A Review of Spread-Spectrum-Based PWM Techniques—A Novel Fast Digital Implementation

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***Abstract*—Spread-spectrum (SS)-based pulsewidth modulation (PWM) techniques play an important role when tackling the electromagnetic interference (EMI) problem in the switch-mode power supply (SMPS) domain. They achieve the best EMI noise reduction and emerge as a promising and very effective solution to comply with electromagnetic standards. The current work provides an insight into the SS techniques: its history, its types, and mainly its ability to mitigate the EMI problem in the SMPS domain. Moreover, it gives a short review of the different SS-based PWM techniques going from the most basic and simple, i.e., the periodic modulation, to the most developed and complex, i.e., the random and chaotic modulations. Besides, a short review of the different implementation methods was addressed and they were categorized into analog and digital implementation techniques where its pros and cons were provided. Finally, a new fast digital implementation method based on a dsPIC33F microcontroller is presented. Its effectiveness was proved and its advantages over the reviewed implementation techniques were recognized. It reached a 20 dBuV EMI level reduction when the digital chaotic and periodic profiles were embedded into a boost converter prototype.**

***Index Terms*—Chaotic pulse width modulation (PWM), digital implementation, electromagnetic compatibility (EMC), spread-spectrum (SS) techniques.**

I. INTRODUCTION

NOWADAYS, much electrical energy is consumed through switch-mode power supplies (SMPSs), which allow adjusting the energy to the desired form. SMPSs, ranging from milliwatt applications to hundreds of megawatts, are widely used in various sectors: renewable energy, military applications, industrial uses, and even in-house equipment. Behind this popularity stand many prominent features, namely, high efficiency, low cost, the capability to work at different levels of currents and voltages, as well as easy control strategies.

However, these power converters are sites of a high level of current surges and voltage slew rates. Combined with the increased value of switching frequency, it generates high-frequency electromagnetic interferences (EMI). These are harmful defects that may cause operating faults in the converter as well as within adjacent sensitive equipment. With a crowded electromagnetic (EM) spectrum, SMPSs are considered as the main factor in the EM environment deterioration. Consequently, meeting the electromagnetic compatibility (EMC) standards (e.g., CISPR22) rises up as a serious challenge for SMPSs designers [1].

Recognizing the need for EMC compliance, designers should provide converters not only to accomplish the required electrical functions but also to achieve the lowest harmonic spectrum. Indeed, the increasing awareness of EM problems within SMPS spurred on researchers to mitigate them [2]–[4]. Mainali and Oruganti [4] elaborated two major classes of strategies in order to reduce the undesired harmonic of the EM noise-spectrum (see Fig. 1). One class of strategies was to reduce the EMI levels generated along the propagation path after the conception of the converter via EMI filters. The other class of strategies regroups methods that mitigate the EMI problem at an earlier stage of design. It intends to lower the EMI levels at the source of the EMI itself. This class can be further subdivided into three main groups: 1) circuit design, layout, and component selection, 2) soft switching techniques, and 3) switch control schemes. However, we are only interested in studying the switch control schemes as they provide the most flexible and practical approach to solving the EMI problem.

This paper aims to review the different control schemes based on pulsewidth modulation (PWM) techniques. Also known as spread-spectrum (SS) techniques, PWM techniques spread the EMI spectrum well and lower its unwanted harmonics leading to EM standards compliance.

The present paper starts with SS definition, types, and role in lowering the EMI noise level (see Section II). In Section III, an overview of SS-based PWM modulation techniques is presented. We detail an implementation review with a short discussion of the different implementation methods in Section IV. A new implementation technique is proposed in Section V. Finally, Section VI presents the work summary and conclusions.

II. SPREAD SPECTRUM: BACKGROUND, DEFINITION, AND TYPES

A. Short Background

The SS concept saw the light in 1942. By creating a system using 88 different frequencies in a piano that allow to transmit and receive the different frequencies with no interruption or interference between the various frequencies being transmitted and received, the musician George Antheil and the silver screen actress Hedy Lamarr published the first work on SS.

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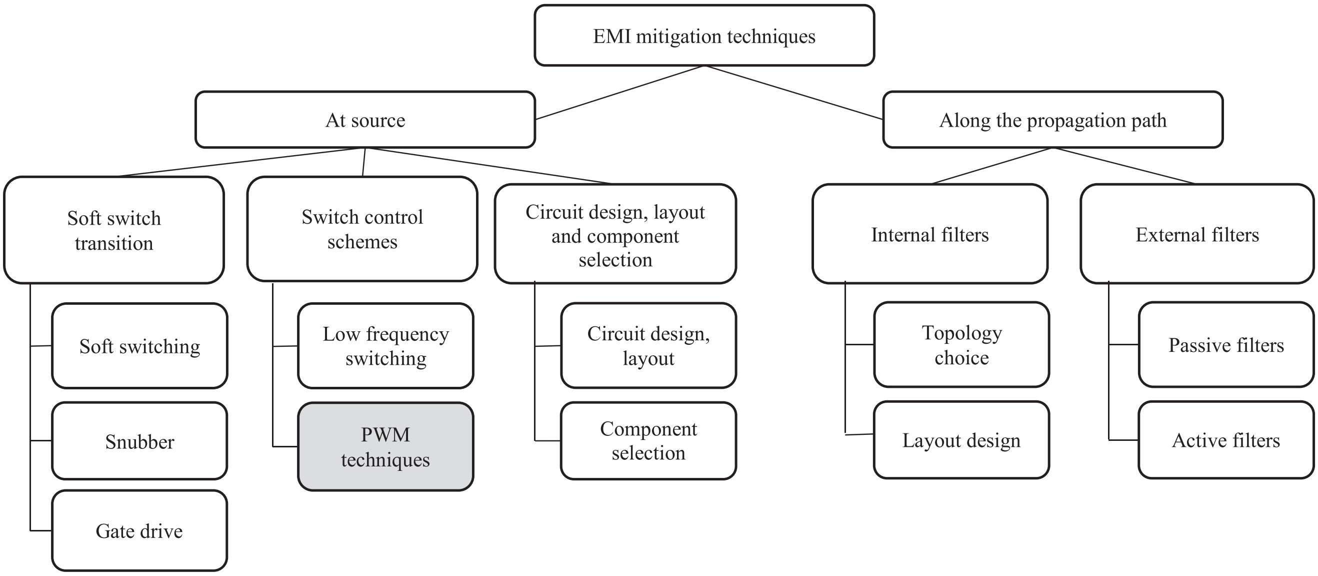


Fig. 1. Classification of EMI mitigation techniques.

Their patent "secret communication system" was the first step in the conceptualization of SS systems.

By the end of World War II, SS signal processing techniques had attracted growing interest [5]. The SS theory had been developed and its ability to provide secure communication had been recognized. SS was a communication method with excellence. Its applications ranged from military antijamming tactical communications to multiple access communication. The number of its applications was increasing from one day to another as they pair or outclass the performances of the existing applications.

However, it had taken five decades before the first implementation of the SS technique in the field of SMPS was introduced. Clarke *et al*. were the first to fruitfully apply the SS technique in the domain of SMPS. In 1969, they published a patent entitled "Switching Regulator With Random Noise Generator" [6] in which they patented the introduction of random noise into the feedback loop of a regulator-converter circuit and succeeded to modulate the switching frequency in a manner that reduced the EMI noise to better than acceptable levels.

In 1970, Clarke applied this method to a self-commutated dc–dc converter and eliminated single-frequency tones from the acoustical spectrum of the converter. The work was entitled "Self-Commutated Thyristor DC-to-DC Converter."

Unfortunately, these works were incapable of drawing attention to the great interest of integrating the SS technique into the SMPS domain. In fact, their integration in the SMPS domain had to wait until 1987 when Trzynaldlowski *et al.* published their work entitled "Random Pulsewidth Modulation Technique for Voltage-Controlled Power Inverters." Two years later Tanaka *et al*. used a random SS scheme to reduce the EMI problem in SMPS. In 1990, Trzynaldlowski *et al.* published their work on a random modulation technique in the case of inverters and Wang and Sander published another work on a random and programmed PWM signal in the case of a dc–dc power converter. Those works were the turning point in the SS technique and SMPS history. Since then, the SS technique has seen a growing interest and has become fruitfully applied to SMPS when tackling the EMI problem.

B. Definition of Spread Spectrum

The SS technique is basically used for transmitting radio or telecommunications signals. The term refers to the practice of spreading the transmitted signal so that it occupies the frequency spectrum available for transmission.

Under this concept, a definition of SS was "*Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery*" [7].

However, in the case of SMPS, this definition is restricted to the fundamental concept of SS. In other words, an SS system is a system that injects a spread code, i.e., the modulating signal, to frequency modulate the PWM signal that controls the SMPS unit. Thus, the fundamental and each harmonic are swept according to the modulating signal. Each single harmonic changes into a number of side-band harmonics with smaller amplitude. The frequency spectrum changes from a train of large spikes concentrated at the switching frequency and its harmonics to a smoother, lower, and more continuous spectrum [8]–[10]. To summarize, using an SS technique in SMPS is a frequency modulation of the control signal, i.e., the PWM signal, in the time domain. The resulting signal has an amount of energy spread in the frequency domain with reduced peak amplitudes.

