IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 29, 2019, accepted December 18, 2019, date of publication December 24, 2019,
date of current version January 6, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2961954

A State-of-the-Art Review on Conducted Electromagnetic Interference in Non-Isolated DC to DC Converters

SUDHAKAR NATARAJAN[1], (Member, IEEE), THANIKANTI SUDHAKAR BABU[2,5], (Member, IEEE), KARTHIK BALASUBRAMANIAN[3], UMASHANKAR SUBRAMANIAM[4], (Senior Member, IEEE), AND DHAFER J. ALMAKHLES[4], (Member, IEEE)

[1]School of Electrical Engineering, Vellore Institute of Technology, Vellore 632014, India
[2]Department of Electrical and Electronics Engineering, G. Pullaiah College of Engineering and Technology (Autonomous), Kurnool 518002, India
[3]Offshore Technology Development Private Ltd., Keppel Offshore and Marine Ltd., Singapore 629353
[4]Renewable Energy Laboratory, College of Engineering, Prince Sultan University, Riyadh 12435, Saudi Arabia
[5]Department of Electrical Power Engineering, Institute of Power Engineering, Universiti Tenaga Nasional, Kajang 43000, Malaysia

Corresponding author: Thanikanti Sudhakar Babu (sudhakarbabu66@gmail.com)

This work was supported by the Renewable Energy Laboratory, Prince Sultan University, Saudi Arabia.

ABSTRACT One of the most challenging and interesting field in power electronics is the ability to mitigate the Electromagnetic Interference (EMI). A natural source of EMI includes the atmospheric discharge/charge phenomena and extra-terrestrial radiation. Man-made source of EMI are line radiation, auto ignition, radio frequency interference and power lines. Suppression of EMI and enhancing the Electro Magnetic Compatibility (EMC) has become essential in high frequency power electronic converters. This review article is a one stop solution for new researchers and practitioners to understand about the effects of EMI and its suppression techniques in detail.

INDEX TERMS Electro magnetic compatibility, electro magnetic interference, mitigation.

NOMENCLATURE

Acronym	Description
APF	active power filter
CFM	carrier-frequency modulation
CPWM	chaotic PWM
CSPWM	chaotic sinusoidal pulse width modulation
CAFM	chaotically amplitude frequency modulation
CPPM	chaotically pulse position modulation
CM	common mode
DM	differential mode
DAEF	digital active EMI filter
DPWM	digital pulse width modulation
DMOS	double diffused MOS
EMC	electromagnetic compatibility
FPGA	field-programmable gate array
FHT	frequency hopping technique
FADEC	full authority digital engine controller
HIRF	high intensity radiated fields
HCFM	hybrid chaotic frequency modulation
IGBT	integrated bipolar junction transistor
LISN	linear impedance stabilization network
LTCC	low temperature co-fired ceramic
MM	Metamaterial
ORPWM	optimal random pulse width modulation
PCFM	periodic carrier frequency modulation
PV	Photovoltaic
PSD	power spectral density
PSM	pulse skipping modulation
PWM	pulse width modulation
RCF	random carrier-frequency
RCFM	randomized carrier frequency modulation
RPPM	random pulse position modulation
SSN	simultaneous switching noise
SVPWM	space vector pulse width modulation
SMPC	switch mode power converters
THD	total harmonic distortions
TL	transmission line
ZCS	zero-current switching
ZCT	zero-current transition
ZVS	zero-voltage switching
ZVT	zero-voltage transition

The associate editor coordinating the review of this manuscript and approving it for publication was Amedeo Andreotti.

I. INTRODUCTION

The invention of power electronics has created a revolution in the life of mankind. Power electronics have brought about ground-breaking changes in domestic and industrial applications [1]. According to the statistics presented in [2], [3], it is estimated that majority of the electricity generated in developed nations i.e. over 90% of generated power, is being managed through power electronic circuits before sending to the utility.

Most of the power conversion system involves power converters. Power converters are power electronics circuits made up of semiconductor switches, magnetic elements (inductor, transformer) and energy storage elements like a capacitor. A large variety of power electronic converters are proposed for power conversion systems in [4]–[6].

Among the various power converters, the most versatile converter for DC voltage regulation is the DC-DC converter. DC-DC power converters were also known as Switch Mode Power Converters (SMPC). The SMPC will transfigure the uncontrolled DC input to control DC output without changing at the anticipated voltage level. Based on the voltage ratio, isolation and nature of switching, several types of DC-DC converters exist [6], [7]. The most commonly favoured configurations are boost, buck, buck-boost and flyback converters. The simplest converter topology adopted for faithful reproduction of higher output voltage for a given input voltage is DC-DC boost converter. It finds a wide range of applications covering front end converters for battery sources, solar PV systems and fuel cells [8]–[10].

Frequent opening and closing of semiconductor switches in boost converter contribute to large voltage spikes and high output voltage ripple. With the objective of meeting high power density, these converters are operated at high switching frequency [11]–[14]. Further, continuous switching of these power converters at high switching frequency triggers a lot of problems in power quality, harmonic injection, reliability and EMI. Among the aforementioned, the most severe phenomenon that leads to catastrophic operation of DC-DC boost converter is EMI and DC-DC converter is a major source of man-made EMI. The natural and man-made sources EMI is shown in Fig.1.

EMI is an undesirable disturbance that occurs due to switching and affects an electrical circuit [15]. EMI is categorized into radiated and conducted EMI.

The conducted and radiated EMI in an operating environment is shown in Fig.2. Statistics to mitigate the adverse effects of EMI and to safeguard the appliances against EMI problem have attributed to much scholarly research [16], [17].

Various methods have been described in the literature to suppress the EMI and to meet the EMC standards. These methods can be broadly categorized into:

- ✓ EMI Filter
- ✓ EMI Shielding
- ✓ Soft switching
- ✓ Random Modulation and
- ✓ Chaotic PWM control.

