

An Aperiodic Modulation Method to Mitigate Electromagnetic Interference in Impedance Source DC–DC Converters

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Abstract—Rapid voltage and current transitions in switched-mode power converter circuits generate electromagnetic interference (EMI) which may interfere with other electronic systems. High-speed (e.g., wide bandgap) switching devices can improve circuit efficiency and compactness, but may increase the bandwidth of the interference generated. The peak interference is concentrated at harmonics of the fundamental switching frequency, and so may be reduced by modulating the converter switching frequency. However, converter topologies incorporating more than one switching device may not be suited to modulation of the switching frequency, and coordinated modulation of other pulse parameters is required to suppress interference. A relatively simple implementation of a hybrid pulse modulation technique is presented to suppress EMI in a quasi-Z-source converter comprising an impedance-source network and GaN-based H-bridge switching circuit. The technique uses two anharmonically related periodic signals to generate a modulated sawtooth carrier, which in turn generates coordinated switching pulses aperiodically modulated in position and width within a constant switching period. Experimental results demonstrated 10 dB suppression of the peak interference with negligible impact upon the converter's efficiency or output voltage. The proposed pulse modulation technique and its method of implementation are generic, and are expected to be widely applicable to other switched-mode dc–dc power converters.

Index Terms—Electromagnetic interference (EMI), impedance source power converters, interference suppression, pulse modulation, wide bandgap (WBG) semiconductors.

I. INTRODUCTION

Switched mode dc–dc power converters are widely used in many applications, such as electric vehicles, cellular phones, and laptop computers. Such applications often require multiple subcircuits to provide various voltage and current levels. Multiple dc–dc converters are often connected to a common dc bus connected to various loads and sources, such as shown in Fig. 1. In distributed systems [1], it is important to minimize

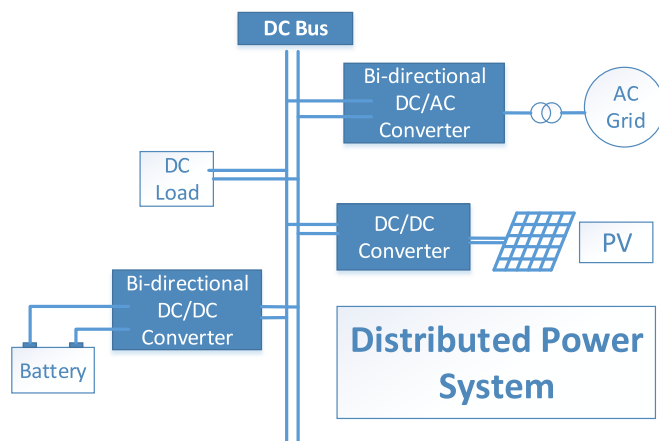


Fig. 1. Distributed power system with dc bus.

interactions between the connected circuits, which can result from conducted electromagnetic interference.

Recent developments in wide bandgap (WBG) power semiconductor devices, such as gallium nitride (GaN) and silicon carbide (SiC) high electron mobility transistors (HEMTs), have enabled the realization of increasingly efficient and compact power converters [2]. The main advantages of WBG power devices in these applications include relatively low on-resistance, high switching speed, high breakdown voltage, and they can withstand high operating temperatures [3].

Switching power converters commonly generate electromagnetic interference (EMI) which may be conducted (common mode and differential mode) and/or radiated to interfere with neighboring electronic circuits and systems. WBG devices can generate EMI with increased bandwidth, due their relatively rapid switching transitions [4].

Filters and shielding techniques are often utilized to suppress EMI, however these methods add cost and weight to power converters, which is contrary to current trends towards low-cost and portability [5]. Various spread-spectrum switching techniques have also been used to suppress the peaks in EMI which would otherwise occur at harmonics of the switching frequency [6]–[8]. For example, chaotic signals can be generated using either analogue or digital circuitry [12], [13] and used to suppress EMI in pulse-width modulated (PWM) switching signals. Chaotic signals are aperiodic in nature and strongly dependent upon initial conditions, which make long term predictions of

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chaotic signals impossible, despite their deterministic nature [14]. Several random pulse modulation schemes have also been reported to suppress EMI in power converters [6], [8], [15], [16].

In this paper, we present a simple method for aperiodic carrier signal generation which can in turn be used to generate aperiodic switching signals for EMI suppression in power converters. The aperiodic switching signals were readily generated using a field programmable gate array (FPGA), programmed using MATLAB Simulink [17].

This paper is structured as follows: Section II presents an overview of causes of EMI in power converters and reviews the various EMI suppression techniques. Section III describes a simple method to generate an aperiodically modulated sawtooth carrier, and its use in generating a coordinated set of switching waveforms for EMI suppression in a quasi-Z-source (qZS) dc–dc converter. The experimental results are presented and discussed in Section IV, followed by the Conclusion in Section V.