C. Types of Spread Spectrum

The SS technique may be classified into five different types [11]–[13].

1) *The direct sequence systems*: This type is one of the most used SS systems. The narrow-band carrier is modulated

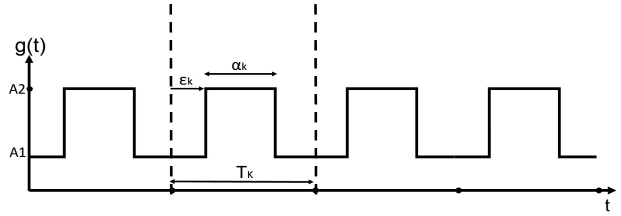


Fig. 2. Gating pulses controlling the SMPS unit.

by a code sequence that is generated by a pseudo-random generator with a fixed length. The narrow-band carrier phase of the transmitted signal is abruptly changed in accordance with that code sequence.

2) *The frequency hopping systems:* For these systems, the carrier frequency of the transmitter abruptly varies in accordance with a pseudo-random code sequence, which dictates the order of the frequencies selected by the transmitter.
3) *The time hopping systems*: This SS system has the period and duty cycle of the pulsed radio frequency (RF) carrier varied in a pseudo-random manner under the control of the code sequence.
4) *The pulsed FM systems*: Under this type, the RF carrier is modulated with a fixed period and a fixed duty cycle sequence. At the beginning of each transmitted pulse, the carrier frequency is frequency modulated causing a further spreading of the carrier.
5) *The hybrid systems:* These systems use a combination of the SS methods in order to use the beneficial proprieties of the systems used. A common combination is the direct sequence method and the frequency hopping method. The advantage of this combination is to capitalize on the characteristics that are not available from one single method.

From all the aforementioned types of SS techniques, frequency hopping is the most used in the SMPS domain. In fact, this type can tailor the frequency range and the hopping sequence in order to maximize the spectral efficiency using the spread-code and the desired statistical proprieties.

D. Spread Spectrum and EMI Reduction in SMPS

In general, complying with EM standards is a serious problem in SMPS, not because of excessive total spectral energy, but due to the concentrated energy in a narrow band frequency in the fundamental switching frequency and its multiples. Applying the SS techniques involves a frequency modulation of the gating pulses controlling the SMPS unit [14]–[16]. To usefully introduce them, the switching signal is modulated by varying one or more of its parameters; the switching frequency F_k, the pulsewidth α_k, or the pulse position ε_k (see Fig. 2).

The frequency spectrum changes from a train of large spikes concentrated at the switching frequency and its harmonics to a smoother and more continuous spectrum. The fundamental and each harmonic is swept by the modulation signal, which will produce an infinite number of sidebands with reduced amplitudes. Thus, it lowers the unwanted EMI levels (see Fig. 3) and satisfies the EMI standards.

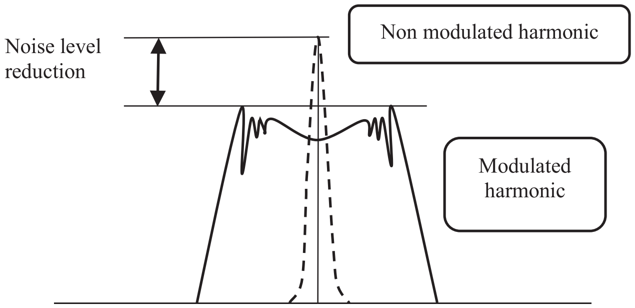


Fig. 3. Spread spectrum effect.

III. SPREAD SPECTRUM SCHEMES

To date, researchers have produced a huge number of research papers dealing with the EMI problem in SMPS. They used different modulation schemes of the PWM to comply with the EM standards. Fig. 4 shows a summary of these modulation schemes and the following section will provide a short review of them.

A. Programmed PWM

This technique is the oldest and the most basic SS method. It was the first step toward the harmonic control of the SMPS spectrum. Since its introduction, the programmed PWM has drawn tremendous research interest and has been integrated into various applications [17]–[24]. Its concept is based on the decomposition of the PWM signal, which depends on the formulation of the given waveform and its statistical properties. It aims to nullify a set of harmonic components or to minimize a weighted square sum of a set of harmonic magnitudes. Thus, the energy from the fundamental frequency can be spread among the subharmonics to reduce the spectral energy peaks. It is also known as a selective harmonic elimination method and it regroups two classes of methods: the harmonic elimination methods and the harmonic minimization and optimization methods. A further detailed review of the different waveform formulations has been considered and analyzed in [21] based on varied technical literature. This method is very attractive when tackling the EMI problem in a wide range of low switching frequency applications. However, it is a tough task when dealing with a large number of harmonics to get rid of and the required switching signal cannot be generated accurately. Thus, more sophisticated PWM techniques need to be used.

B. Random PWM

This section addresses a short review of random PWM and its applications to SMPS [25]–[48]. The random pulsewidth is the most prominent method to modulate the switching signal. It is the “cornerstone” of the modulated PWM control signal. The fundamental idea behind random PWM is to vary in a randomized manner one or more of the gating signal parameters

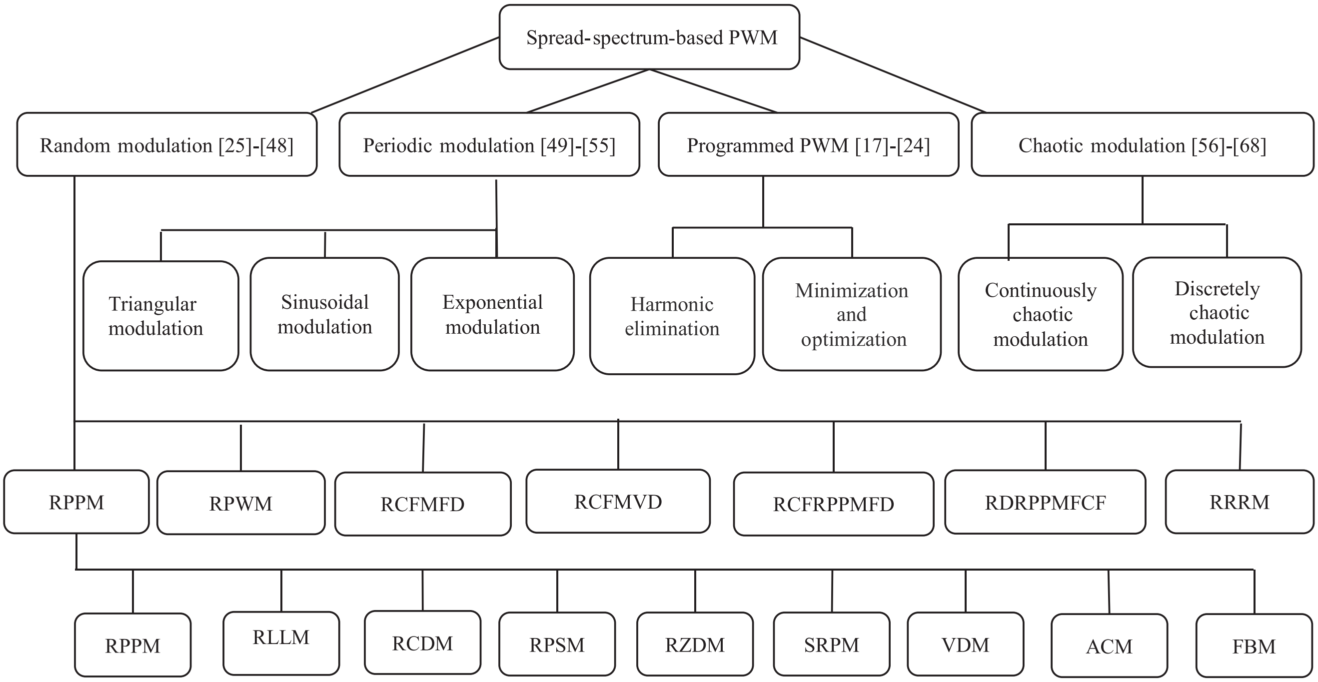


Fig. 4. Spread-spectrum-based PWM techniques.

TABLE I
SUMMARY OF THE POSSIBILITIES OF SWITCHING SIGNAL PARAMETERS

Scheme	T_k	α_k	ε_k	$d_k = \alpha_k / T_k$
PWM	Constant	Constant	Constant	Constant
RPPM	Constant	Constant	Random	Constant
RPWM	Constant	Random	Constant	Random
RCFMFD	Random	Random	Constant	Constant
RCFMVD	Random	Random	Constant	Random
RCFRPPMFD	Random	Random	Random	Constant
RDRPPMFCF	Constant	Random	Random	Random
RRRM	Random	Random	Random	Random

(see Fig. 2). Table I shows which parameter to be randomized under each of the different random modulation schemes.

