance of the RCFMFD is better than for the RRPM case.

Table 2. Comparison of the current harmonics for a simple buck converter (harmonics values are in dB).

Frequency (kHz)		**20**	**40**	**60**	**80**	**100**
Harmonics		**First**	**Second**	**Third**	**Fourth**	**Fifth**
Switching Schemes	PWM	−39	−55	−63	−65	−69
	RPWM	−44	−69	−78	−80	−81
	RPPM	−49	−64	−75	−79	−80
	RCFMVD	−47	−67	−77	−78	−82
	RCFMFD	−46	−67	−75	−80	−80

The power spectral density (PSD) of RPPM and RPWM modulation schemes contains discrete and multiple harmonics of the switching frequency. This is because the switching frequency or time period is constant for these schemes. Due to this, higher harmonic contents in Figure 7 waveforms were noticed for RPPM and RPWM waveforms. On the other hand, as the switching frequency is randomized in RCFMFD and RCFMVD, this makes the PSD more continuous with the spreading of power spectral density of these schemes [1,6,22]. The continuous spectrum nature of switching current harmonics after the second/third harmonics with the lowest level are noticed for the RCFMFD and RCFMVD signals.

4.2. Switching Current Harmonic Results for an Interleaved Buck Converter

Figure 8a shows the comparison of the observed current spikes of the interleaved buck converter for all five switching schemes. Table 3 presents the comparison of the output voltage of simple and interleaved buck converter schemes. It can be noted from Table 3 that, when we apply RCFMFD, we obtained a 2.97 V output voltage for the interleaved case and 2.96 V for a simple buck converter circuit. For the RPPM, the output voltage is also near to 3 V but the switching harmonics are high in this case. We observed that, in the case of the RCFMFD switching scheme, the switching current harmonics were the lowest when compared to the other schemes as illustrated in Table 4 .

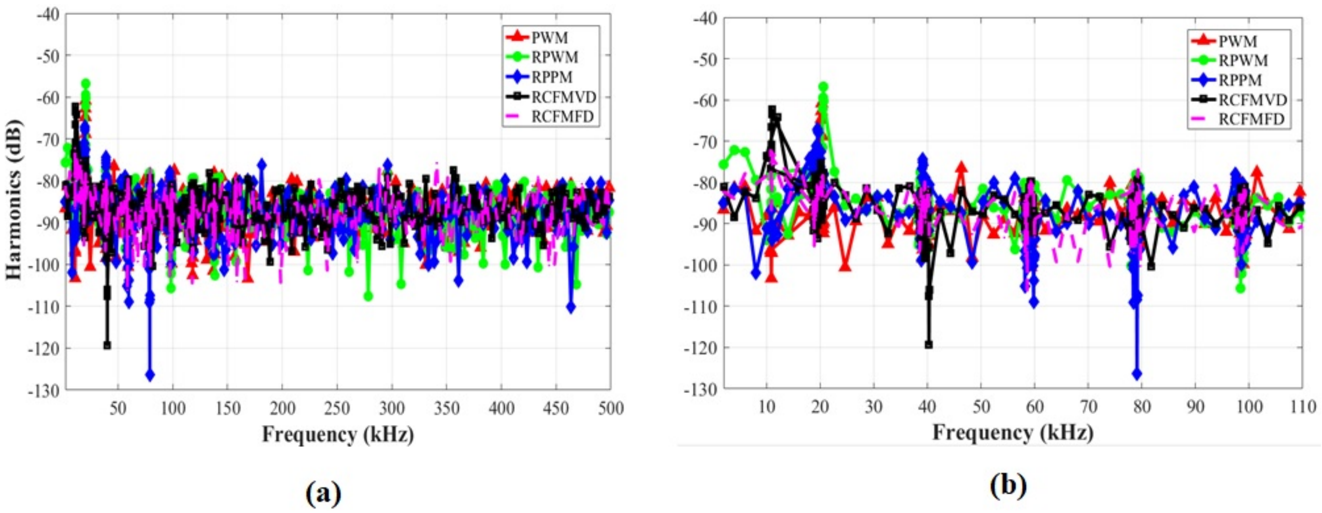

Figure 8. Comparison result for an interleaved buck converter for different modulation schemes: (**a**) switching current harmonics and (**b**) switching current harmonics up to the fifth harmonic.

Table 3. Comparison of current harmonics for an interleaved buck converter (harmonics values are in dB).

Frequency (kHz)		20	40	60	80	100
Harmonics (dB)		First	Second	Third	Fourth	Fifth
Switching Schemes	PWM	−61	−70	−74	−79	−79
	RPWM	−56	−69	−78	−79	−81
	RPPM	−67	−74	−79	−80	−80
	RCFMVD	−75	−76	−78	−79	−81
	RCFMFD	−78	−79	−80	−81	−80

Table 4. The impact of different switching schemes on output voltage variations for simple and interleaved converters.