FIGURE 1. Typical EMI sources.

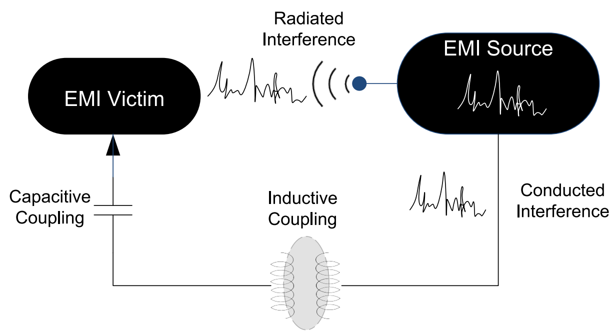

FIGURE 2. Schematic block diagram of electromagnetic interference (EMI) coupling path.

Among the above-mentioned methods, EMI filtering and EMI shielding are the methods incorporated to alleviate EMI, after generated from the source. The other methods are exclusively used for preventing the EMI in the source itself. Moreover, EMI shielding has much relevance with radiated EMI and the source of EMI is covered under the shielding, so as not to affect another system by means of radiation.

Though, many works have been proposed in literature focusing on minimization and suppression of EMI, none of the researcher has attempted to provide a complete overview and comprehensive survey on various methods applied for EMI mitigation. Hence, in this article, authors have made an attempt to collectively present the various EMI suppression methodologies, advantages, disadvantages and the applications relevant to the field of EMI suppression. EMI mitigation is extremely important for researchers and engineers working in the field of EMI suppression [18]–[21].

II. CONCEPT OF ELECTROMAGNETIC INTERFERENCE AND ITS CLASSIFICATION

Radiated and conducted EMI are categorized based on the frequency of operation. EMI coupling path and electromagnetic field propagation. The representation of EMI coupling path is shown in Fig. 2.

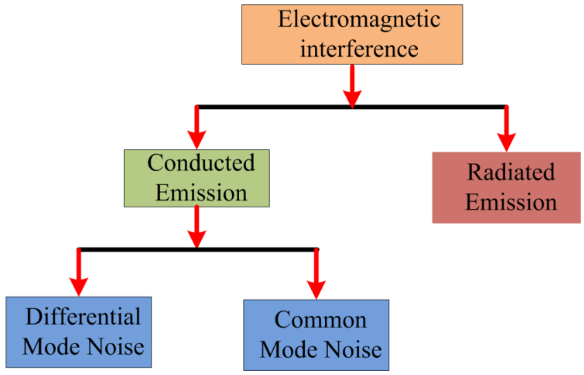

FIGURE 3. Classification of electromagnetic interference in an electrical circuit.

A. CONDUCTED EMI

Generally, conducted EMI occurs at lower frequencies i.e. frequencies below 30 MHz. Differential mode (DM) and Common mode (CM) noise are the further classification of conducted EMI as shown in Fig. 3.

- CM noise is always present with high source but low load impedances.
- DM noise is mostly caused by pulsating currents. For frequencies lesser than or equal to 5 MHz, the noise tends to be DM type. For frequencies greater than 5 MHz, noise in the currents tends to be CM noise [22].

B. RADIATED EMI

The concept of radiated EMI is clearly explained with electric and magnetic fields in the next sections.

III. EMI MITIGATION TECHNIQUES

EMI filtering is used to minimize the EMI to a minimal frequency as per EMC standard. The Both methods EMI filtering and Shielding can suppress the EMI. In order to overcome the disadvantages like high cost, weight etc. of EMI and to meet the required EMC standards, various methodologies have been proposed in this field. The methodologies include EMI filtering, soft switching, random modulation and chaos control. Among these, chaotic PWM based EMI mitigation technique is the easiest to implement and provides the most promising solution to EMI problems. Chaotic carrier is the one most effective method in reducing conducted EMI; however, it requires high speed digital processors for its experimental investigation.

A. EMI FILTERING

The basic EMI filters are used to supress the conducted interference which is found on the signal or power lines by using passive or electronics devices. These filters provide considerably higher input resistance to attenuate the high frequency content in the power circuit. EMI filters are nothing but low pass filters which restricts or impedes the flow of high frequency signals into ground directly. The main objective of EMI filters is to minimize the interference effect on the other

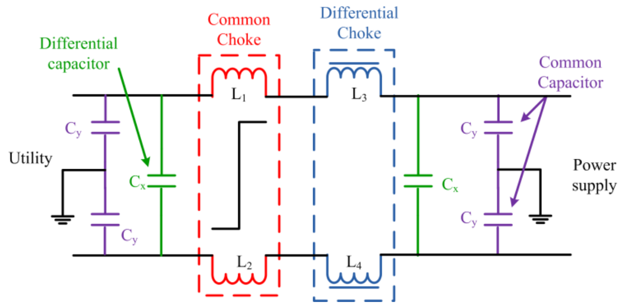

FIGURE 4. Schematic circuit diagram of passive EMI filter.

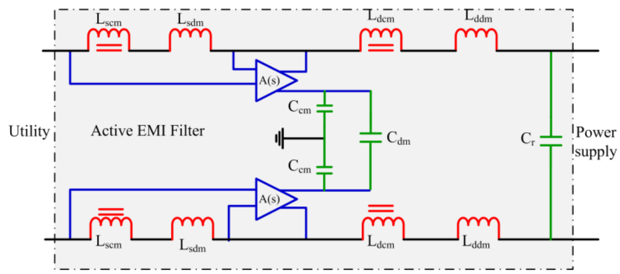

FIGURE 5. Schematic circuit diagram of active EMI filter.

power electronic devices or components [1], [7]. The EMI filters can be broadly classified into: Passive filters, active filters and hybrid active filters.