1) Randomized pulse position modulation (RPPM),
2) Randomized pulsewidth modulation (RPWM),
3) Randomized carrier frequency modulation with fixed duty ratio (RCFMFD),
4) Randomized carrier frequency modulation with variable duty ratio (RCFMVD),
5) Randomized duty ratio and an RPPM with fixed carrier frequency (RDRPPMFCF),
6) Randomized carrier frequency and an RPPM with fixed duty ratio (RCFRPPMFD), and
7) Randomized carrier frequency and a randomized duty ratio, with RPPM (RRRM).

A further subdivision of the random pulse position is given in what follows with a brief description of each scheme.

1) Random Pulse Position Modulation (RPPM): As the average output voltage over an interval is independent of the pulse position, the time intervals of zero states are controlled randomly within a switching cycle. The general case, independent random parameters $\delta 0$, $\delta 1$, and $\delta 2$ are adopted [25]–[27], [48].

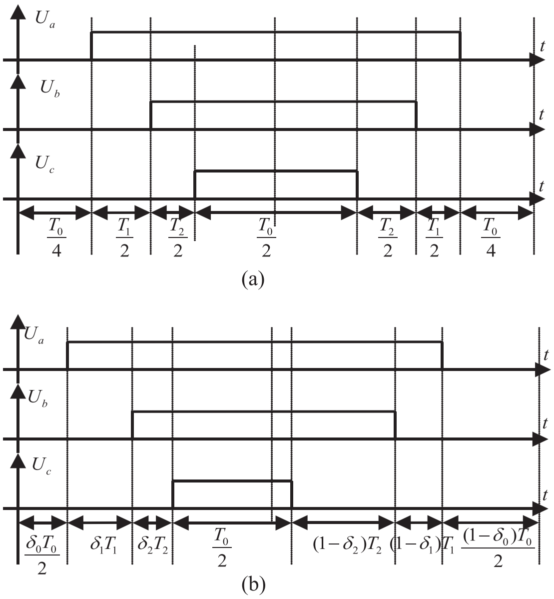


Fig. 5. (a) Standard SVPWM. (b) RPP pulse signal.

The duty ratio of each pulse is calculated as in the standard space vector modulation (SVM), then the pulse position is determined according to the random parameters $\delta 0$, $\delta 1$, and $\delta 2$ [41] (see Fig. 5).

2) Random Lead-Lag Modulation: The pulse position is either generated at the beginning of the switching interval, known as leading-edge modulation, or at its trailing edge, named lagging-edge modulation. A random number generator controls the choice between leading and lagging edge modulation [37] (see Fig. 6).

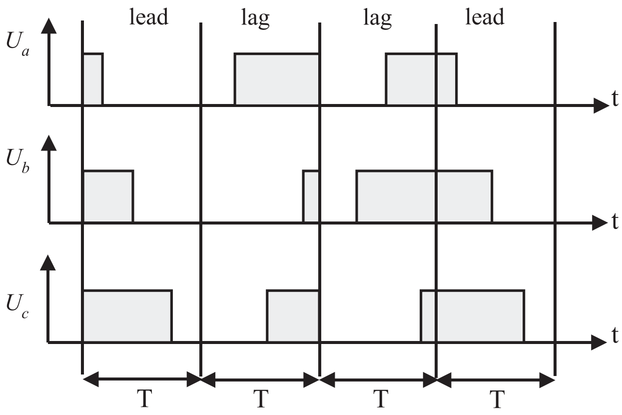


Fig. 6. RLL pulse signal.

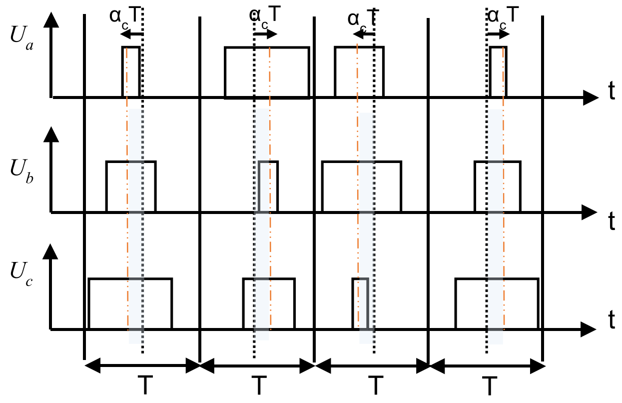


Fig. 7. RCD pulse signal.

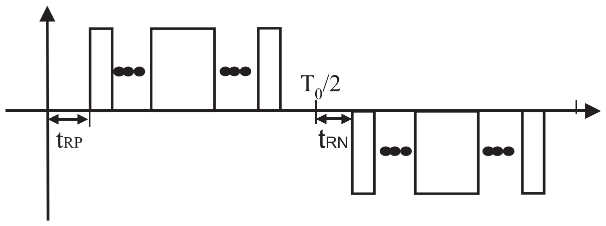


Fig. 8. RPS pulse signal.

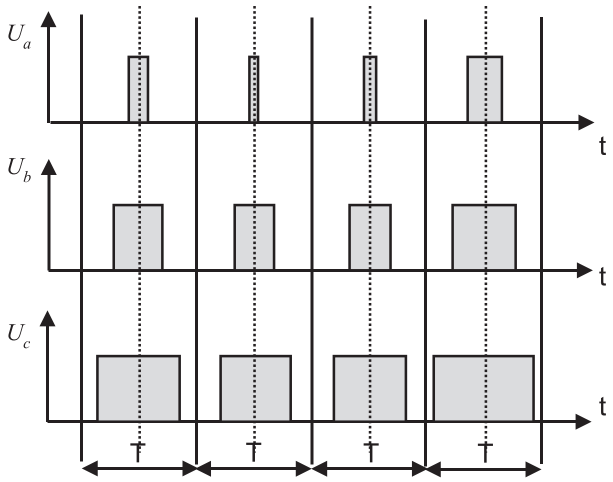
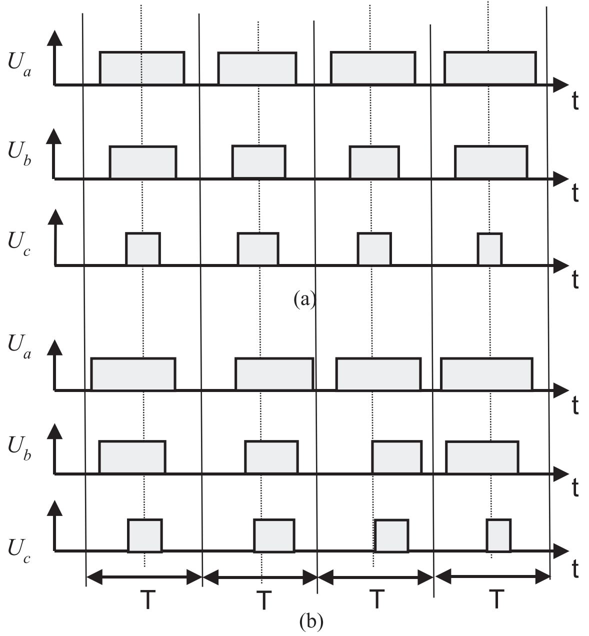


Fig. 9. RZD pulse signal.



(a)

(b)

Fig. 10. Switching patterns. (a) Symmetrical SVPWM. (b) SRP-PWM.

3) Random Displacement of the Pulse Centre Modulation: Fig. 7 shows an RCD pulse signal. Before the modification, the pulses are mutually center-aligned. However, after the use of the RCD modulation, the common pulse center is shifted by the amount $\alpha_c T$ from the middle of the period. The parameter $\alpha_c T$ is randomized within a band-limited by the maximum duty cycle [25]–[27].

4) Random Phase Shift Modulation: In this method, the phase shift is randomized keeping the switching frequency constant. To do so, t_{RP} is the random phase shift time in the positive half-cycle, and t_{RN} is the random phase shift time for the negative half-cycle. At each half-cycle, both t_{RP} and t_{RN} are altered randomly (see Fig. 8) [27].

5) Random Distribution of the Zero-Voltage Vector Modulation: As the duration of the zero voltage vector does not alter the phase voltage, the proportion between the time durations for the two zero-vector states 111 and 000 is randomized in a switching cycle (see Fig. 9) [25]–[27].

6) Separately Randomized Pulse Position Modulation (SRPM): This method is used to randomize the pulse position. Unlike the symmetrical space vector PWM (SVPWM) with a fixed switching frequency in which the pulses are placed in the center of the switching interval, the SRP-PWM places the pulses in a random position in each modulation interval (see Fig. 10) [27].

7) Variable Delay Modulation (VDM): In this method, a random delay is added at the trailing edge of the next PWM output cycle. Fig. 11 shows the block diagram to generate the variable delay for the VD-PWM pulse signal [27], [37].