II. OVERVIEW OF EMI AND ITS SUPPRESSION IN POWER CONVERTERS

A. EMI Generation in Switched-Mode Power Converters

All modern power converter circuits contain reactive elements (for energy storage) and switching devices (for energy control). The switches are usually driven at a fixed frequency, and with a fixed or varying duty cycle, depending upon the control strategy. Switching often results in large voltage and/or current transients (dv/dt and di/dt), which in turn generate broadband electromagnetic emissions which may be conducted and/or radiated from the power converter to interfere with the operation of nearby electronic systems. Allowable levels of EMI are determined by various standards for electromagnetic compatibility (EMC) [18]. The amount of EMI generated at any given frequency depends upon:

- 1) the rate of change of each transition (inversely proportional to the EMI bandwidth),
- 2) the number of transitions per unit time (proportional to the EMI magnitude, and the spacing of harmonics of the switching frequency), and
- 3) the relative timing of each transition (which determines whether constructive interference occurs at specific frequencies).

WBG power semiconductor devices, such as gallium nitride high electron mobility transistors (GaN HEMTs) are capable of relatively fast, i.e., nanosecond, switching transitions [4]. The rapid switching reduces switching losses and enables high switching frequencies for realizing compact power converters, but also produces relatively broadband EMI, i.e., to hundreds of MHz for GaN devices. (Note: the Fourier transform of an ideal switching or signum function is $(j\omega)^{-1}$, consequently the magnitude of EMI produced by an ideal switch reduces by only 20 dB per decade in frequency).

B. EMI Mitigation Techniques in Power Converters

EMI mitigation techniques fall into one or more of the following four classes:

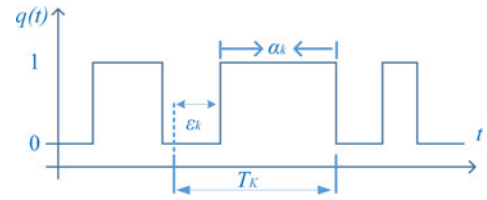


Fig. 2. Parameters available for modulation in a pulsed switching signal.

- 1) EMI filtering, i.e., adding one or more filters to prevent conducted EMI escaping from the circuit. This increases the cost, size, and weight of the power converter [5].
- 2) Electromagnetic shielding, i.e., enclosing the source of EMI with shielding material to block radiated EMI from escaping the circuit enclosure. Shielding is relatively expensive, and often compromised by leakage through joints in the shield [5].
- 3) Soft switching, i.e., slowing of switching transitions, thereby reducing the bandwidth of EMI generated. Various slow switching transition techniques are also reported. These solutions require additional components and circuit complexity.
- 4) Modulation of one or more switching pulse parameters (e.g., frequency, pulse width, pulse position) to spread the spectrum of the switching harmonics over a wide range of frequencies [6]. The modulation style can be further classified as periodic, aperiodic, and random.

The EMI-suppressing pulse modulation method used in this work relies on modulation of switching pulse parameters, as shown in Fig. 2, in which the switching waveform, $q(t)$, consists of one pulse per switching cycle, each of which is defined by three parameters; ϵ_K is the delay from the start of the k th switching cycle to the switch turn-ON time, α_k is the pulse duration in the K th switching cycle, and T_K is the total duration of the k th switching cycle [6]. Given the latter parameters the duty ratio of the k th switching cycle may be defined as $D_K = \alpha_K/T_K$.

Based on variation of the afore-mentioned parameters, many spread-spectrum pulse modulation techniques may be defined, as summarized in Table I (adapted from [6], and expanded).

The latter pulse modulation techniques for suppressing EMI in power converters (i.e., by spreading the spectra of switching harmonics) are readily applied to single-switch converter topologies. However, there are very few reports of their application in converters with multiple switches, as the coordination of multiple switching signals can be difficult, especially if the switching cycle duration varies.

This paper presents a simple implementation of a hybrid pulse width modulation technique in which both the pulse position and the pulse width are modulated in each switching cycle. The theoretical basis of EMI suppression by modulating one or more parameters of $q(t)$ is well understood [8]–[10] and the spectrum of several such PWM techniques, including the hybrid PWM presented here, has been calculated analytically [10].

In the following sections a simple aperiodic carrier generation method is described, followed by its application in coordinated hybrid pulse modulation for EMI suppression in H-bridge based impedance source converters.