1) PASSIVE FILTERS

The filter is a combination of series inductors and parallel capacitors i.e.; an LC filter constitutes a passive filter. The schematic circuit diagram of passive EMI filter is shown in Fig.4. Differential choke filters the DM noise and common choke eliminates the CM noise. These types of filters were introduced by the authors in [23]–[25].

2) ACTIVE FILTERS

The first active filter was proposed in [26] and many authors have shown interest in the development of active filters [27]–[30]. In [28], an active filter topology has been proposed for utility interface of switched mode power supply as shown in Fig.5. Active filters are more effective and desirable to optimize the cost and size of the passive elements.

3) HYBRID ACTIVE FILTERS

The effect of passive and active filters in combination forms the concept of EMI filter. A hybrid EMI filter reduces the noise over a wide bandwidth [9], [27], [31].

4) EMI FILTER DESIGN

The noise frequencies which are in measuring range can be obtained by conducting the emission testing. The attenuation Areq of noise can be calculated as the alteration between the true measurement Vmes and the reference standard Vref as

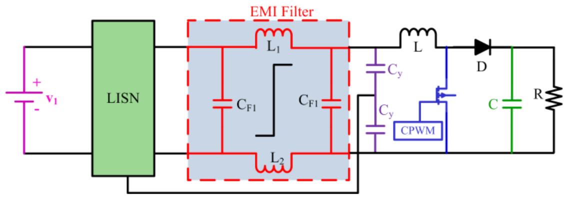

FIGURE 6. **General block diagram of EMI filtering.**

in equation (1).

$$A_{req} = V_{mes} - V_{ref} + \Delta A_s \tag{1}$$

where ΔA_S is defined as the safe margin added to the calculated attenuation. The CM and DM noise components are illustrated in equation 1. The schematic circuit diagram of EMI passive filter is shown in Fig. 4. It is a typical configuration which constitutes of L_1, L_2, C_y for common mode section and L_3, L_4, C_x for differential mode section.

Mathematically, the CM or DM frequency f_r for EMI filter can be estimated using equation (2).

$$f_r = f_{Pk}^{I} 10^{-\frac{(A_{req})_{dB}}{40}} \tag{2}$$

where f_{Pk}^{I} is defined the first peak frequency of the attenuating noise signal. By finding the corner frequency, the component values of filter can easily be identified with the help of equation (3) and (4) for CM and DM filter respectively.

$$f_{R,CM} = \frac{1}{2\pi\sqrt{L_1 2C_y}} \tag{3}$$

$$f_{R,CM} = \frac{1}{2\pi\sqrt{(2L_3 + L_l)C_x}} \tag{4}$$

L_l refers to the CM mode leakage inductance. The degree of freedom can be used to find the component selection, and *L* and *C* values are calculated based on available commercial datasets. The general block diagram representing the EMI filtering is shown in Fig. 6. Apart from the EMI filter, shielding techniques are also used to mitigate the EMI. The bulkiness, design limitation for the desired frequency band, parasitic reactive elements and chances for attenuation of useful signal has limited its usage. Various works on EMI filtering that are available in the literatures are consolidated and presented as follows. Moo *et al.* [7] presented an approach of integrating the two passive filters into a single filter.

In [8], Chen Wenjie et al. Discussed an EMI filter for the power electronics module. Ho *et al.* [9] describes a prototype with efficient noise suppression. Wu *et al.* [10] and Tsai and Wu [11] designed a filter for suppression of common mode noise and concluded that the developed filter is able to provide excellent signal integrity for the DM signals. Balan *et al.* [12] discussed the limitations of EMI filters used for harmonic perturbations. Chenbin Tao *et al.* [13] and Wu *et al.* [14] introduced solution to reduce CM EMI in SMPS with hybrid filter (HEF). Li *et al.* [15] used the system on package (SOP) Multi-order low pass filter for EMI and simultaneous switching noise suppression. It is concluded that the performance of noise isolation is achieved at a higher level with a smaller size. Bai *et al.* [16] delivered efficient new passive filtering technique to reduce EMI caused by power supply. Chen and Lai [17] presented the systematic EMI filter design procedure and software for noise separation method. Fukuda *et al.* [18] confirmed that the radiated EMI is generated by power electronic equipment.

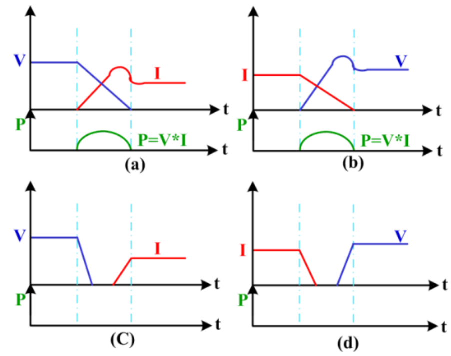

FIGURE 7. **Switching sequences of power MOSFET.**

Hamza *et al.* [19], Ye *et al.* [20], Wang *et al.* [21], Bona and Fiori [32], Hamza *et al.* [33], Amini [34], Luo *et al.* [35] primarily discussed about EMI filter for the DC-fed three-phase motor drive system and APF system. The authors concluded that, multilevel inverters are able to make direct connection of the APF to high rated voltage network. Reference [36] confirms that, the Digital Active EMI Filter (DAEF) is able to control the digital controller concurrently. Ali *et al.* [37] talks about the technology named hybrid integration. Danilovic *et al.* [38], Chou and Lu [39], Xu and Wang [40], Paulis *et al.* [41], Wang and Xu [42], Natarajan and Natarajan [43], Hsiao *et al.* [44], Chen *et al.* [45] discussed new and low cost inverters related to EMI filter design. For easy understanding, the aforementioned published works have been categorized based on switching frequency, power level, hardware implementation, and level of suppression and presented in Table 1.

B. SOFT SWITCHING

The concept of soft switching is illustrated in Fig. 7. Consequently, the rate of change of current and voltages across the switches are reduced, therefore, EMI can be mitigated in DC-DC converters [8], [10], [11].