8) Asymmetric Carrier Modulation: This modulation technique generates the voltage vector with a different frequency in the rising time and in the falling time period. The new voltage

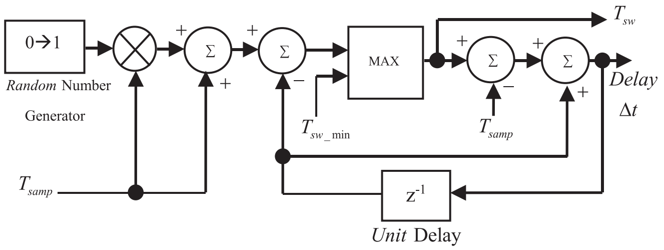


Fig. 11. Block diagram generating the variable delay for the VD-PWM.

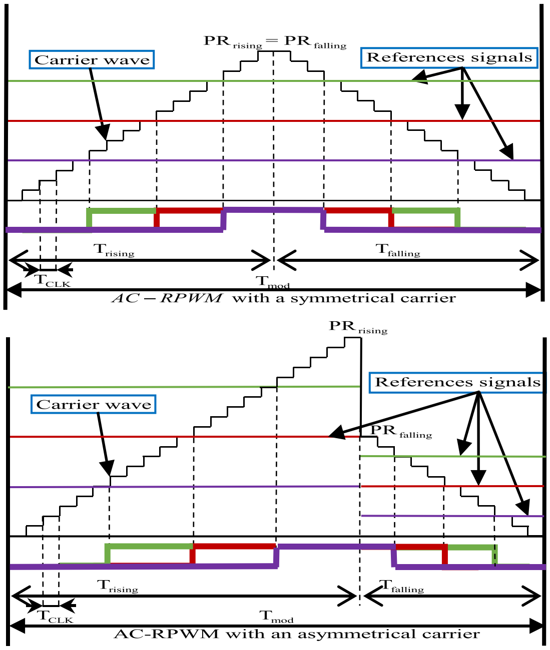


Fig. 12. Switching patterns asymmetric carrier random PWM (AC-RPWM).

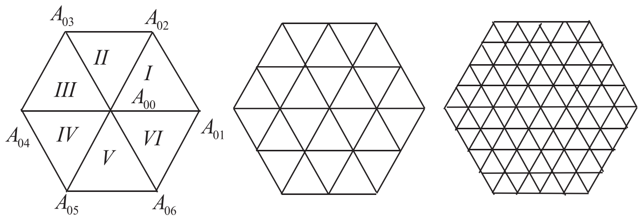


Fig. 13. 2-Level, 3-level, and 5-level SVPWM.

vector is updated with a constant frequency. The time length for the falling edge, as well as the rising edge for every modulation period, is varied randomly (see Fig. 12) [27], [32].

9) Fractal-Based Modulation: Fractals are a geometric shape that can be split into parts, each of which is a reduced-size copy of the whole (see Fig. 13). The fractal-based scheme is used in the case of the multilevel inverter. It uses the technique of triangularization to identify the sector that contains the tip of the instantaneous reference vector to implement the SVPWM [27], [36].

C. Periodic PWM

Periodic modulation of the switching gates is the simplest frequency modulation scheme among the SS-based PWM modulation techniques [49]–[55]. It modulates the frequency of the gate signal. Three main modulation profiles: the sinusoidal, the triangular, and the exponential have been used. The main idea behind these modulations schemes is to spread each individual harmonic into a preset frequency band leading to reduced peak amplitudes and lower EMI levels (see Fig. 14).

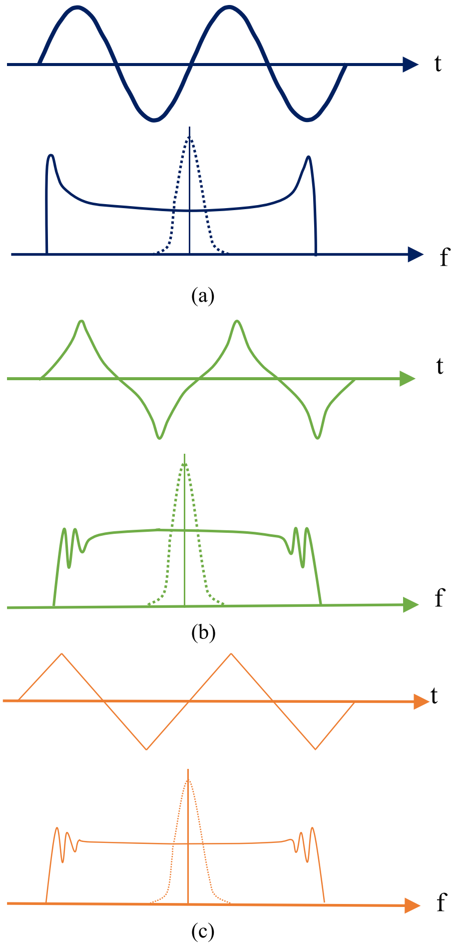


Fig. 14. Output spectra achieved by (a) sinusoidal, (b) exponential, and (c) triangular modulation profile.

The general analytical expression of a sine wave following one of the aforementioned modulation profile is

$$S(t) = A \cdot \cos\left[2\pi f_c \cdot t + \theta(t)\right] \tag{1}$$

where A is the amplitude of the original nonmodulated signal, f_c is the carrier frequency of the nonmodulated signal, and $\theta(t)$ is a time-dependent phase angle as follows:

$$\theta(t) = \int_0^t k_w \cdot m(t) \cdot dt \tag{2}$$

where k_w is a factor to control the peak of frequency-deviation and $m(t)$ is a periodic modulating profile function characterized by unitary amplitude and the modulating frequency f_m.

The mathematical expression of each modulation profile is given in what follows:

1) sinusoidal profile:

$$m(t) = M_m \sin(2\pi f_m t). \tag{3}$$

2) triangular profile [53]:

$$\begin{cases} 0 \leq t < k_s \cdot \frac{T_m}{2}, & m(t) = M_m \cdot f_m \cdot \frac{2}{k_s} \cdot t \\ k_s \frac{T_m}{2} \leq t < \left(1 - \frac{k_s}{2}\right) T_m, & m(t) = \frac{M_m}{(1-k_s)} \cdot (1 - 2 f_m t) \\ \left(1 - \frac{k_s}{2}\right) T_m \leq t < T_m, & m(t) = M_m \cdot \frac{2}{k_s} \cdot (f_m t - 1) \end{cases} \tag{4}$$

where k_s is a symmetry index that ranges from 0 to 1. If $k_s = 0.5$, then the triangular profile has a symmetrical triangular pattern.

3) exponential profile (Hershey–Kiss profile) [53]:

$$\begin{cases} 0 \leq t < \frac{T_m}{4}, & m(t) = \frac{M_m}{\left(e^{\frac{p}{4 \cdot f_m}} - 1\right)} \cdot \left(e^{p \cdot t} - 1\right) \\ \frac{T_m}{4} \leq t < \frac{T_m}{2}, & m(t) = \frac{M_m}{\left(e^{\frac{p}{4 \cdot f_m}} - 1\right)} \cdot \left(e^{\frac{p}{2 \cdot f_m}} \cdot e^{-p \cdot t} - 1\right) \\ \frac{T_m}{2} \leq t < \frac{3T_m}{4}, & m(t) = \frac{M_m}{\left(e^{\frac{p}{4 \cdot f_m}} - 1\right)} \cdot \left(1 - e^{\frac{-p}{2 \cdot f_m}} \cdot e^{p \cdot t}\right) \\ \frac{3T_m}{4} \leq t < T_m, & m(t) = \frac{M_m}{\left(e^{\frac{p}{4 \cdot f_m}} - 1\right)} \cdot \left(1 - e^{\frac{p}{f_m}} \cdot e^{-p \cdot t}\right) \end{cases} \tag{5}$$

where p is a concavity coefficient.

The sinusoidal modulation is much simpler to implement and analyze. However, it does not give the best spectrum shape and the harmonic attenuation is not optimum. On the other hand, the exponential modulation is too complex to implement and analyze but has the flattest spectrum and achieves a better EMI reduction. A good compromise between the above-mentioned modulation profiles is the triangular modulation. One important advantage when using a periodic PWM technique is that it introduces lower unwanted low-frequency harmonics at the output compared with the other modulation schemes.

D. *Chaotic PWM*

Chaos theory is a field of study in mathematics, which has received much attention in diverse disciplines: physics, communication, economics, and engineering. It is known that chaos often occurs in power converters. It has noise-like characteristics and can exhibit erratic and irregular behavior. Moreover, chaotic signals are typical pseudorandom signals that are deterministic, aperiodic, and very sensitive to initial conditions. Thus, most designers prefer that it does not manifest in their designs. In 1984, Brockett and Wood have studied nonlinear dynamics of dc–dc converters. Since then, chaos and nonlinear phenomena in power converters have attracted the attention of researchers and the modulation techniques have seen a revolutionary change [56]–[68]. Chaos modulation techniques have seen the light and they were of two kinds: one is to modulate circuitry parameters of the converter and is known as chaotic peak current mode control [58]. This method is out of the main focus of the current work. The other one is to modify the traditional PWM control technique in a chaotic way known as the chaotic PWM [58], [59]. To make the switching frequency chaotic, two strategies of modulation are to be distinguished [56].