TABLE I
CLASSIFICATION OF VARIOUS SPREAD-SPECTRUM MODULATION METHODS

Modulation Style	Scheme	Subclassification	Pulse modulation parameters			Duty ratio (α_K/T_K)	References
			Switching cycle duration (T_K)	Pulse width (α_K)	Pulse position (ε_K)		
Periodic OR Aperiodic (pseudo-random, chaotic, deterministic) OR Random*	PWM	–	Fixed	Variable	Fixed	Variable	Basic
	PPM	–	Fixed	Fixed	Variable	Fixed	[25]
	DRM + PPM + fixed carrier frequency	–	Fixed	Variable	Variable	Variable	This paper, [6]*
	CFM	CFM with fixed duty cycle	Variable	Synchronized	Fixed	Fixed	[6], [7]*
		CFM with varying duty cycle	Variable	Fixed or Variable (not synched)	Fixed	Variable	[6], [7]*
	CFM + PPM + fixed duty ratio	–	Variable	Variable (synched)	Variable	Fixed (synched)	[6]*
CFM + PPM + DRM	–	Variable	Variable	Variable	Variable	[6]*	

PWM = Pulse Width Modulation, PPM = Pulse Position Modulation, DRM = Duty Ratio Modulation, CFM = Carrier Frequency Modulation.

*All the techniques reported in [6] assumed random modulation of the pulse parameters.

III. APERIODIC MODULATION METHOD FOR EMI SUPPRESSION

In this section, an aperiodic modulation method is presented that can be implemented using either analog or digital electronics. First, a method of generating an aperiodically modulated carrier from two periodic input signals is presented. It is then shown how the aperiodically modulated carrier may be used to generate a coordinated set of hybrid pulse modulation signals to drive the H-bridge of switches in a qZS dc–dc converter selected.

A. Aperiodic Sawtooth Carrier Generation

Traditionally, a sawtooth wave with fixed frequency (i.e., a repetitive sequence of identical ramp functions) is used as a carrier signal and precursor to generating a periodic PWM signal, which in turn is used to drive the active device in a switched-mode power converter. In single-switch converter topologies, the switching harmonics may be suppressed by modulating the carrier frequency. However, in more complicated power converter topologies (e.g., impedance source converters) modulating the carrier frequency is not possible, or not convenient. In such cases, it is desirable to generate a sawtooth carrier in which the amplitude and/or duration of each successive ramp function is modulated aperiodically, but the overall switching period is constant.

A method for generating such a waveform is shown schematically in Fig. 3, in which two anharmonically related periodic signals, i.e., a sawtooth and a sinusoid with dc offset, are compared and multiplied to generate a sawtooth carrier in which

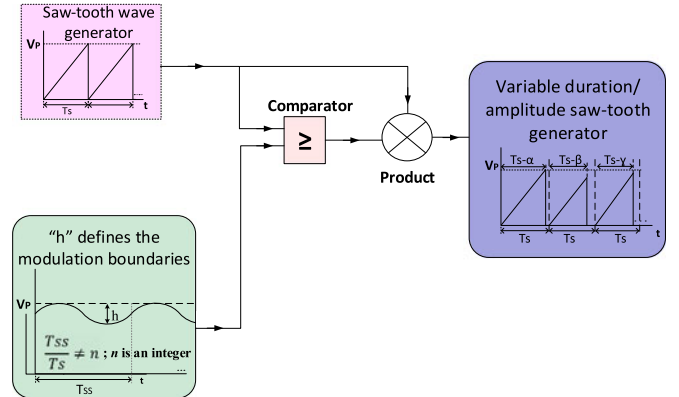


Fig. 3. Schematic showing generation of the aperiodically modulated carrier signal.

each consecutive ramp varies randomly in amplitude and duration whilst the duration of each switching cycle is constant [11]. It will later be shown that by comparing the resulting sawtooth carrier with a fixed level, a periodic sequence of pulses modulated randomly in position and width are generated (i.e., a hybrid of PPM + PWM).

The amount of pulse position and width modulation in the output carrier, and hence spectral spreading, is determined by the peak-to-peak amplitude, h , of the input sinusoid in Fig. 3. (Note: If the input sinusoid and sawtooth carriers are harmonically related in frequency, then the output sawtooth carrier will be modulated periodically at the difference frequency. When

TABLE II
KEY PARAMETERS FOR PERIODIC AND APERIODIC SAWTOOTH

Parameter	Periodic sawtooth	Aperiodic sawtooth
$f_S = 1/T_S$ (carrier frequency)	25 kHz	25 kHz
$f_m = 1/T_{SS}$ (modulation frequency)	NA	9.1 kHz
V_P (Peak value of carrier signal)	1 V	1 V
" h " (peak-peak value of modulation signal)	NA	10% of V_P

NA = Not applicable.