The soft switching technique can be classified as, zero-voltage switching (ZVS), zero-current switching (ZCS), zero-voltage transition (ZVT) and zero-current transition (ZCT). The combination of PWM control and soft switching has been widely implemented in plethora applications specifically to aircraft power conversion systems [46], [47]. Soft switching of DC-DC converters have its own limitations due to requirement of auxiliary components namely resonant inductors, resonant capacitors, and auxiliary diodes, and switches.

TABLE 1. Different types of EMI filters used and its suppression level.

Author & Ref. No	Year	Type of Filter	Switching Frequency	Power Level	Type of Converter used	Suppression Level
C.S. Moo [7]	2003	Conducted EMI Filter integrated with PFC low pass filter	50 kHz	40 W	Buck- Boost PFC Converter	40 dBµV
W.C. Ho [9]	2008	Hybrid EMI Filter	1 MHz	20 W	Switching Power Converters (operating in MHz range)	20 - 50 dBµV
Shu-Jung Wu [10]	2009	Common Mode Filter	MHz range	-		More than 15 dBµV
C.H. Tsai [11]	2009	Common Mode Filter	Megahertz range	-	High speed digital circuit & Microwave circuit	More than 20 dBµV
Horia Balan [12]	2012	3 phase Passive EMI Filter	50 kHz	-	Power Grid (SKM 200GB 1700)	Harmonics reduced to 46.16% (3^{rd}) and 45% (5^{th}) of fundamental
P.S. Chen [17]	2010	EMI Filter	15 kHz	3.7 kW (motor)	3 phase Inverter applied to Motor Drive	40 dBµV
D Hamza [19]	2011	Combination of active and passive filters	700 kHz	30 W	DC-DC Converters	More than 30dBµV
Fang Luo [35]	2011	AC side and DC side EMI Filter (proposed model)	2 - 5 MHz	2 kW (motor)	Dc fed 3 phase motor drive system	40 dBµA
Marwan Ali [37]	2012	Hybrid Integrated EMC Filter	212 kHz	30 W	DC-DC Converters	50 dBµA
Milisav Danilovic [38]	2012	Single Stage EMI Filter	0.97 MHz	70 W	DC-DC Converter (for low voltage bus aircraft app.)	40 dBµA
Chenchen Xu [40]	2013	Planner EMI Filter	150 kHz	-	Flyback Converter	
Djilali Hamza [36]	2013	Digital Input EMI Filter	80 kHz	80W	AC-DC Converter with PFC control	30 dBµV
F. De Paulis [41]	2013	8 GHz EBG based Filter	8 GHz	-	PCB design of the Filter	
Sudhakar N [43]	2014	Integrated Filter	100 kHz	40 W	DC-DC Boost Converter	4 dBµV
C.Y. Hsiao [44]	2015	Ultra Compact Common Mode Band Stop Filter	2 - 4 GHz	-	3C modified-T using the IPD process	-

This increases the power loss of converters and makes the systems design more complicated.

The addition of EMI filter to switched DC-DC boost converter contributes significantly to EMI reduction. However, this combination is pertinent to certain drawbacks such as, EMI filters act as a remedy after EMI is generated and can even of attenuate useful signal. Furthermore, boost converters are hard switched.

Due to hard switching, voltage and current level changes abruptly, leading to high stress on the device, increased switching losses and thermal management problem. Hence, to overcome the aforesaid drawbacks, a soft switching technique in combination with the PWM method has been suggested in [47]. The general block diagram of soft switched DC-DC converter suitable for EMI suppression is shown in Fig.8. Ogiwara *et al.* [48] presents a novel quasi resonant high frequency inverter for mitigation of EMI.

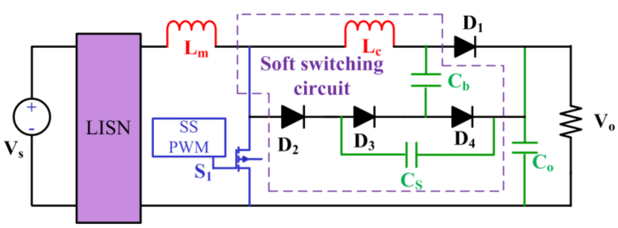

FIGURE 8. General block diagram of boost converter with soft switching for EMI suppression.

Taniguchi *et al.* [49] and Kongsakorn and Jangwanitlert [50] talks about a converter that reduces the EMI noise

TABLE 2. Different types of soft switching techniques used in power converters.

Author	Year	Type of switching	Switching Frequency	Power Level	Type of Converter Used	Suppression Level
Katsunori Taniguchi [49]	2004	SPS (Simple Partial Switching)	-		OSAKA converter	-
N Sudhakar [51]	2013	ZCS	100 kHz		Boost Converter	-
H. Ogiwara [48]	2004	ZVS	20 kHz	2.7 kW	SEPP Inverter	-
W Li [55]	2007	ZVT	50 kHz	1 kW	Interleaved Boost Converter	Efficiency of converter is improved by 7% at full load condition
KhademiAstaneh, et al. [46]	2011	Turn on with ZCS and turn off with ZVS	80 kHz	220 W	Boost Converter	-
M.R. Yazdani [59]	2012	ZCT	150 kHz	80 W	Flyback Converter	Reduced By 10dBμV
Jun-Ho Kim [61]	2012	ZVT	40 kHz		Interleaved Boost Converter	-
Apollo Charalambous [62]	2015	ZVS	50 kHz	1.4 kW	Auxiliary Commutated Pole Inverter	Harmonic reduction is achieved between 1 to 20kHz frequencies

due to current. Sudhakar *et al.* [51] incorporated chaotic mapping method to convert the periodic sawtooth carrier into chaotic.