Schemes	Interleaved V_0 (V)	Simple V_0 (V)
PWM	3.01	2.91
RPWM	3.23	3.14
RPPM	3.03	2.90
RCFMVD	3.21	3.10
RCFMFD	2.97	2.96

The lowest low-frequency switching current harmonics were observed for the RCFMFD case for the interleaved buck converter (see Table 4 and Figure 8). The spreading of the current harmonics power at a multiple of the used switching frequency of 20 kHz brings the low frequency harmonics to the lowest level for the RCFMFD modulation scheme. This is because that duty cycle remains unchanged in every switching frequency cycle for RCFMFD, which ensures the stability of the output voltage and thus lower switching harmonic contents.

The duty cycle has a random nature for modulation schemes of RPWM, and this becomes the reason for the relatively higher low frequency harmonic contents for this case. The duty cycle is also randomized in RCFMVD modulation as with RPWM. However, this randomization is because of different factors. In RPWM, the pulse width is varied, while the switching period is changed in RCFMVD for randomization of the duty cycle. Due to this reason, higher low frequency harmonics contents are observed for RPWM as compared to RCFMVD cases. Among all analyzed cases of random modulation schemes, RCFMFD is the suitable choice for both simple and interleaved schemes as the lowest level of switching current harmonics were noticed for this scheme.

5. Conducted Emission (CE) Analysis

This section describes the conducted emission results for simple and interleaved buck converter circuits for the different random modulation switching schemes.

5.1. Conducted Emission Analysis for Simple Buck Converter

Figure 9 shows the experimental setup of the conducted emission measurements for the simple buck converter. For the CE analysis, a laboratory fabricated 5 μH line impedance stabilization network (LISN) was inserted between the battery source and the buck converter as shown in Figure 9.

A spectrum analyzer was connected at the output port of the LISN to measure the CE levels [24]. Figure 10 depicts the measured CE results of a simple buck converter for five random modulation switching schemes. The comparison of Figure 10 confirms that, as with the current harmonic spikes, the minimum levels of CE were observed for the RCFMFD case for the simple buck converter scheme. The observed CE levels for RCFMFD were around 11 dBμV lower when compared to the other modulation schemes as illustrated in Figure 10.

5.2. Conducted Emission Analysis for an Interleaved Buck Converter

Figure 11 depicts the experimental setup for the CE measurements of the fabricated interleaved buck converter. As with the simple buck converter, a LISN was inserted for CE measurements.

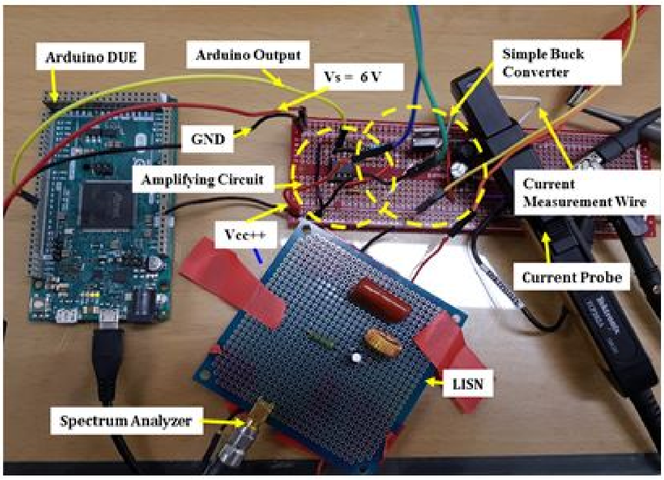

Figure 9. Experimental setup for the conducted emission analysis of a simple buck converter.

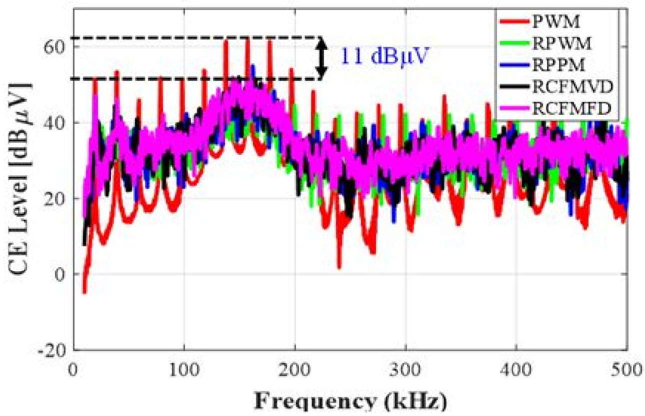

Figure 10. Comparison of the conducted emission results for different random schemes for a simple buck converter.