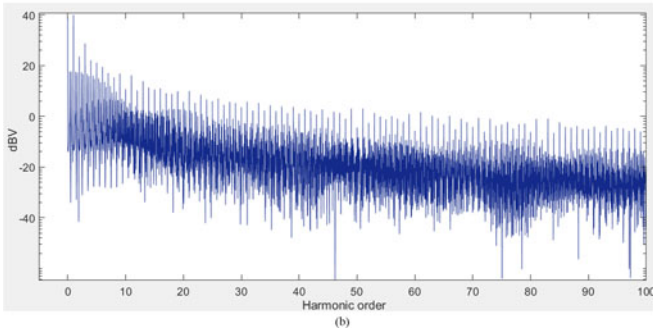
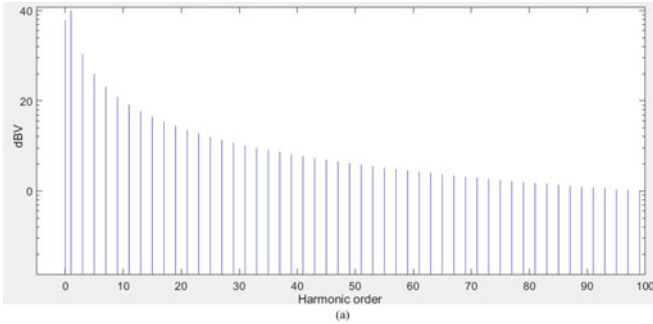


Fig. 4. Frequency spectrum of: (a) simple PWM; (b) aperiodic PWM.

used to produce a PWM signal this will result in less complete spreading of the switching harmonics [19]).

The amount of EMI suppression was modelled numerically in MATLAB simulink by calculating the spectrum of a gate drive signal with $h = 0$ (no spreading) and $h = 10\%$ of the peak sawtooth waveform amplitude. The parameters of the PWM signals modeled are listed in Table II.

The numerical results shown in Fig. 4 demonstrate that the amount of EMI suppression increases with the order of harmonic relative to the fundamental switching frequency, saturating at about 10 dB for frequencies greater than 100th harmonic.

B. Implementation of Aperiodic Pulse Modulation in a Quasi-Z Source DC-DC Converter

The quasi-Z-source converter topology, shown schematically in Fig. 5, has been shown to have many desirable features relative to other converter topologies, including a high voltage gain. Like other impedance-source converters, the qZS converter utilizes a “shoot-through” state, in which either or both legs of the H-bridge are shorted – this state is prohibited in the more traditional voltage source inverter (VSI) topologies. The voltage gain of the qZS dc–dc converter is given by

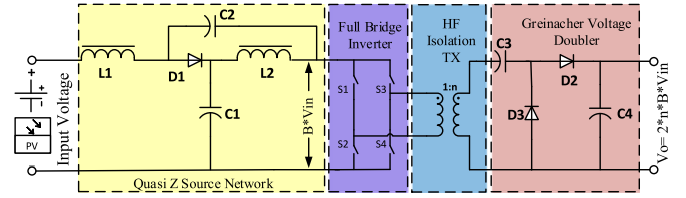


Fig. 5. An isolated quasi-Z-source dc–dc converter [21].

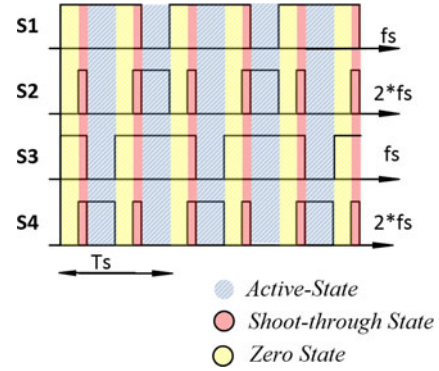


Fig. 6. Reference modulation scheme for a qZS dc–dc converter [21].

$G = 1/(1 - 2D_{ST})$, where D_{ST} is defined as the shoot-through duty cycle, $D_{ST} = T_{ST}/T_S$, T_{ST} is the shoot-through time period, and T_S is the duration of each switching cycle. The two other switch states of the qZS converter are the “active state” (the diagonal switches in the H-bridge are on together), and the “zero state” (both upper or lower switches in the H-bridge are off together). The corresponding duty ratios could then be defined as $D_A = T_A/T_S$ and $D_Z = T_Z/T_S$, respectively, in which T_A and T_Z are the active and zero state durations. It is important to note that in the qZS converter the sum of duty ratios must equal unity, i.e., $D_A + D_Z + D_{ST} = 1$. A general overview of the qZS converter and its design considerations are given in [20].