Wu and Liang [52] implements the single ended push pull (SEPP) soft switching high frequency inverter where the operating frequency range is widened for convenience. It is concluded that if the proposed topology is added or operated at a high resonant frequency, it can be operated at switching conditions. Monteiro *et al.* [53] concluded that, the harmonics at high frequencies can be minimized with optimal values of voltage rise and fall time. Wai *et al.* [54] introduced an auxiliary voltage clamped reset winding into a quasi-resonant converter for improving the defect of the common voltage drop across resonant switches. Here, the parasitic capacitance of the switch is used with the magnetizing inductance of the transformer. Li and He [55] proposed an interleaved boost converter to extend the voltage gain and to reduce the switching voltage loss.

Morimoto *et al.* [56] affirm that the soft switching technique is basically used in the pulse width modulation generator with particularly higher frequency. Lu *et al.* [57] assert that the soft switching techniques were employed as they attract unity power factor AC-DC converter in the view of the size reduction and EMI suppression. A bidirectional AC-DC converter normally accompanies switching losses and induced EMI. In order to reduce that, an additional magnetic energy recovery switch, MERS turn-off snubber circuit is introduced by Iijima *et al.* [58] and the prototype suggested proves the reduction of EMI.

Astaneh *et al.* [46], Yazdani and Farzanehfard [59] discussed about the soft switch boost converter for active power factor correction and EMI mitigation techniques. Hoshi and Matsui [60] talks about snubber commutation technology. As a solution, adjustable dead time control in a lossless snubber commutation is proposed in the range of low output current. The output efficiency is increased by 3% when this methodology is followed. Lee *et al.* [61] developed the LC resonance and passive clamping technique. The circuit achieves high efficiency and low voltage stress by adopting a soft switching method using LC resonance. The proposed topology increases the efficiency, reduces switching loss and high voltage stress. Charalambous *et al.* [62] investigates how soft-switching topologies can attenuate EMI by addressing it at the source level. Various soft switching categories used for the reduction of EMI have been consolidated in Table 2.

C. RANDOM MODULATION

Random modulation means that the switch frequency is varied according to the given random signal [63]. Thus, the total energy is spread over a wide range of frequency band. The peaks appearing in the converter operating in the periodic mode is smoothened by this type of modulation. Thus, the reduction in the peaks signifies that EMI has been suppressed. There exist two limitations in this type of modulation: one is the generation of random signals in real time which is difficult and the other one is that parameter design is also difficult due to random frequency.

D. CONCEPT OF RANDOM CARRIER FREQUENCY MODULATION

PWM technique is generally used for generating the pulses required for the switching in DC-DC converter.

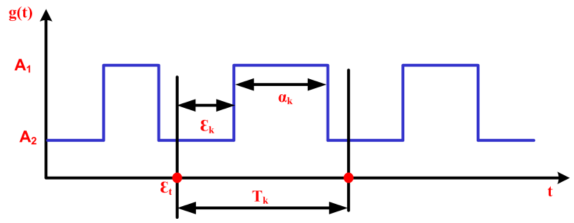

FIGURE 9. Switching signal for randomization of parameters.

Fig. 9 illustrates the k^{th} switching cycle begins at a time ξk, where

$$\xi_k = \sum_{i=0}^{k-1} T_i \quad \mathrm{k} = 1, 2, \ldots, \mathrm{T_o} = 0$$

The general block diagram for random modulation is shown in Fig. 9. Tse *et al.* [63], Ma and Kawakami [64], Bhajana *et al.* [47], Mihalic and Kos [65] concluded that, by controlling the degree of randomness, all the converters gradually spread the discrete frequency harmonic power over the frequency spectrum. The authors of [66]–[75] implemented the spread spectrum technique for the suppression of EMI and to mitigate the effect on acoustic and electromagnetic noise emitted by the supplied system. The majority of the work from the aforementioned papers is to mitigate the effects of EMI.

Mainali and Oruganti [76] implemented the technique for noise mitigation at the generation stage. Lim *et al.* [77] described a technique that involves the use of the pseudo-random carrier modulation scheme. Şahin and Güzelis [78] used PWFM since it is a reliable and cheap method which could be used in small high frequency converters. From the authors response, it has been concluded that non-periodic chaotic modulation contains high attenuation from EMI.

Ming *et al.* [79] promoted a technique, where the circuit adopted an advanced pseudorandom sequence to change the clock frequency discretely, thus enhancing the consistency of the spectrum in defined range of frequency. Li *et al.* [80] implements the technique that involves the use random Pulse width modulation (PWM). Random PWM techniques allow the elimination of the harmonics, resulting in a continuous spectrum of noise. Thus, EMI can be reduced at the output. Boudouda *et al.* [81] described the Optimal Random Pulse Width Modulation (ORPWM) for the control of the three-phase inverter in a Variable Speed Drive (VSD). The two advantages over this method are (a). It ORPWM gives more accuracy than DPWM. (b). This system can be inserted in the closed loop of speed control of an induction motor based on field orientation technique. Tsai *et al.* [82] discussed the technology that uses here combines Random Pulse Position Modulation (RPPM)/digital pulse width modulation (DPWM) for a buck converter to achieve low-conductive EMI and a fast-transient response. The system automatically switches between RPPM mode and DPWM mode smoothly. González *et al.* [83] explained about the technique that involves the interleaving and the modulation of some characteristics of the switching patterns.

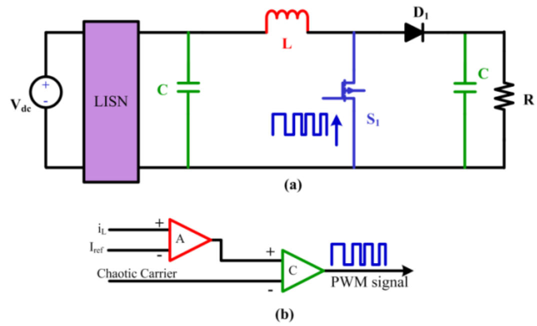

FIGURE 10. (a) Schematic circuit diagram of chaotic PWM boost converter, (b) block diagram for chaotic PWM pulse generation.