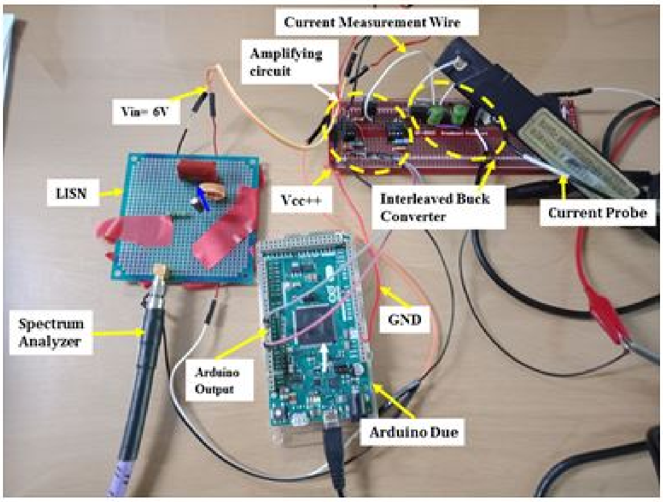

Figure 11. Experimental setup for the conducted emission analysis of the interleaved buck converter.

The CE results of the interleaved buck converter are illustrated in Figure 12. We found that RCFMFD was the most useful switching scheme as we observed the lowest level of CE for this switching scheme when compared to other schemes. The observed CE levels for the RCFMFD scheme were almost 14 dBμV lower when compared to the CE levels of other modulation schemes.

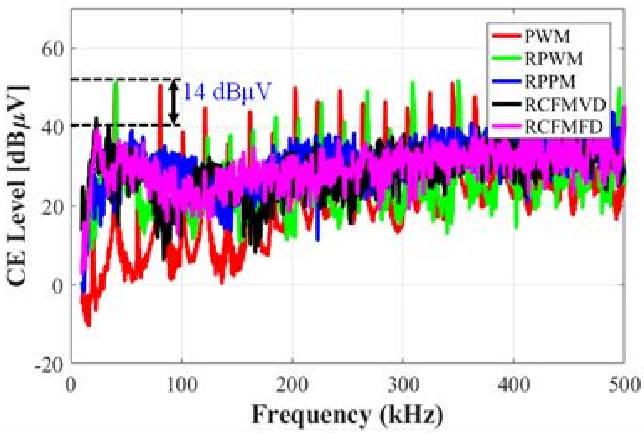

Figure 12. Comparison of the conducted emission for different random schemes for an interleaved buck converter.

6. Comparison

Figure 13 shows the comparison of the switching current harmonics of the RCFMFD modulation scheme for the simple and interleaved buck converters. For brevity, comparison curves are shown only for the RCFMFD scheme, as the lowest levels of current harmonics spikes and CE levels were observed for this scheme in both the simple and interleaved cases. For the simple buck converter, the fundamental switching current harmonic value at 20 kHz was −50 dB, which reduced to the level of −73 dB for the interleaved case. It can be noted from Figure 13 that the interleaved harmonics were around 23 dB lower than the simple buck converter circuit harmonics. When we used a switching modulation signal of RCFMFD for a simple buck converter, the CE highest spikes were around 52 dBμV as illustrated in Figure 14.

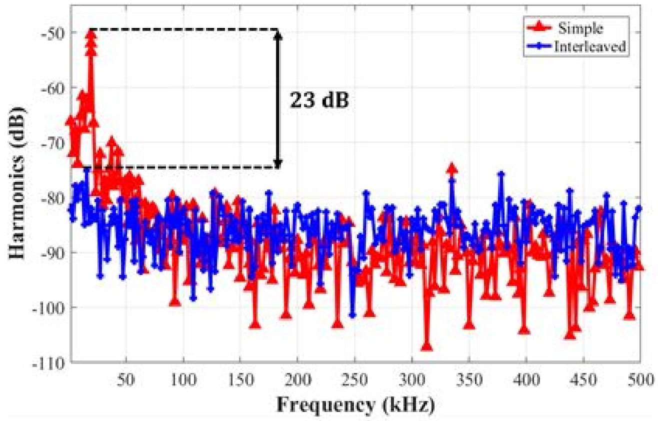

Figure 13. Comparison of the switching current harmonics of the RCFMFD modulation schemes for simple and interleaved buck converters.

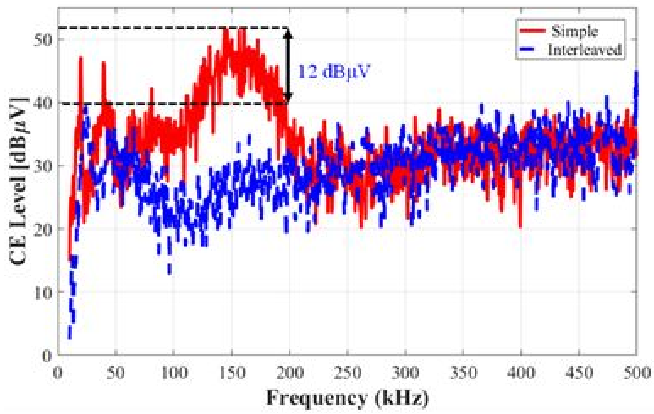

Figure 14. Comparison of the conducted emission results of the RCFMFD modulation schemes for simple and interleaved buck converters.