Numerous switch modulation schemes have been developed for the qZS converter [22]. These modulation schemes are differentiated by the relative positions of the three basic switching states (active, zero, and shoot-through) in one switching cycle. In the following sections, we evaluate the EMI suppression performance of the proposed hybrid aperiodic modulation method against a reference periodic modulation method. The selected reference periodic modulation scheme is shown in Fig. 6, and its generation logic is presented in [21]. The reference modulation method has a number of desirable features, such as

- 1) independent control of the active and shoot-through states;
- 2) a low number of switch commutations per switching cycle;
- 3) only two shoot-through states per switching cycle.

We now show how the aperiodic sawtooth waveform in Fig. 3 can be used to derive an EMI-suppressing modulation scheme for the qZS converter. The principles underlying the design and implementation of the aperiodic modulation method are as follows:

- 1) the duration and position of the active and zero states are varied aperiodically in every switching cycle;

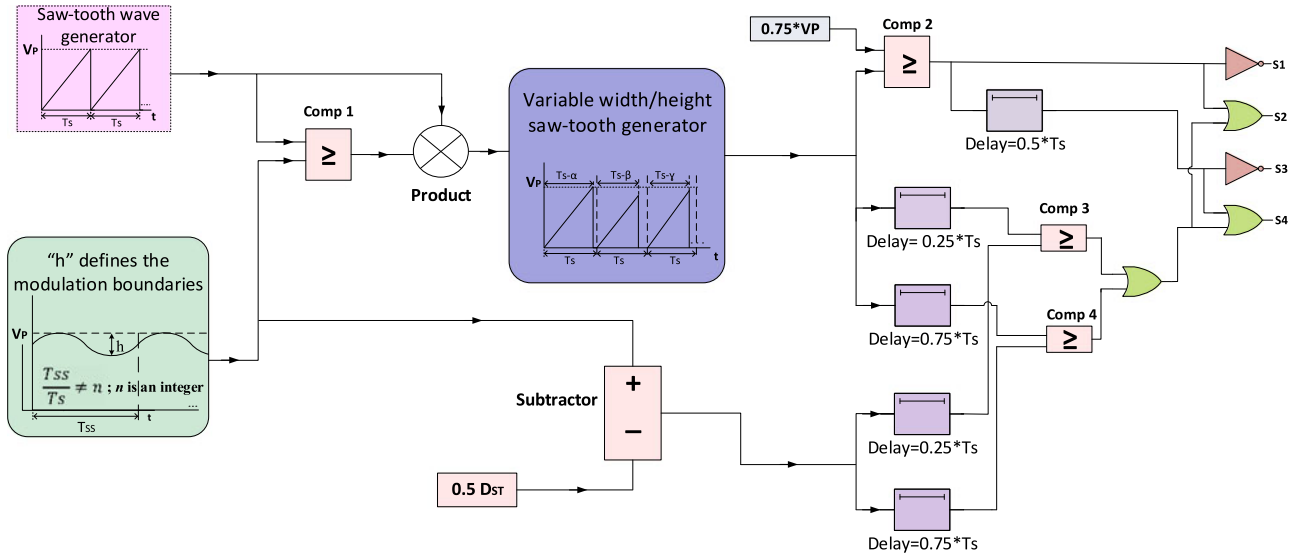


Fig. 7. Logic diagram to implement the aperiodic switching signals.

- 2) the shoot-through state durations must be equal in each switching cycle (i.e., to keep the voltage gain constant);
- 3) the pair of active switching states must be balanced (i.e., equal duration) in each switching cycle to ensure zero net flux in the transformer core.

The logic for generating the hybrid aperiodic pulse modulation signals is shown in Fig. 7. The main difference between the logic shown in Fig. 7 and that used for generation of the periodic reference modulation scheme [21] is that a periodic sawtooth carrier has been replaced by the aperiodically modulated sawtooth carrier, from Fig. 3. The sinusoidal waveform amplitude (h , relative to V_p) is set to produce a few percent modulation in the nominal output pulse positions and widths, thereby preventing the accumulation of energy at harmonics of the fundamental switching frequency, $1/T_s$.

Whilst various aperiodic modulation methods have been used to suppress EMI in single switch and half-bridge based power converters [5], the modulation scheme described here also includes “shoot-through” states, which are fundamental to impedance source converters [23].

The functional block diagram shown in Fig. 7 was programmed in MATLAB-Simulink utilizing blocks from the HDL coder library. The corresponding HDL code was auto-generated and then compiled to run on a Xilinx Spartan 6 FPGA development board, which generated the driving signals for the GaN HEMTs [17]. The resulting aperiodically modulated sawtooth and pulsed switching waveforms are shown schematically in Fig. 8.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A prototype qZS dc–dc converter was adapted and used to test the proposed aperiodic pulse modulation technique by measuring the reduction in EMI relative to the reference modulation scheme. The key design parameters and components used in the experiment are listed in Table III.