Santolaria *et al.* [84] executed the method that involves the use of the frequency modulation technique which modulates the constant switching frequency. This technique is transformed from simple frequency modulation technique. It is derived such that chaotic frequency spreading scheme can generate a well-defined sequence which look like random and hence gives flexibility. The authors in [68], [85] implemented the technique that involves the use of the random space vector pulse width modulation (RSVPWM). The paper discussed the realization method of RSVPWM in a 32-Bit Single-Chip Microcontroller. Here, dual-tone triangular and random modulation profiles are merged to minimize the effect of electromagnetic interference. The summary related to random modulation technique is derived in the form of Table 3.

DC-DC boost converter is subjected to EMI when operated with constant periodic PWM switching. Further, EMI in DC-DC converters can be regarded as a serious issue since it limits the capability of the DC-DC converter. In order to overcome the problem pertinent with periodic PWM method, Chaotic PWM (CPWM) method is considered an alternative method to mitigate EMI by a large amount. Hence, a review of CPWM method proposed for suppression of EMI in DC-DC boost converter in literature is presented. The chaotic PWM pulse generation for DC-DC converter is shown in Fig.10 (b). The authors in [86]–[91] discussed the chaotic attractor that has been observed with an extremely simple autonomous circuit. In addition, the authors also simulated spatio-temporal phenomena in discrete CNNs of dimension one, two, and three.

The authors in [92]–[95] showed that the chaos phenomenon can be effectively used in minimizing EMI problems in power electronic circuits, since, the controllers based on chaos, spreads the spectrum of converters. Therefore, can reduce the interference power at any target frequency and strengthen the signal strength and frequency.

The authors in [96], [97] implemented the technique that involves the use of the chaotic pulse width modulation (CPWM). The methodology here deals with the logistic mapping to choose a frequency-modulated signal which then modulates the carrier frequency. Mukherjee *et al.* [98]

TABLE 3. Different types random modulated switching used in power converters.

Author	Year	Switching Frequency	Type of switching	Power Level	Type of converter used	Suppression Level
K. K. Tse [63]	2002	100 kHz	PCFM, RCFM	--	DC-DC converter	RCFM Introduces low frequency harmonics
Yue Ma [64]	2004	250 kHz (for Buck) 1000 kHz (for Boost)	PWM Feedback Control	10 W	Voltage mode-controlled Buck Converter & Current mode control Boost Converter	-
Bhajana, V et al. [47]	2005	60 Hz	RPWM based on Programmed PWM	0.18 kW	Inverter	Low order harmonics from 3 to 21 are eliminated
F. Mihalič [65]	2005		Randomized PWM	-	DC-DC converter	reduces conductive noise ripple in the low-frequency range up to 2 MHz
Arthur Knitter [66]	2005	75 kHz	CFM (Carrier Frequency Modulation)	-	Switched mode DC-DC converter	Suppression upto 20dB is achieved for fundamental carrier harmonic
Shahriyar Kaboli [70]	2007	25 kHz	RPWM	1 kW	Boost Converter	Upto 20dBμV
Ki-Seon Kim [73]	2009	3 kHz	New Hybrid RPWM with Triangular Carrier Wave	1.5 kW	3 phase Induction Motor Drive	30% improvement than conventional method
Jui-Chi Wu [74]	2009	1 MHz	Random Pulse Position Modulation (RPPM)	-	Buck Converter	Upto 18dBμV
Young Cheol Lim [77]	2010	3 kHz	Pseudo Random Carrier Modulation	200 W	H-bridge Multilevel Inverter	37% improvement is achieved by proposed methodology
Xin Ming [79]	2011	300 kHz	PRM (Psudo Random Modulation)	-	Class-D Amplifier	
A.Boudouda [81]	2012	3 kHz	ORPWM (Optimal RPWM)	1.5 kw	VSD	15dBμV
Chien-Hung Tsai [82]	2013	1 MHz	RPPM	1 W	Buck Converter	--
D. González [83]	2007	200 kHz & 40 kHz	Spread Spectrum Frequency Modulation	2.5 W for Buck and 600 W for Boost Converters	Buck Converter & PFC Boost Converter	For buck converter 10dBμV is obtained
Jaehyeok Yang [68]	2014	100 Hz	Random Modulation	15.8 mW	Phase Rotor based digital PLL	Achieved upto 43 dBμV

described the design of a ramp-generator IC based on a modified modulation technique being used. The authors concluded that this system has a feature by which the user may tune the developed converter hardware to match various EMC standards. A new negative-gm LC chaos oscillator topology is presented. Li *et al.* [99] implemented the technique that involves the use of the CPWM. The methodology here uses analog chaotic PWM suitable for high-frequency operation also its cost is low. From the observations, the authors concluded that the analog chaotic carrier can greatly suppress EMI. Li *et al.* [99] used the technique that involves the use of the chaotic pulse width modulation (CPWM). The methodology here deals with the designing of a chaotic carrier wave. The paper showed that the analog chaotic carrier can greatly suppress EMI. Kapat *et al.* [100] discussed the technique that utilized the pulse skipping modulation (PSM). In this methodology, the duty cycle ratio is controlled by the voltage applied. Thus, this system is good for reducing the EMI.

Zhang *et al.* [101] discusses the technique that involves the use of the chaotic pulse width modulation. The methodology used here is logistic mapping to simultaneously change both the carrier frequency and the pulse position. It can be concluded that the system shows better performance using this technique. Dousoky *et al.* [102] implemented the technique that involves the use of the field-programmable gate array (FPGA). The methodology here uses FPGA-based controller. It is operated on common-mode, differential-mode, and total conducted-noise mode. Aruna and Premalatha [103] discussed how the voltage controlled buck converter is analyzed by FFT for EMI reduction under the used technique of chaos control. The methodology chaos is induced using Wien bridge oscillator as it operates in various mode. Conclusion made shows that the spectrum power spread at switching frequency reduces the level of the emission spectrum. Chen and Shen [104] discussed the technique that involves the use of the CPWM. The methodology used here is simple where the peak EMI magnitude is reduced, and the energy is spread to a wide range of frequencies. It can be concluded that controlling the degree of chaos can gradually spread the discrete frequency over the frequency spectrum.