In the case of an interleaved buck converter, the highest spike was at 20 kHz (40 dBμV) as shown in Figure 14. We noticed that the CE spikes were reduced by 12 dBμV for the interleaved case. This comparison suggests that an interleaved scheme is more appropriate than a simple buck converter due to its continuous conduction mode operation. The interleaved scheme with parallel buck converters can reduce the switching harmonics and CE levels more than the simple circuit of a buck converter. The results of Figures 7b, 8b, 10 and 12–14 indicate that the best modulation scheme among the analyzed switching modulation schemes of Figure 1 was found to be RCFMFD.

7. Impact of Randomness Level (RL)

The different parameters of Figure 4 waveforms are randomized to generate the switching modulation scheme as illustrated in Table 1 and Figures 5 and 6. The presented analysis in Sections 3 and 4 was for the fixed randomness level of 40%. This section describes the effect of changes in the randomness level on the current harmonics for simple and interleaved buck converter circuits.

7.1. Randomness Level Analysis for Simple Buck Converter

Our designed buck converter required a DC voltage conversion of 6 V to 3 V. First, we analyzed the impact of the randomized level of the switching signal on the buck converter output with the RCFMFD switching signal. The objective is to determine the minimum and maximum value of the randomness for which we obtain the output value of around 3 V with 6 V input. The randomness level analysis was performed in the range of 30% to 85% for all modulation schemes of Figure 1 and Table 1.

The switching frequency (20 kHz) and the duty cycle (T = 50 µs) was constant in the analyzed RCFMFD case of Figure 15. We randomized the duty cycle of the kth cycle and analyzed its effect on the output voltage and current harmonics level. Figure 16 shows the comparison of the on-time histograms of the randomized switching signal for the simple buck converter.

The variations in the output voltage are summarized in Table 5. Table 5 also summarizes the mean (μ) and variance (σ) of the on-times of the randomly generated switching signal for different randomness levels of Figure 16. This shows that, although the mean value of the on-time for different randomness levels of RCFMFD signal was around 25 µs (24–25 µs), the concentration of more than 50% of the duty cycle components (more than 25 µs) increased as the randomness level increased (see Figure 16d,e).

Figure 15 shows the switching current harmonics for various randomness levels of the RCFMFD waveform. We noticed that, as with the output voltage values, randomness also affects the level of current harmonics. The switching current harmonics level reduces with the increases in the randomness level due to the spreading of the more than 25 µs on-time components in the switching signal as can be noted from Figure 16c–e. We observed that, when the randomness level was high, the output voltage approached 3 V as illustrated in Table 5.

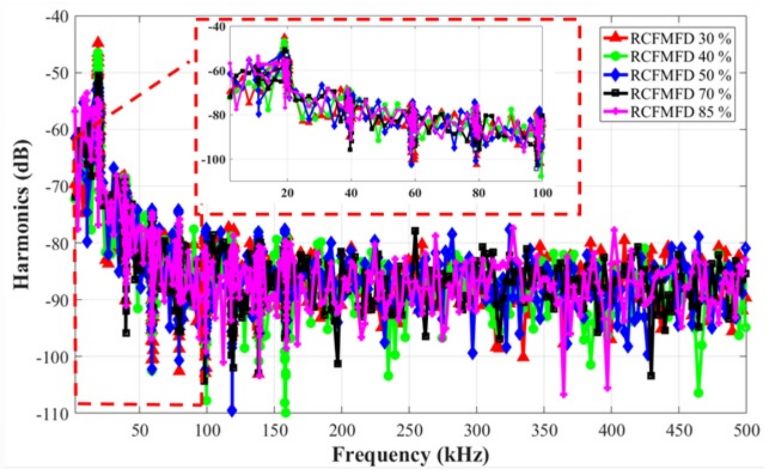

Figure 15. Comparison of the switching current harmonics results for various randomness levels of RCFMFD for a simple buck converter.