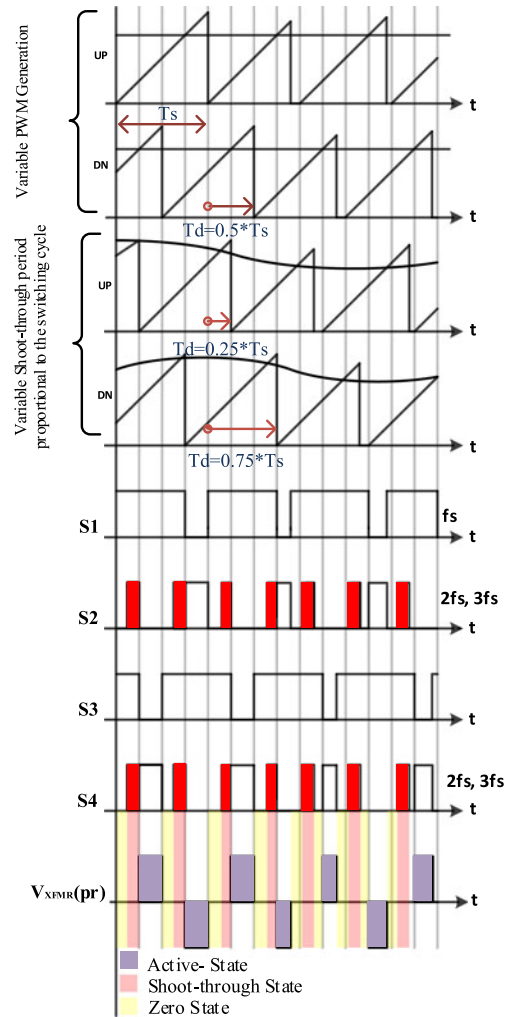


Fig. 8. Switching sequence for an aperiodic modulation scheme for a qZS dc–dc converter.

TABLE III
PARAMETERS AND COMPONENTS FOR PROTOTYPE

Parameter	Value, description
Switching frequency	24 kHz
Turns ratio for transformer	1:1
qZS inductors L1, L2	1.3 mH
Capacitors C1–C4	1000 μ F
Rectifier diode D1–D3	SiC schottky diodes, C3D06060G
Power switches S1–S4	Hybrid GaN HEMTs, TPH3006PS
Shoot-through duty ratio	10%

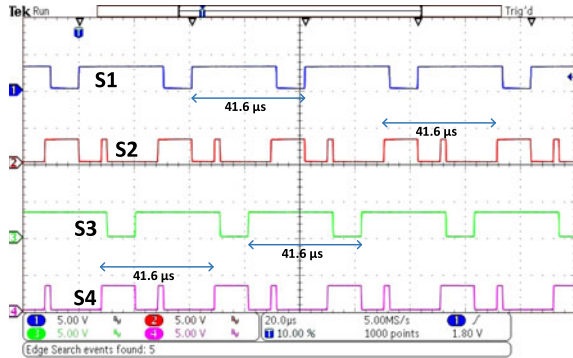


Fig. 9. Switching sequence for the reference modulation scheme.

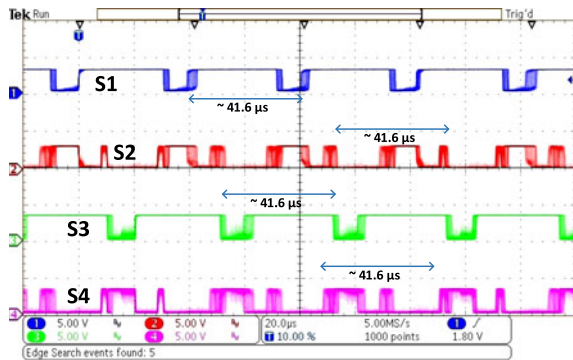


Fig. 10. Switching sequence for the aperiodic modulation scheme.

It should be noted that although GaN HEMTs are usually used at much higher switching frequencies, the experimental results reported here were deliberately obtained using a 24 kHz switching frequency in order to 1) investigate the performance of the qZS network as a low pass filter, and 2) be able to observe a large number of switching harmonics over a broad bandwidth using a standard RF spectrum analyzer.

The measured switch drive signals for the reference and aperiodic modulation schemes are shown in Figs. 9 and 10, respectively. The blurred edges evident in Fig. 10 show the extent of the random variation in the switching pulse timing and duration produced by the aperiodic modulation scheme.

The switching waveforms are also presented in Figs. 11 and 12, in which a wider temporal window is used to more clearly show the cycle-to-cycle variation of the switch modulation. Figs. 11 and 12 show the reference and proposed aperiodic modulation schemes, respectively.