The authors in [105], [106] implemented the technique that involves the use of the chaotic sinusoidal pulse width modulation (CSPWM). Here, the methodology depends on a chaotic carrier as it is the key to realize the chaotic SPWM control. The paper concluded that by using chaotic SPWM control, not only the EMI but also the THD are reduced without increasing the ripples. Zhao *et al.* [107] talked about the technique that involves the use of the chaotic space vector pulse width modulation (SVPWM) control to improve the EMI. The methodology used here is chaotic sequence with continuous power spectrum to suppress the peak switching harmonics. Thus this method is effective in reducing the EMI. Chau and Chan [108] evaluated the technique that involves the use of the chaotic sinusoidal pulse width modulation (CSPWM). The three modulation techniques used here are the chaotically amplitude, frequency modulation (CAFM), the chaotically pulse position modulation (CPPM), and the hybrid chaotic frequency modulation (HCFM). It can be concluded that this model can produce a better performance for the EMI. Hong Li et al. executed the technique that involves the use of the CSPWM based on double Fourier series. In this article, authors proved that the total harmonics reduction is the same as that carried out in SPWM. Finally, this system shows the effectiveness of the spread frequency technology on EMI suppression. Li *et al.* [109] implemented the technique that involves the use of the CPWM, where, a chaotic saw tooth carrier is used in the SPWM control. This model shows a good reduction in the EMI in the output voltage. Sudhakar et al. discussed the EMI mitigation using chaotic PWM generated using FPGA technology, the generation of pulses seems to be comparatively simple and the suppression was effective [110]. Shanmuga Sundari et al. discussed the conducted EMI suppression using chaotic PWM developed by Lab VIEW tool [111]. Bi-Directional DC-DC converter is used. However, the conclusion says that at low change in the frequency, the lower probability density around the probability density curve center, the better the performance [112]. Quyen *et al.* [113] implemented the technique that involves the use of the CSPWM and it includes the spectrum calculation method based on double Fourier series for PV inverters.

Ravelle and Wilson [114], Hill and Pozzobon [115], and See [116] noticed that noise can appear in receivers by current, voltage, electric or magnetic field coupling, the principle coupling mechanism is used. (In this case conductive coupling from the overhead DC catenary with inductive coupling from adjacent-track crosstalk), and the separate influences of the power supply and traction harmonics are visible.

Lim and Hamill [117], Tse *et al.* [118], and Redoute and Steyaert [119] presented a novel and integrable current mirror structure insensitive to the common charge pumping phenomenon, typically occasioned by conducted EMI. Rea *et al.* [120], Richelli [121], and Poire *et al.* [122] said when subjected to electromagnetic interference, an operational amplifier will generate a DC offset. Reducing the impact of EMI for operational amplifiers can be accomplished by placing a low pass filter at the differential pair input. The embedded LC filtering method can be set up more easily, but current splitting ensures a better control of RC filtering for high frequency harmonics. Britto *et al.* [123] discussed with the EMI suppression in flyback Converter. Also, the authors say that the produced interference can be in the form of conduction or radiation. Further the authors in [124], [125] developed a new EMI suppression method named frequency hopping technique (FHT) using DC-DC converter and developed a mathematical model to estimate the effectiveness of the FHT of a DC-DC converter. The proposed FHT method reduces the power spectrum by 13.5 dB compared with conventional techniques. The differential mode noise is dominant in a interleaved power factor correction circuit. Hence, a differential mode filter is connected in the circuit [126]. In addition, a simplified differential mode noise model is developed by the authors in [127]. The authors in [128] proposed a magnetic modelling of an interleaved power factor correction converter with an input differential mode EMI filter. A study on DPWM based control method and spectral flattening technique for a medium rated power DC-DC converter is proposed by the authors in [129]. The various types of chaotic modulated switching's used in power electronic converters were presented in Table 4.

IV. SUGGESTIONS BASED ON THE DISCUSSIONS

✓ EMI filter is the most widely used mitigation method for narrow band frequencies. Hence, EMI filter should be equipped with provisions for hybridization with other technique.

TABLE 4. Different types chaotic modulated switching used in power converters.

Author	Year	Switching Frequency	Type of switching	Power Level	Type of Converter Used	Suppression Level
Matsumoto [86]	1984	-	Control using Microprocessor	-	Boiler System in Thermal Power Plant	-
G Poddar [88]	1995	1 kHz		-	Current controlled Boost Converter	-
Zheng Wang [96]	2007	150 kHz	CFMPWM & CAMPWM	400W	Motor Drives	4.6 dB & 5.6 dB
Rupam Mukherjee [98]	2008	100 kHz	Chaotic pulse using Ramp Generator	5W	Buck Converter	20 dB
Zhang [101]	2010	100 kHz	ZVT	-	PFC Boost Converter	A few dB
Shantunu Kapat [100]	2011	33 kHz	PSM (Pulse Skipping Modulation)	-	DC-DC Converter	-
Sudhakar N [110]	2014	15 kHZ	RCFMFD based CPWM	-	DC-DC Boost Converter	4 dB

- ✓ Soft switching archives EMI suppression with additional auxiliary circuits. However, additional circuitry for minimizing dv/dt and di/dt stress increases design complexity. Therefore, appropriate care should be taken in selecting the soft switching scheme. At the same time, this technique is limited to power levels above 30W.
- ✓ Modulation in an arbitrary method is an interesting approach to reduce EMI.
- ✓ The easiest method of EMI mitigation method is chaotic PWM. Applying a chaotic carrier is much more effective in reducing EMI at the low frequency band. However, it requires high speed digital processors for its implementation.