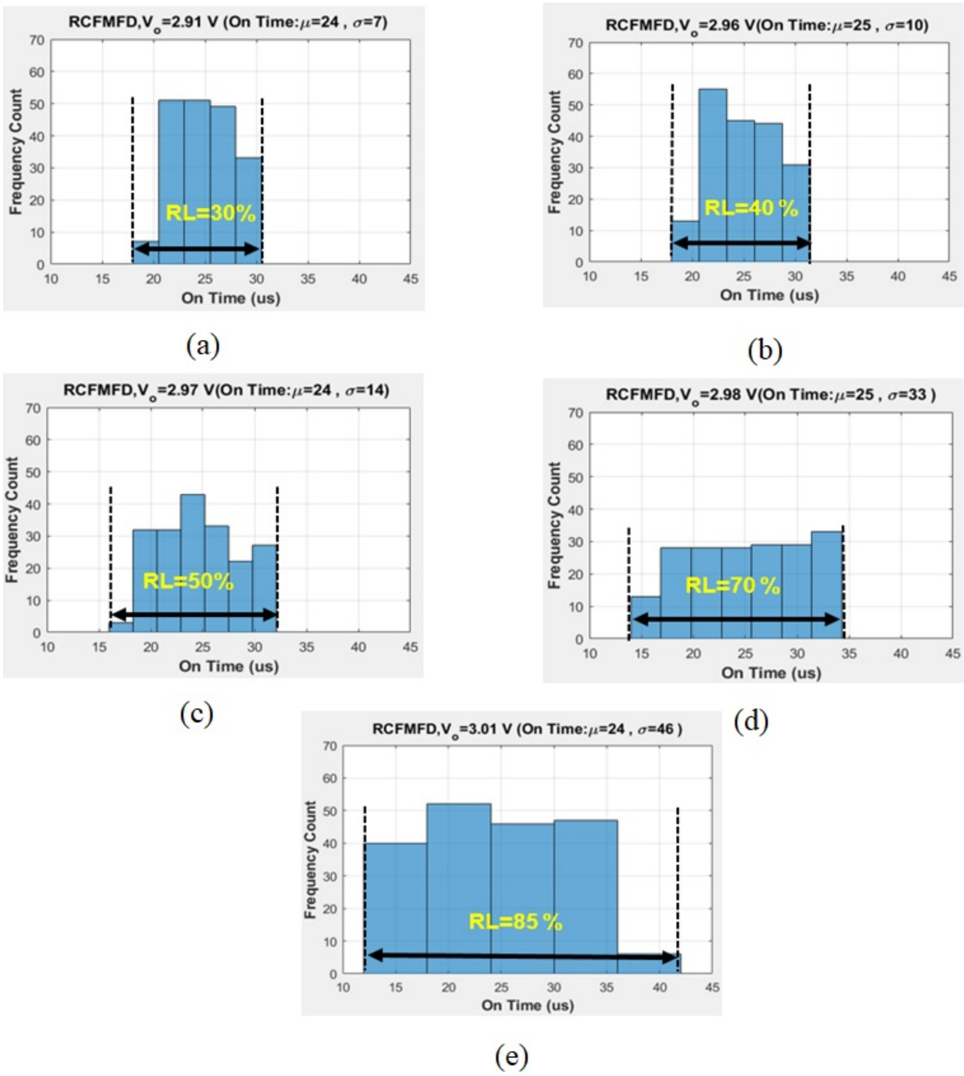

Figure 16. Comparison of histograms of switching signals for various randomness levels (RL) of RCFMFD for a simple buck converter (**a**) 30% RL, (**b**) 40% RL, (**c**) 50% RL, (**d**) 70% RL, and (**e**) 85% RL.

Table 5. Comparison of the output voltages mean and variance of the on-time for simple buck converters for different randomness levels of RCFMFD switching modulation schemes.

RL (%)	V_0 (V)	μ	σ
30	2.91	24	7
40	2.96	25	10
50	2.97	24	14
70	2.98	25	33
85	3.01	24	46

7.2. Randomness Level Analysis for an Interleaved Buck Converter

Figure 17 shows the result of the current harmonics of the interleaved schemes for random level analysis of the RCFMFD *k*th duty cycle. As in the simple buck converter cases, when the randomness level was high, the switching current harmonics reduced as shown in Figure 17.

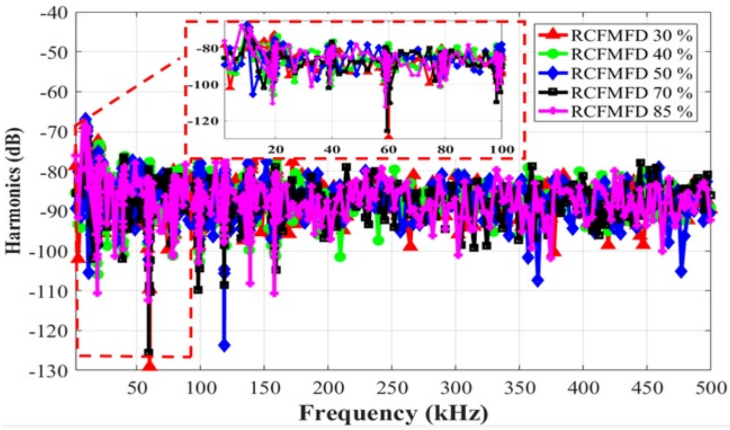

Figure 17. Comparison of the switching current harmonics results for various randomness levels of RCFMFD for an interleaved buck converter.

Similar results as in Figures 15 and 17 were obtained for the other modulations schemes of RPWM, RPPM, and RCFMVD for both buck converter circuits. However, here only the results of the RCFMFD modulation technique are reported for brevity. The parallel structure of the interleaved scheme maintains the output voltage approaching the desired level despite the change in randomness level of the different stochastic parameters of the modulation schemes. All the analysis of the switching current harmonics for RPWM, RPPM, RCFMVD, and RCFMFD modulation schemes were performed with a 40% randomness level in Sections 3–6 for both buck converter typologies.