1) Continuously Chaotic Modulation: In the continuously chaotic modulation strategy, a sawtooth carrier wave is compared with a constant value known as the reference value (see Fig. 15). The frequency of the sawtooth follows a chaotic series $\{x_i\}$ in such a way that

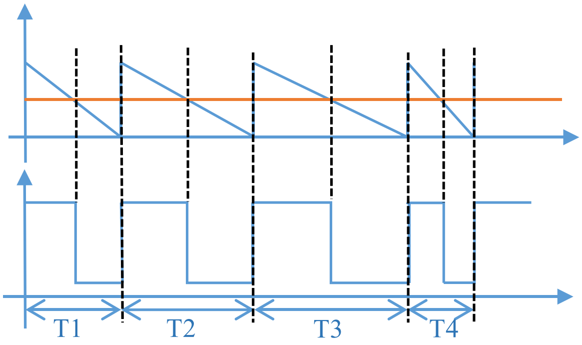


Fig. 15. Principle of the continuously chaotic modulation strategy.

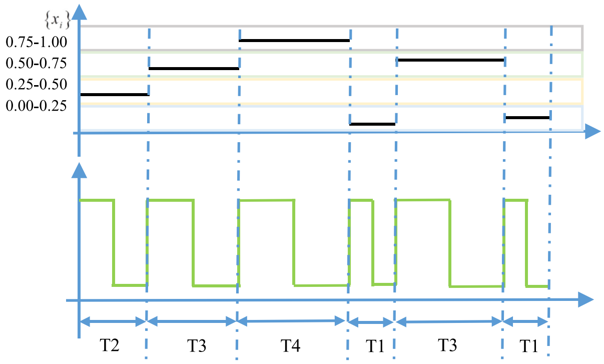


Fig. 16. Principle of the discretely chaotic modulation strategy.

$$f = f_c + (2x_i - 1) \times \Delta f \tag{6}$$

where f_c is the central switching frequency, Δf is the changing range of the switching frequencies, and x_i is the chaotic series, which is distributed evenly in $[0, 1]$.

2) Discretely Chaotic Modulation: Unlike the continuously chaotic modulation strategy, where the switching frequencies are of infinite values, a finite number of switching frequencies characterize the discretely chaotic modulation strategy. If the chaotic series value is located in one of N predefined domains within $[0, 1]$, then there are N different switching frequencies. For example, if the chaotic series $\{x_i\}$ is located within the domains of $[0, 0.25)$, $[0.25, 0.5)$, $[0.5, 0.75)$, and $[0.75, 1)$, then there are four switching frequency values f_1, f_2, f_3, and f_4 that are adopted, respectively (see Fig. 16).

IV. IMPLEMENTATION TECHNIQUE OF THE SPREAD SPECTRUM SCHEMES

The implementation techniques of the SS-based PWM schemes depend strongly on the converter topology, the main function of the converter and the hardware used for the pulse generation and its modulation profile. Thus, it is impossible to give detailed guidelines on how to implement a universal PWM generator that satisfies all converters needs [69]–[71]. However, we may classify the different implementation procedures into a logical implementation procedure and digital implementation procedure.

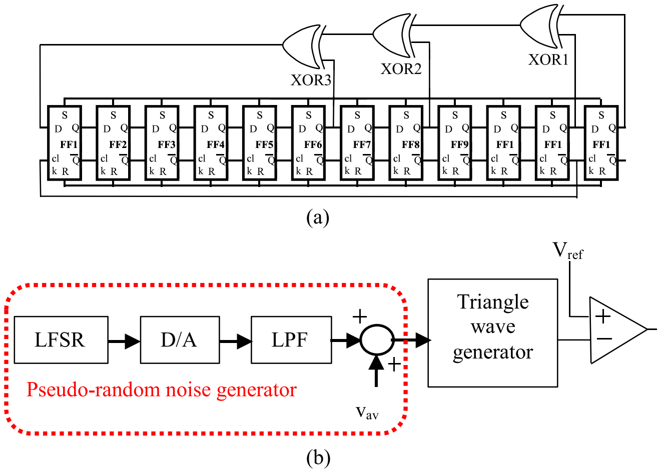


Fig. 17. LFSR-based analog implementation. (a) 12-bit linear feedback shift register. (b) The implementation method.

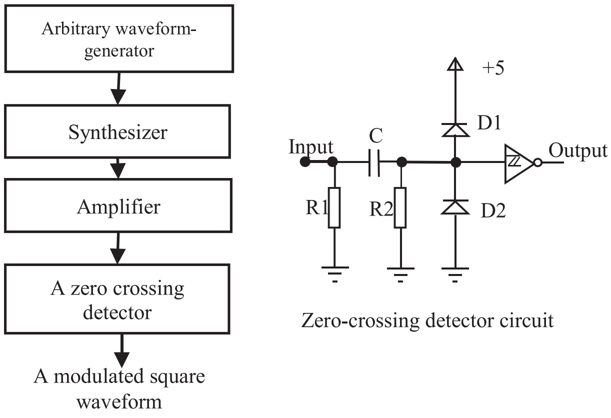


Fig. 18. SSCG-analog implementation using a zero-crossing detector.

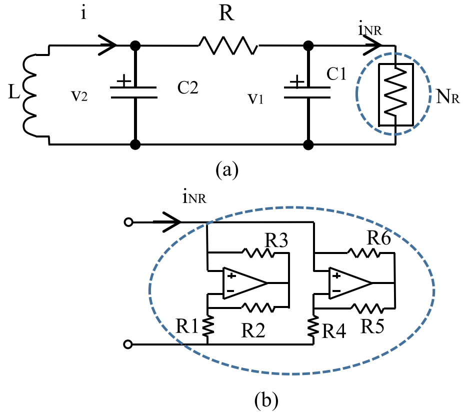


Fig. 19. Chua's circuit based analog implementation. (a) Chua's circuit. (b) Nonlinear resistor.

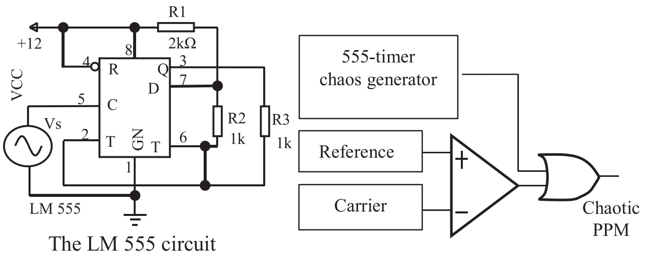


Fig. 20. Chaotic pulse position modulation based on LM 555-timer.

A. Logical Implementation

1) Popular Analog Control Circuits: Analog or logical control is widely used in SMPS circuits [72]–[82]. In fact, analog implementation is much easier to apply to power converters. It is based on analog and logical electronic circuits like resistors, capacitors, bascules, comparators, and linear feedback shift registers (LFSRs). A simple and basic block diagram of an analog approach to implement a modulated PWM signal is shown in Fig. 17. The general idea of this implementation is to generate a pseudo-random noise signal to modulate the sawtooth signal frequency and then to compare the resulting signal to a reference signal [82]. The most popular pseudo-random noise generator is the LFSR. It has some advantageous properties such as easy implementation, good probability, and correlation. The analog pseudo-random noise signal is obtained by low-pass filtering of the output bit pattern of the shift register via a digital-to-analog converter. Then, it is added to the average control voltage. It generates the triangle wave with random switching frequency using a voltage-controlled oscillator. Finally, the random PWM is generated by comparing the triangle wave with the reference signals.

One analog implementation circuit, referred to as SS clock generation (SSCG), is shown in Fig. 18. An arbitrary waveform generator produces the modulating signal, which is fed to a frequency synthesizer to provide a frequency modulated sine wave. Then, the modulated sine wave passes through a zero-crossing detector after being amplified to generate a 5-volt square signal [81]. Another very popular analog experimental circuit is Chua's circuit [80] (see Fig. 19), a kind of chaotic oscillator, which is used to generate a chaotic PWM. It is widely used due to its simplicity and maturity [76]. However, there are other chaotic PWM analog implementations [74]. For example, the generation of an analog chaotic PWM may be accomplished using a simple LM 555 Timer and an OR gate. It was used to accomplish a chaotic pulse position modulation of the conventional PWM signal (see Fig. 20).

2) Drawbacks of Analog Implementation: Analog circuitry has been excessively used in the control of SMPS due to its simplicity and low implementation cost. However, it cannot meet the requirement of today's circuit and command strategies. Unfortunately, the analog implementation has several disadvantages, such as low flexibility, low reliability, sensitivity to the environmental influence, aging, and difficulty to get the accurate control algorithms with the required high performance. Thus, digital control becomes more and more attractive and emerges as a better solution in the area of digital control of switching power supplies. It represents a better alternative that can meet the desired and more and more stringent requirements of today's and future SMPS.