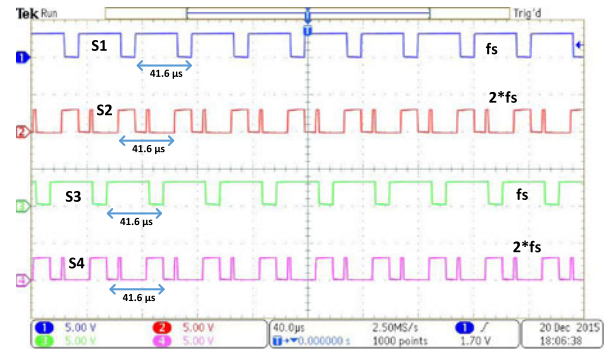


Fig. 11. Switching sequence for the periodic reference modulation scheme.

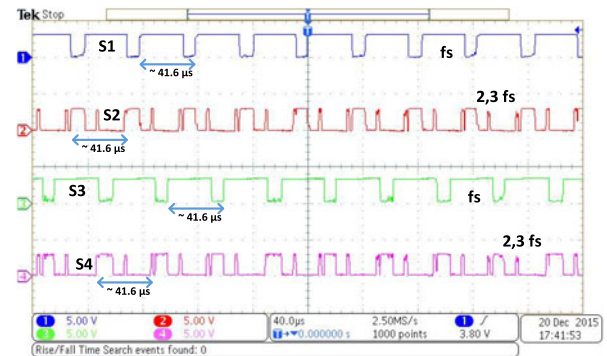


Fig. 12. Switching sequence for the aperiodic modulation scheme.

To measure the conducted EMI the qZS supply voltage was set to 100 volts and a programmable electronic dc load set to 100 watts was connected to the qZS converter output. A line impedance stabilization network (LISN) [24] was inserted between the dc source and the power converter input. The EMI spectra were displayed over a broad bandwidth using a RIGOL DSA815 RF spectrum analyzer, as shown in Figs. 13 and 14.

The EMI spectra measured with the periodic reference modulation are shown in Figs. 13(a) and 14(a). Discrete harmonics of the fundamental switching frequency are clearly evident up to very high frequencies, especially between 1 and 6 MHz, but also up to 30 MHz. Some attenuation of the switching harmonics is evident at low frequencies, especially around 1 MHz, probably due to the low-pass nature of the impedance source network.

The EMI spectra measured under identical conditions as previously, except using the aperiodic modulation method, are shown in Figs. 13(b) and 14(b). Comparisons with Figs. 12(a) and 13(a) show that the harmonics of the fundamental switching frequency were significantly suppressed, i.e., by up to 10 dB at most frequencies, when using the aperiodic modulation method.

The impact of the proposed modulation scheme on efficiency and voltage gain are presented in Figs. 15 and 16, respectively. There was <1% reduction in converter efficiency with the proposed aperiodic modulation method, most likely associated with additional switching transitions of the two lower HEMTs in the H-bridge.

As shown in Fig. 16, there was no observable change in voltage gain with the aperiodic modulation.

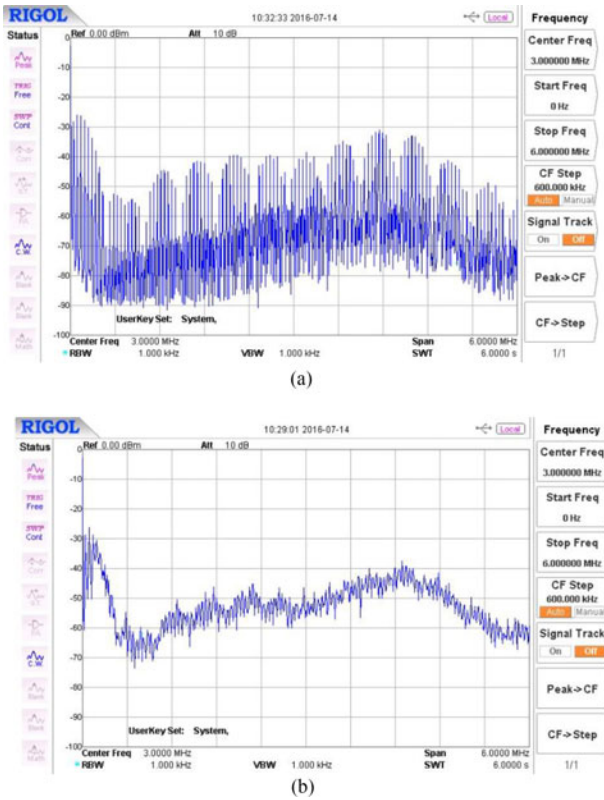


Fig. 13. Spectrum of conducted EMI (0–6 MHz) for (a) periodic reference modulation scheme and (b) proposed aperiodic modulation scheme.