Figures 18 and 19 show the histograms of switch 1 and switch 2 of the interleaved circuit for the RCFMFD switching scheme for various randomness levels. We notice that, when the randomness level increases, the variance of the on-time for both switching signals 1 and 2 also increases with the mean value of the on-time of around 12.5 µs (see Tables 6 and 7). As in the simple buck converter case, the spreading of the on-time for both switch 1 and switch 2 of the interleaved case can be noted in Figures 18c–e and 19c–e, respectively, with the increase in RL, which becomes the cause of the reduction of the switching current spikes as shown in Figure 17.

Table 6. Comparison of the output voltages, mean, and variance of the on-time for an interleaved buck converter switch 1 for different randomness levels of RCFMFD switching modulation schemes.

RL (%)	V_0 (V)	μ	σ
30	3.21	12.6	1.6
40	2.96	12.7	2.2
50	2.97	12.7	3.3
70	2.97	12.7	6.2
85	2.98	12.1	9.1

Table 7. Comparison of the output voltages, mean, and variance of the on-time for an interleaved buck converter switch 2 for different randomness levels of RCFMFD switching modulation schemes.

RL (%)	V_0 (V)	μ	σ
30	3.21	12.6	1.6
40	2.96	12.7	2.2
50	2.97	12.7	3.3
70	2.97	12.7	6.2
85	2.98	12.1	9.1

However, we also notice that the current harmonics level reduces with increases in the randomness level, and the output voltage remains within the range of the desired output voltage level (i.e., 3 V) for an interleaved case (see Figure 17a and Tables 6 and 7). This suggests that we may choose a higher randomness level for the interleaved scheme for the further reduction of current harmonics. We monitored the on-time for each switching experiment on Arduino Due, and Figures 16, 18 and 19 show the total 200 frequency count. It can be observed that the histograms of both the switching signals of interleaved schemes (Figures 18 and 19) and the simple buck converter scheme (Figure 16) were not truly uniform. This is due to the limitations of the random number generation of the Arduino board.