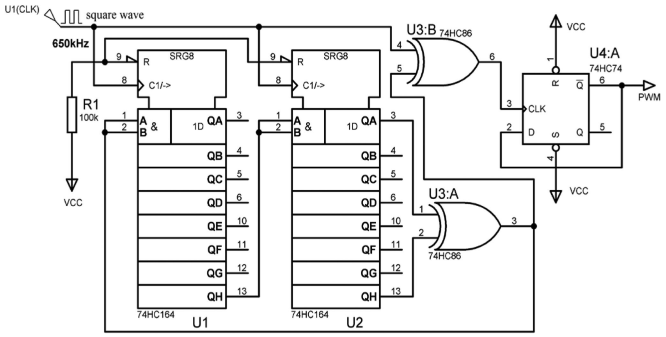


Fig. 21. Linear congruential generator.

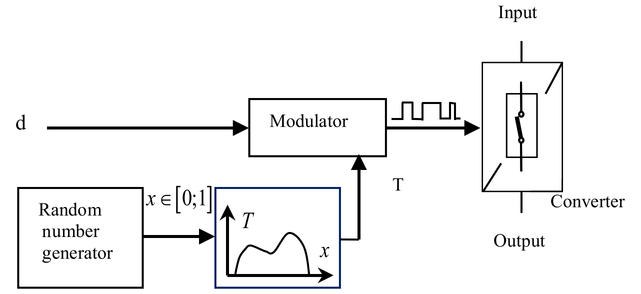


Fig. 22. Digital random PWM based on a linear congruential generator.

B. Digital implementation

1) Advantages of Digital Implementation: There have been many developments in the field of integrated circuits (IC), which led to integrate the power stage as well as the analog stage along with the digital blocks on a single tiny chip. This development in the IC enabled many researchers to excel in the field of power electronics and led to a growing potential of digital circuits use [83]–[100]. Although digital implementation is costlier than analog, it is more efficient in terms of quality and performance. First, fewer components are used leading to optimized not only space but also weight. Thus, the digital control system becomes less susceptible to environmental variations and offers more reliability improvements and EMI reduction. Besides, the digital control systems have high programmability. In fact, all the control algorithms are realized by software. If the design requirements change, then it is very easy and fast to change the corresponding software to satisfy the new ones. Moreover, different types of control algorithms can be easily implemented into the same control system hardware. Therefore, there will be a gain in development time and cost. Furthermore, advanced control techniques are much easier to implement. They are easily built in the digital control system and can greatly improve the dynamic performance of the power converter system leading to an improvement in the system viability. In addition, the digital control system has a great flexibility. Therefore, connecting multiple controllers and power stages becomes an easy work, and important operation data are much easier to manipulate.

2) Popular Digital Control Circuits: Like the analog implementation, the most used structure is the digital pseudo-noise generator (see Fig. 21), which is used to generate a random stream in order to vary the desired parameter of the pulsing gate. The principle of a random frequency modulation is shown in Fig. 22. Two basic ways to generate the random stream are to be distinguished: the linear congruential generator directly used by a microprocessor implementation and the generator for random switching frequency using a look-up table to store the random stream calculated priory offline. The first type was accomplished using a digital signal controller DSC [11] and some microcontroller like the pic. The second type, most used circuit, is the field programmable gate array based controller, which includes a pseudo-random stream generator and a digital PWM modulator [86], [91], [97]. Its widespread use is due to its high performance with a reduced cost. Thus, it is suitable for different power supply applications.

V. New Fast Digital Implementation

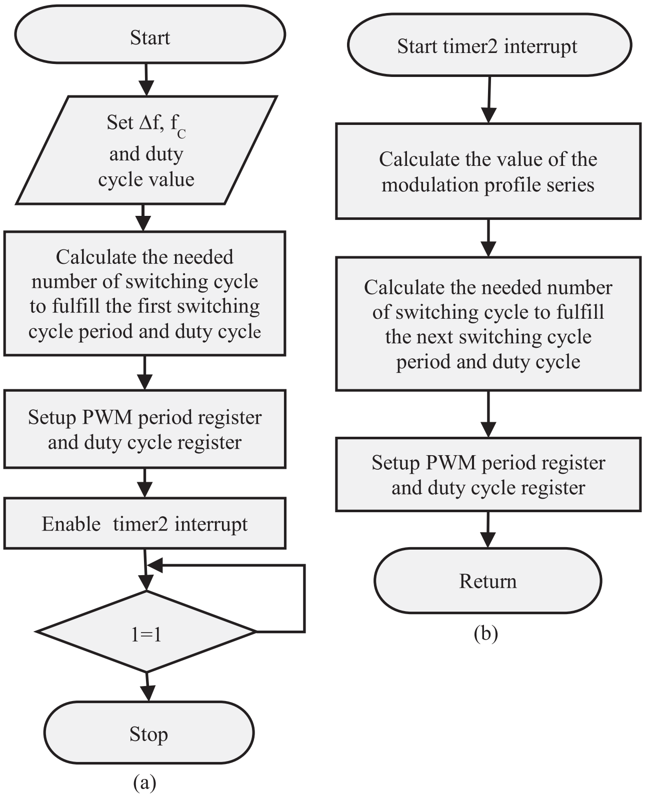
A. DsPIC-Based Digital PWM Implementation Methodology

1) Why the dsPIC Microcontroller: The proposed method was implemented by means of a dsPIC33fj12mc202 microcontroller due to its many prominent features. First and foremost, it is a cost-effective implementation method with the ability to generate the desired PWM rapidly. Its speed can reach 40 MIPS. Moreover, this method uses simple code line to perform the desired SS profile. It can also easily generate one of the most complicated profiles; the chaotic profile, as will be exposed in what follows, with no need to complicated Chua's circuit [76], [80]. Finally, the control signal is generated using an interrupt routine in a continuous way with no need for a look-up table or a store memory size for a precalculated random stream [86], [91], [97].

2) Proposed Fast Digital Implementation Strategy: The useful features of the dsPIC microcontroller for this implementation are the output compare/simple PWM module (OC/PWM), the timer2 circuit (a 16-bit timer), and the interrupt comparator. The OC/PWM is configured to generate the PWM signal. To create the PWM signal, the timer2 counts upward from zero to the specified value of the period. Another register contains the duty cycle value, which is constantly compared with the timer period value. The duty cycle register determines the period of time for which the PWM output should remain in the active state. To modulate the switching signal a *software interrupt*, which comes from a program run by the processor, is generated. It "requests" the processor to stop running the main program, to make an interrupt, and then to return to continue executing the main program.

Fig. 23 plots the flowchart of the main program and the interrupt routine. The switching periods and control parameters are updated at each switching cycle in the interrupt routine. The following steps are responsible for the frequency modulation of the PWM signal:

1) setup the timer2 period for the current switching cycle;
2) calculate the value of the modulation profile;
3) calculate the period value for the next switching cycle; and



(a) (b)

Fig. 23. Flowchart of digital implementation of the spread spectrum modulated PWM signal. (a) Main program. (b) The interrupts routine.

4) calculate the needed number of clocks cycle to fulfill the fixed value of the duty ratio using the new value of the switching cycle period.

B. Simulation and Experimental Validation

Both simulation and experimental results are given to verify the performance of the proposed dsPIC-based digital implementation, especially the SS effect.

1) Analysis of the PWM Signal: Simulation and Experimental Results: In the dsPIC-based SS application, our principal aim is to apply the SS modulation that can achieve the best-conducted EMI reduction performances. In this regard, we investigated, using the CCS compiler tool, several modulation parameters and different modulation profiles. The investigated modulation profiles go from the simplest and most used profile, i.e., periodic profiles, to the most complex modulation profiles, i.e., chaotic profiles. For the former, the expression of each modulation profile is presented in Section III-C. For the chaotic PWM, the switching frequency may be generated in analog or in digital ways. The analog generation is achieved using electronic oscillators mainly Chua's circuit [74], [76], [80] and the digital method is based on chaotic maps. Obviously, these maps can generate a large number of noise-like sequences having low cross-correlation. A particular chaotic map with a particular initial condition can generate infinite chaotic sequences. Some of the most popular chaotic maps are logistic-map, iterative-map, tent-map, and sine-map [61] whose equations are reported as follows:

Iterative map $$x_{i+1} = \sin\left(\frac{a\pi}{x_i}\right), \quad a = 0.7\, x_i \in (-1, 1) \tag{7}$$

Logistic map $$x_{i+1} = a x_i \left(1 - x_i\right), \quad a = 4\, x_i \in (0, 1) \tag{8}$$

Tent map $$x_{i+1} = \begin{cases} \frac{x_i}{0.7} & x_i < 0.7 \\ \frac{10}{3}\left(1 - x_i\right) & x_i > 0.7 \end{cases}, \quad x_i \in (0, 1) \tag{9}$$

Sine map $$x_{i+1} = \frac{a}{4} \sin\left(\pi x_i\right), \quad a = 4\, x_i \in (0, 1). \tag{10}$$

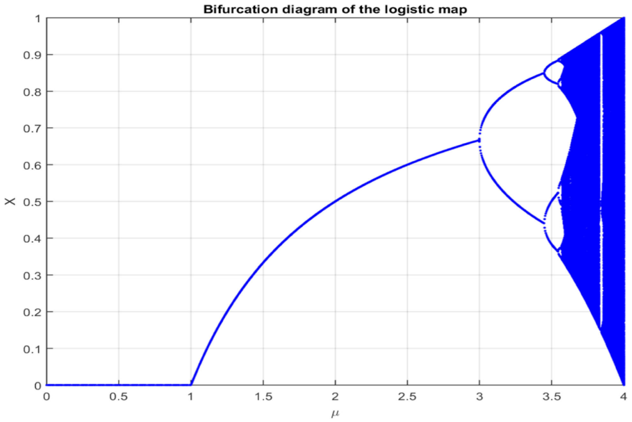


Fig. 24. Bifurcation diagram of the logistic map.