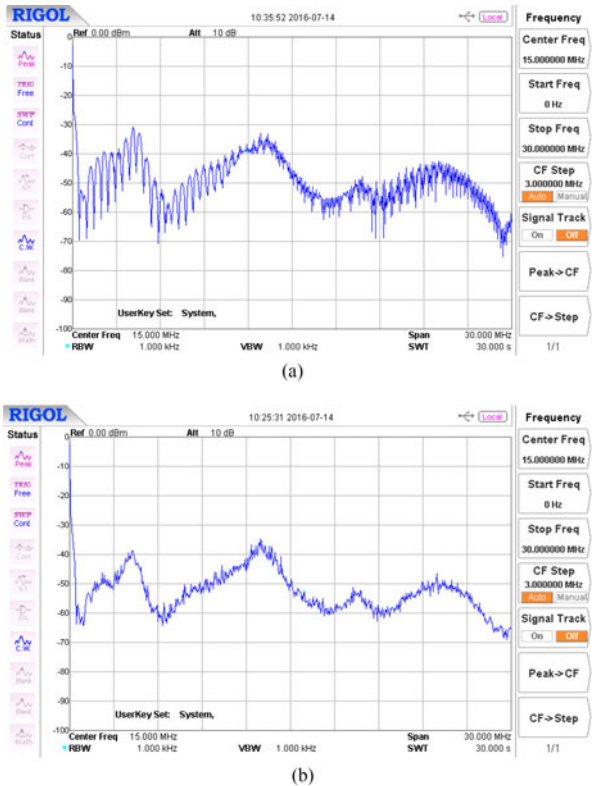


Fig. 14. Spectrum of conducted EMI (0–30 MHz) for (a) periodic reference modulation scheme and (b) proposed aperiodic modulation scheme.

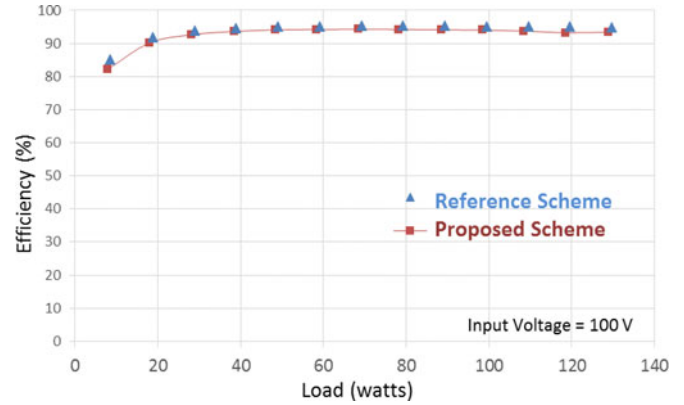


Fig. 15. Efficiency versus load index for the reference and proposed scheme.

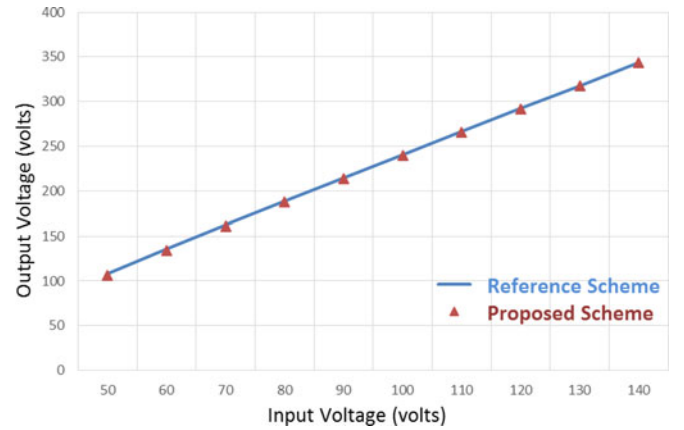


Fig. 16. Voltage gain index for the reference and proposed scheme.

V. CONCLUSION

A simple method for generating aperiodic hybrid pulse modulation to suppress EMI in switched-mode power converters has been described. The method uses two anharmonically related waveforms to produce an aperiodic sawtooth carrier signal, which can subsequently be used to generate one or more coordinated pulses modulated aperiodically in width and position within a constant switching cycle. The modulation technique and EMI suppression were validated experimentally on a quasi-Z-source dc–dc converter with four hybrid-GaN HEMTs driven by an FPGA. Up to 10 dB suppression of the peak conducted EMI in the converter’s supply circuit was measured with negligible impact upon the converter’s voltage gain or efficiency. We believe this is the first report of an aperiodic pulse modulation method for EMI suppression to be implemented in an H-bridge based impedance source converter in which “shoot-through” states must be taken into account. The method for generating the aperiodic hybrid pulse modulation is generic, and is expected to be equally effective with other converter topologies.

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