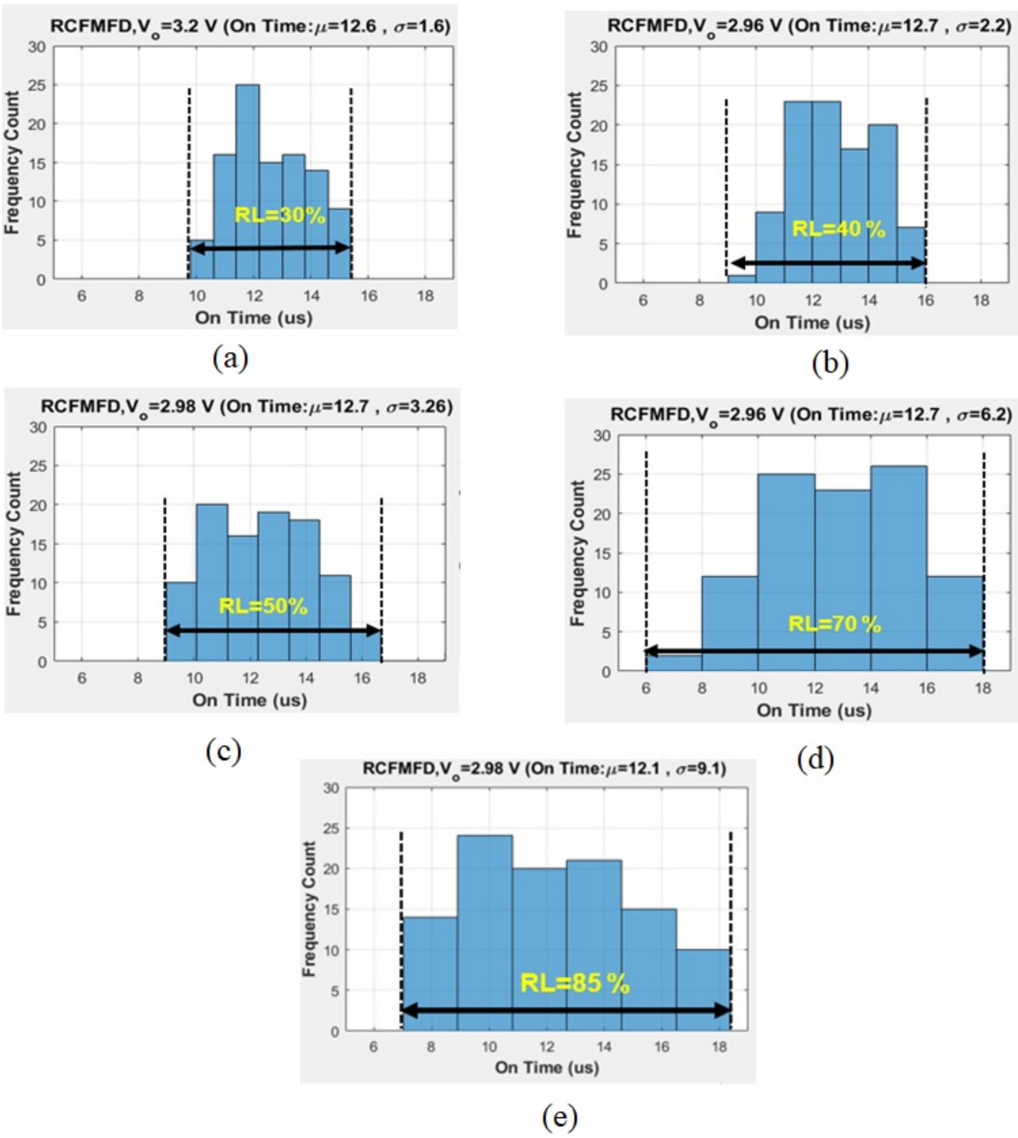

Figure 18. Comparison of the histograms of the switch 1 switching signal for various randomness levels (RL) of RCFMFD for an interleaved converter (**a**) 30% RL, (**b**) 40% RL, (**c**) 50% RL, (**d**) 70% RL, and (**e**) 85% RL.

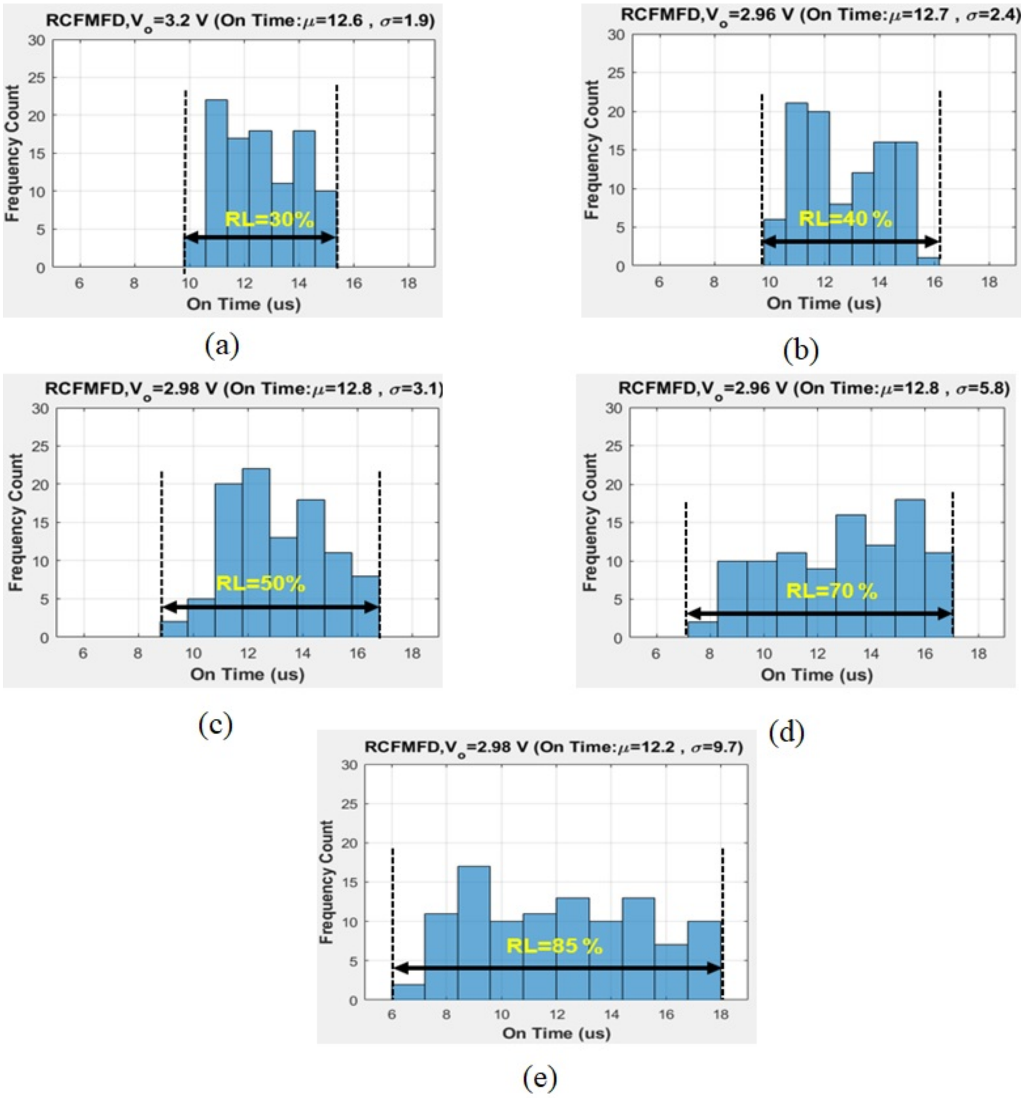

Figure 19. Comparison of the histograms of the switch 1 switching signal for various randomness levels (RL) of RCFMFD for an interleaved converter (**a**) 30% RL, (**b**) 40% RL (**c**) 50% RL, (**d**) 70% RL, and (**e**) 85% RL.