The previous implementation strategies have their pros and cons and the choice of one or the other method is driven by the circuit circumstances and the designer preference. In this work, we opted for using the logistic map to generate the chaotic sequences. Its expression is as follows:

$$F_i = F_c + (2 \times X_i - 1) \times \Delta F, \quad i = 1, 2, 3, ..., \; X_i \in [0, 1] \tag{11}$$

where ΔF is the switching frequency band, F_c is the central switching frequency, and X_i is a chaotic series generated by the logistic map as follows:

$$X_{i+1} = \mu X_i \left(1 - X_i\right), \quad i = 1, 2, 3, ..., \; X_i \in [0, 1], \quad \mu \in [0, 4] \tag{12}$$

where μ is the bifurcation parameter.

The logistic map is a well-known chaotic map. It is a one-dimensional discrete-time nonlinear series. With the rising value of μ, the logistic map can exhibit varying dynamical behaviors (see Fig. 24). The chaotic behavior of the logistic map is visible when the bifurcation parameter μ lies in $[3.57, 4]$. In this paper, $\mu = 4$ is chosen to create X_i the pseudo-random series for the chaotically modulated PWM signal.

Noting that the harmonic spectrum in the case of the SS technique is nondeterministic, the fast Fourier transform (FFT) of the signal can hardly be used as a metric. The natural quantity to be studied in this case is *the power spectrum*, which is defined as the Fourier transform of the autocorrelation function of the signal. One trusted estimate of the power spectral density (PSD)

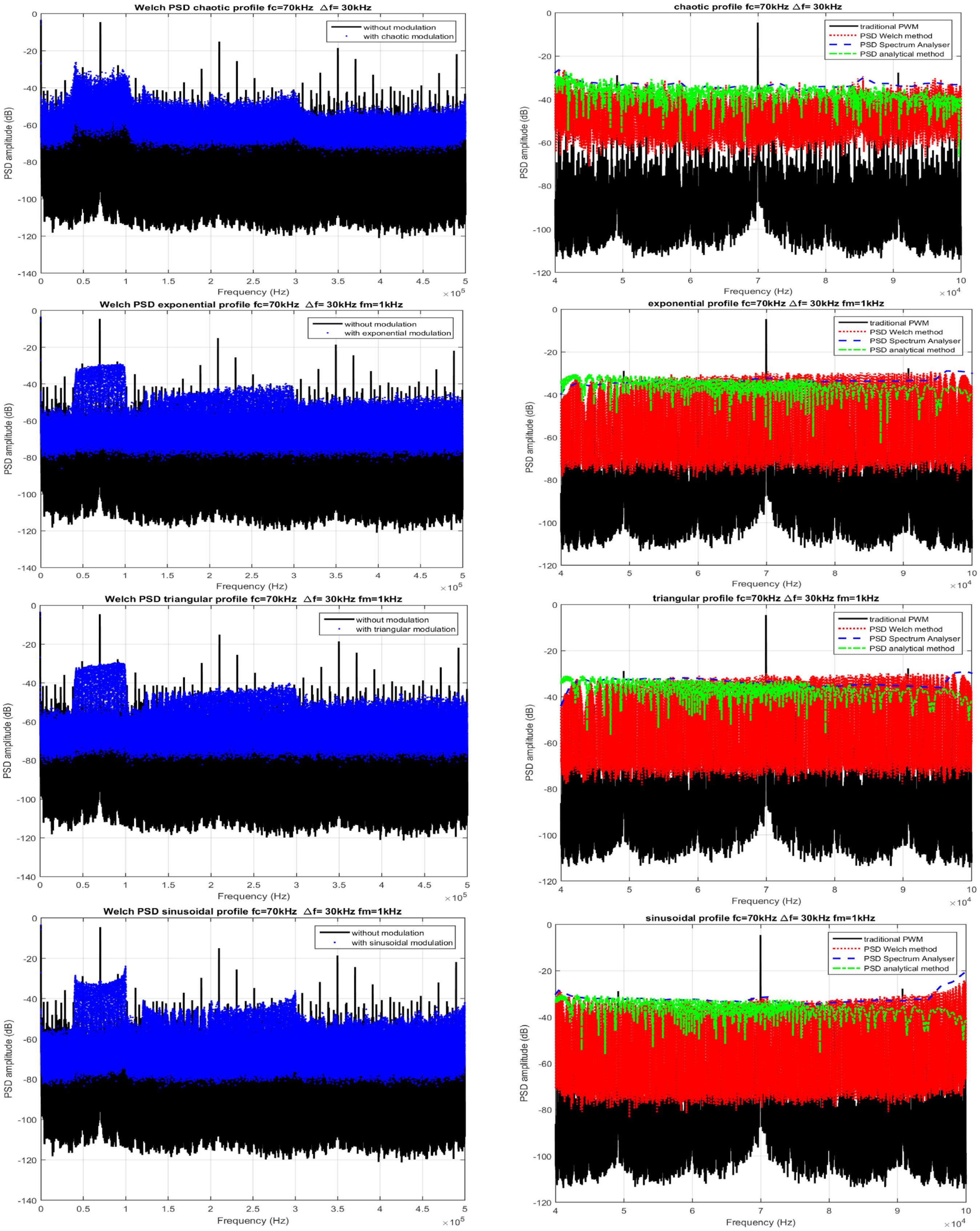


Fig. 25. PWM spectrum: Welch PSD estimates (first column) and a zoom in the fundamental harmonic using the Welch PSD estimates, the measured results, and the analytical results (second column).

TABLE II
SUMMARY OF THE HARMONIC REDUCTIONS AND STATISTICS OF THE DIFFERENT MODULATION PROFILES

Scheme	First harmonic reduction	Third harmonic reduction	Fifth harmonic reduction	Mean harmonic reduction
Traditional	0 dB	0 dB	0 dB	0 dB
Chaotic	21.73 dB	26.93 dB	28.72 dB	25.79 dB
Sinusoidal	19.34 dB	21.19 dB	26.83 dB	22.45dB
Triangular	24.80 dB	25.27 dB	27.33 dB	25.80 dB
Exponential	24.50 dB	24.79 dB	26.40 dB	25.23 dB

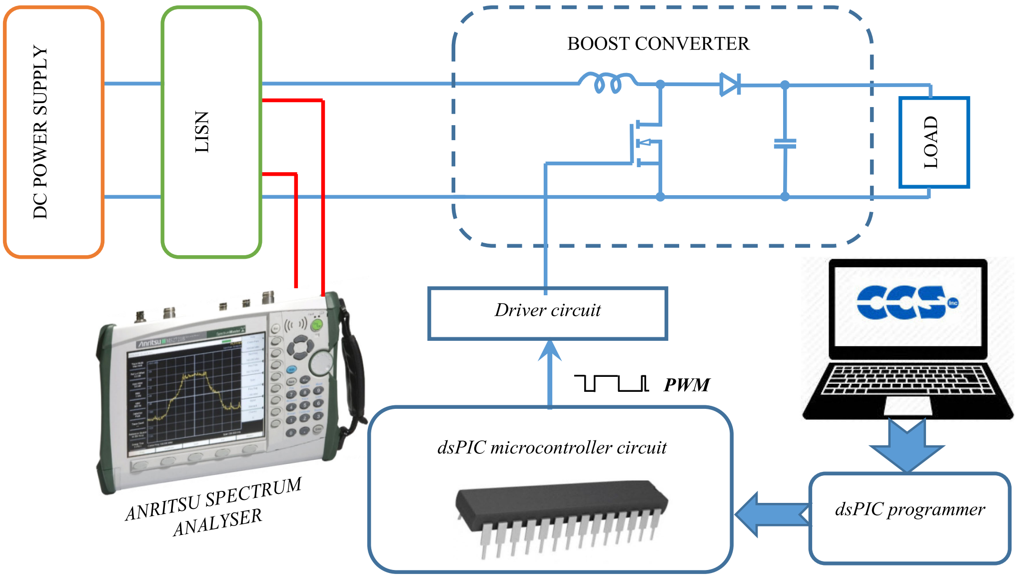


Fig. 26. Proposed dsPIC-based digital implementation.

is obtained using the Welch method [104]. The Welch method provides a transformation from the time domain to the frequency domain. It computes an estimate of the PSD as follows: first, each time record is multiplied by a chosen window function (in this case the Hamming window). Then, the modified record is transformed by using the FFT. Finally, a number of successive records are averaged with a 50% overlap to reduce the variance. The estimated PSD of the signal is obtained.

Fig. 25 (column one) shows the PSD of the four modulation profiles considered for a center frequency $f_c = 70$ kHz and a frequency bandwidth $\Delta f = 30$ kHz. The obtained results validate the new digital implementation. It clearly reveals the SS effect of the studied modulation profiles. The energy at each of the spectrum harmonic is spread over the defined bandwidth and its multiples giving reduced peak amplitudes. Fig. 25 (column two) shows a zoom-in of the fundamental harmonic using three methods: the Welch method, the analytical method, and the measured results. The Welch method was exposed previously. The analytical method is based on the works of Bech as well as Trzynadlowski [101]–[106]. The general PSD formula is the following:

$$S(f) = \frac{1}{T} E\left\{ \sum_{k=-\infty}^{\infty} G(f;\alpha_0)G^*(f;\alpha_k)e^{jw(t_k-t_0)}e^{jw(\varepsilon_k-\varepsilon_0)} \right\} \tag{13}$$

where G is the Fourier transformation of pulse signal $g(t)$ (see Fig. 2) and G^* is its complex-conjugated Fourier transformation. The developed analytical expressions may be found in [104, ch. 4]. The measured results were collected using a spectrum analyzer in the frequency range 9–150 kHz with a resolution bandwidth RBW = 200 Hz.

Table II summarizes the peaks reduction for the first three harmonics of the studied modulation profiles. It clearly shows that all used modulation profiles give a harmonic reduction greater than 20 dB. It reaches a reduction means of 25 dB for the chaotic, the exponential, and the triangular profiles. As a summary, we can say that the simulation, the analytical, and the experimental results are in great correspondence. They reveal the SS effect of the command signal and show up the spectral-shaping effect of the studied profiles.

2) Experimental Setup and Results of the EMI Noise Spectrum: In order to test the effectiveness of the previous simulated modulation profiles using our new digital dsPIC-implementation, the different modified PWM techniques are embedded in a small-power laboratory prototype boost converter (see Fig. 26). The boost converter is chosen because it is one of the basic topologies of dc–dc converters and very popular in many practical circuits, such as power factor corrector. In the test setup, the boost converter was supplied through a line impedance stabilization network. The measuring EMI receiver is a spectrum analyzer using a peak detector mode. As our goal

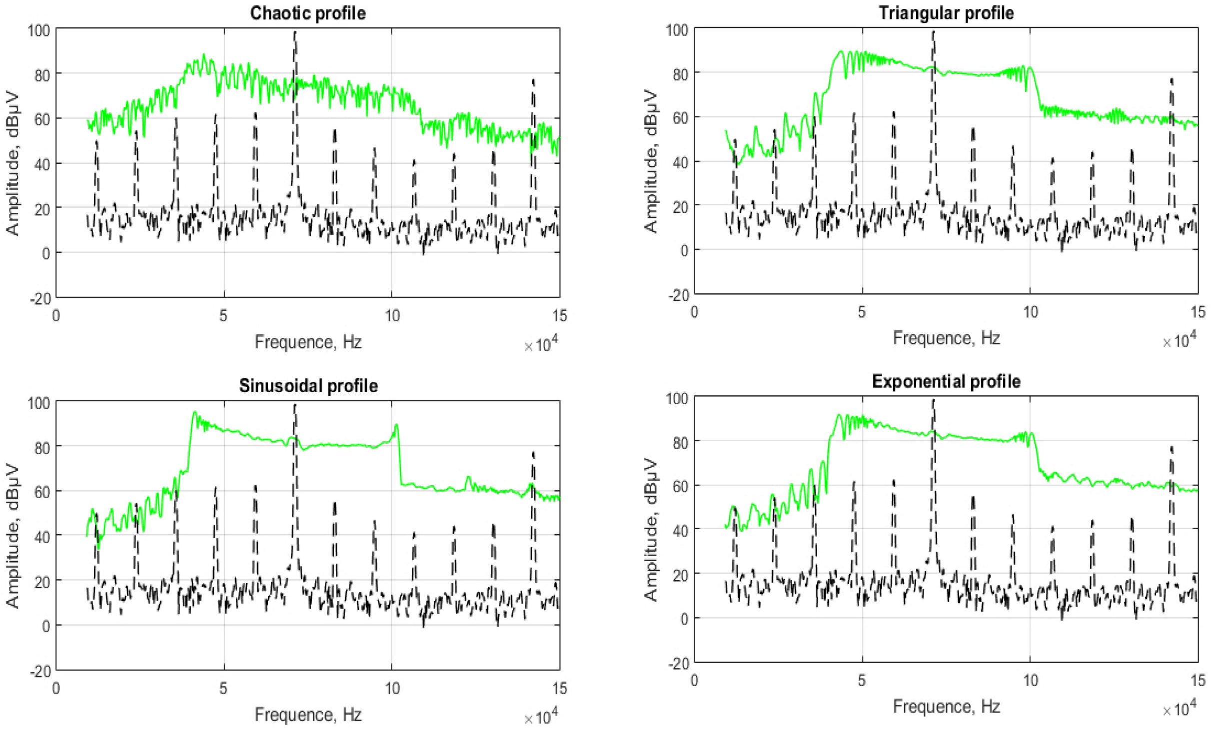


Fig. 27. Measured power spectrum of the EMI noise density of the boost converter with different modulation profiles $\Delta f = 30$ kHz, $f_m = 1$ kHz for the frequency range 9–150 kHz.

was to show the SS effect and to validate our digital implementation, the conducted EMI was considered only in the band 9–150 kHz. Then, the resolution bandwidth of the measuring instrument was RBW = 200 Hz. Further detailed results in the band 150 kHz to 30 MHz will be subject to future work. The converter was operated with the chaotic modulation using the logistic map and with the three periodic modulation profiles; the sinusoidal, the triangular, and the exponential profiles. We assume the central switching frequency $f_c = 70$ kHz, the frequency bandwidth $\Delta f = 30$ kHz, and the modulation frequency $f_m = 1$ kHz. Since $D = 0.5$ gives the worst scenario in terms of EMI peak disturbance, the duty cycle is maintained constant and equal to 50%.

Fig. 27 shows the experimental results obtained for each modulation profile. In all the cases, a reduction of about 20 dBuV is obtained on the fundamental frequency. The best performance is given by the chaotic profile and the worst is visible with the sinusoidal profile.

In short, the new digital implementation has proven its correctness. Furthermore, we succeeded in the realization of the different modulation profiles, in particular, the chaotic modulation profile. This was easily made in a digital manner with no need for an extra circuit or a complicated algorithm. Finally, the SS effect was clearly revealed and its EMI reduction capability was recognized.

C. Merits of the New dsPIC-Based Fast Digital Implementation

As shown above, there are different ways to implement the modified PWM signal. Analog circuits are popular and can suppress EMI effectively; however, it suffers from numerous disadvantages such as degraded performance due to aging, inaccurate pulse generation, and carrier frequency limitation. In contrast, the digital circuits have various advantages that make them a good alternative: They are capable of providing an accurate pulse in comparison with analog circuits; they are more reliable, flexible, and autonomous. Although the existing digital PWM techniques published so far have their own unique merits and demerits, we aimed at developing a new implementation method that can take advantages of digital circuits and improve the dynamic performance of the switching power supplies. Our implementation was based on a dsPIC33fj12mc202.

This choice was justified by the numerous advantages of the dsPIC implementation listed as follows:

1) a speed that reaches 40 MIPS facilitating a fast digital implementation, a better reliability with lesser hardware requirement;
2) lesser memory size requirement;
3) lower level of harmonic contents;
4) all of the modulation work is performed with a software without a need for an extra circuit to generate the modulation signal;
5) simplicity for the dsPIC microcontroller implementation of the different modified PWM: periodic, chaotic, or random modulation: use of simple code line and avoiding the use of complicated equations; and
6) flexibility to modify the modulation signal to any desired modulation profile and to modify the reference and the carrier signals to any desired value. Thus, it is convenient for diverse application of switch-mode converters.

VI. CONCLUSION

SMPSs are a dominant factor in the EM environment deterioration. They produce unwanted EMI. When the energy levels exceed the allowable thresholds, the offending signals should be addressed. SS-based PWM techniques provide a cost-effective method to lower these EMI levels. The current work addresses an overview of the different SS modulation schemes and their implementation methods. Furthermore, a new fast digital implementation based on a dsPIC microcontroller was proposed. It is an effective SS method for reducing EMI, which may be easily integrated into any power converter topology. In the experimental results, the SS effect was clearly revealed and its EMI reduction capability was recognized in the band 9–150 kHz. However, further detailed analyses and studies on the conducted and radiated emissions using this new fast digital implementation will be the subject of future investigations.

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