8. Interleaved Switching Dependency

The inter-dependency mechanism of the switching signals in the interleaved circuit of Figure 3 could also have an impact on the switching current and CE levels. This inter-dependency of switching signals was analyzed using the sample Pearson correlation coefficient of (8). In (8), x represents the modulation signal of switch 1, and y corresponds to the modulated switching signal of switch 2.

We analyzed the dependency between switch 1 and switch 2 using (8) to determine how much switch 1 and switch 2 were correlated with each other during the operation of the interleaved buck converter. In this study, we analyzed the inter-dependency for all switching modulation signals i.e., PWM, RPWM, RPPM, RCFMVD, and RCFMFD with different randomness levels.

$$r_{xy} = \frac{\sum(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2 \sum(y_i - \overline{y})^2}} \quad (8)$$

In (8), r_{xy} is the correlation coefficient between the variables x and y. x_i is the value of the variable in a sample, and $\bar{x}$ corresponds to the mean of the values of the x-variable.

Similarly, y_i corresponds to the value of the y-variable in the sample, and $\bar{y}$ is the mean of the values of the y-variable. Table 8 presents the comparison of the variations in the correlation coefficient for various switching modulation signals of an interleaved buck converter with different randomness levels.

The variations in the randomness level of pulse width in RPWM, pulse position in RPPM, and carrier frequencies in RCFMVD and RCFMFD cases brings a slight change in the correlation coefficient for each case as illustrated in Table 8. We observed that the switching signals of RCFMFD had the lowest value of the correlation coefficient for the whole range of randomness level variations. This shows that, when the switching signal tends towards the least in-dependency scale, it reduces the switching current harmonics along with the conducted emissions as can be noticed from the results of Figures 7b, 8b, 10 and 12 (the lowest levels for the RCFMFD case).

Table 8. Comparison of the correlation coefficient of switch 1 and 2 of an interleaved circuit with different randomness levels and random modulation schemes.

	Correlation Coefficient (r_{xy})				
RL (%)	30	40	50	70	85
RPWM	−0.32	−0.33	−0.32	−0.32	−0.34
RPPM	−0.15	−0.15	−0.15	−0.15	−0.16
RCFMVD	−0.18	−0.18	−0.18	−0.18	−0.18
RCFMFD	−0.15	−0.15	−0.15	−0.15	−0.15

Possible limitations of the proposed study include the randomness range of the generated random switching signals for different modulation schemes using an Arduino Due board. The accuracy and randomness range of the random number generator along with the frequency of the switching signal could be improved by using digital signal processing (DSP) or field-programmable gate array (FGPA) boards in possible future work.

The analyzed switching schemes were pulse width modulation (PWM), random pulse width modulation (RPWM), random pulse position modulation (RPPM), random carrier frequency modulation various duty (RCFMVD), and random carrier frequency modulation fixed duty (RCFMFD). The experimental analysis was performed for all aforementioned switching modulation schemes at the switching frequency of 20 kHz and different randomness levels (RL) (30% to 85%).

For a fixed RL of 40%, the switching current harmonics/conducted emission (CE) levels were 5–10 dB/11 dBμV and 17 dB/14 dBμV lower for the RCFMVD case when compared to conventional PWM for both simple and interleaved buck-converters, respectively. The observed switching current harmonics and CE levels for interleaved schemes were around 23 dB and 12 dBμV lower when compared to the conventional simple buck converter scheme for the analyzed circuit configurations.

The EMI levels decreased with the increase in the randomness levels from 30% to 85% with less variations in the output voltage level. The findings suggests that interleaved buck converter circuit with the least-independent switching mechanisms and higher randomness was more appropriate for the reduction of both current spikes and CE levels with RCFMFD as the switching modulation scheme.

9. Conclusions

In this work, we described a detailed analysis of the effect of various random modulation switching schemes (PWM, RPWM, RPPM, RCFMVD, and RCFMFD) and their switching mechanisms on the current harmonics spikes and conduced emission (CE) levels for the designed simple and interleaved DC-DC buck converter circuits for smartphone applications.

The analysis suggests that the interleaved buck converter circuit is more appropriate for the reduction of both current spikes and CE levels with RCFMFD as the switching modulation scheme. The interleaved configuration reduced the current spikes and CE levels to 23 dB and 12 dBμV, respectively, when compared with the conventional configuration.

For the best performing RCFMFD modulation scheme, the enhancement of the switching randomness from 30% to 85% for RCFMFD modulation and making both switches of the interleaved circuit more independent further reduced the EMI levels. The findings of the conducted study could be useful to the design engineers of the electronics industry for the selection of an appropriate design of buck converter, switching modulation scheme, and employed level of switching randomness for the higher quality compliance of designed DC to DC conversion systems.

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