V. CONCLUSION

This paper presented a technical review for mitigating conducted EMI occurring due to power converters. Power electronic converters are inevitable due to its significant penetration in various applications covering all domains. However, its, bulkiness and attenuation of useful signal limits its usage. Application of soft switching technique is critical in achieving high level of EMI suppression in power converter. The additional space needed for auxiliary components and design complexity restricts its usage for power wattage for only above 30W. Well-designed soft switching circuits can achieve high level of spectral peak reduction. Use of single switch for achieving ZVS and ZCS operation can also be researched.

Large part of the literature concentrates on suppression of EMI after its generation. Alternatively, EMI on its source can be minimized via modulation technique. Random modulation techniques have a greater impact on EMI mitigation. However, the effectiveness of this mitigation method depends on obtaining real random signals. Simplified and more accurate techniques are needed for pseudo random pulse generation. Due to the rapid development of digital signal processing, the chaotic PWM method assumes significance. Further issues such as EMI reduction, spectral distribution over the wide range of frequency are well handled by this method. However, it seems that chaotic PWM with EMI filter, chaotic soft switching is a good solution for active and accurate EMI Mitigation. It is hoped that this review will be a very useful reference for the researchers and practicing engineers.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to VIT University, Vellore, and the G. Pullaiah College of Engineering and Technology (Autonomous), India, for giving the opportunity to do the project in this area. They would also like to acknowledge Renewable Energy Laboratory, College of Engineering, Prince Sultan University, Saudi Arabia, for providing technical guidance for the execution of this research activity.

REFERENCES

[1] H. Li, Z. Li, B. Zhang, W. K. S. Tang, and W. A. Halang, "Suppressing electromagnetic interference in direct current converters," *IEEE Circuits Syst. Mag.*, vol. 9, no. 4, pp. 10–28, 4th Quart., 2009.

[2] D. M. Witters and P. S. Ruggera, "Electromagnetic compatibility (EMC) of powered wheelchairs and scooters," in *Proc. 16th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, vol. 2, Nov. 1994, pp. 894–895.

[3] F. Briault, M. Helier, D. Lecointe, J.-C. Bolomey, and R. Chotard, "Broad-band modeling of a realistic power converter shield for electric vehicle applications," *IEEE Trans. Electromagn. Compat.*, vol. 42, no. 4, pp. 477–486, Nov. 2000.

[4] J.-S. Lai, S.-R. Moon, R. Kim, F.-Y. Lin, Y.-H. Liu, and M.-H. Lin, "A general-purpose three-phase DC-DC converter building block for fuel cell applications," in *Proc. 33rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2007, pp. 1639–1644.

[5] W. H. Parker, "Electromagnetic interference: A tutorial," in *Proc. IEEE Aerosp. Appl. Conf.*, vol. 3, Feb. 1996, pp. 177–186.

[6] J. H. Deane and D. C. Hamill, "Improvement of power supply EMC by chaos," *Electron. Lett.*, vol. 32, no. 12, p. 1046, 1996.

[7] C. S. Moo, H. C. Yen, Y. C. Hsieh, and Y. C. Chuang, "Integrated design of EMI filter and PFC low-pass filter for power electronic converters," *IEE Proc.-Electr. Power Appl.*, vol. 150, no. 1, pp. 39–44, Jan. 2003.

[8] T. V. Dixit, A. Yadav, and S. Gupta, ''Experimental assessment of maximum power extraction from solar panel with different converter topologies,'' *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 2, p. 2712, 2019.

[9] W. C. Ho, C. K. Lee, X. Liu, P. K. Chan, S. Y. R. Hui, and Y. S. Lee, ''A hybrid EMI filter with ultra-wide bandwidth,'' in *Proc. 23rd Annu. IEEE Appl. Power Electron. Conf. Expo.*, Feb. 2008, pp. 676–681.

[10] S.-J. Wu, C.-H. Tsai, T.-L. Wu, and T. Itoh, ''A novel wideband common-mode suppression filter for gigahertz differential signals using coupled patterned ground structure,'' *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 4, pp. 848–855, Apr. 2009.

[11] C.-H. Tsai and T.-L. Wu, ''A metamaterial-typed differential transmission line with broadband common-mode suppresssion,'' in *Proc. Int. Symp. Electromagn. Compat.-EMC Eur.*, Jun. 2009, pp. 1–4.

[12] H. Balan, M. I. Buzdugan, C. Chiorean, A. Iacob, and P. Karaisas, ''A passive EMI filter for the reduction of active filter generated network distortions,'' in *Proc. Int. Conf. Appl. Theor. Electr. (ICATE)*, Oct. 2012, pp. 1–6.

[13] C. Tao, P. Wang, and J. Zhang, ''An efficient common-mode hybrid EMI filter used in switch-mode power supply,'' in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, May 2009, pp. 951–953.

[14] T.-L. Wu, H.-H. Chuang, and T.-K. Wang, ''Overview of power integrity solutions on package and PCB: Decoupling and EBG isolation,'' *IEEE Trans. Electromagn. Compat.*, vol. 52, no. 2, pp. 346–356, May 2010.

[15] L. Li, Y. Wang, L. Wan, X. Liu, R. Sun, and S. Yu, ''Electromagnetic interference suppression and simultaneous switching noise mitigation in system on package using a lowpass filter structure with embedded capacitor,'' in *Proc. 11th Electron. Packag. Technol. Conf.*, 2009, pp. 692–696.

[16] Y. F. Bai, X. H. Wang, X. W. Shi, Y. Y. Yang, and P. Li, ''The optimization design of power filter by genetic algorithm,'' in *Proc. 5th Asia–Pacific Conf. Environ. Electromagn.*, 2009, pp. 122–125.

[17] P.-S. Chen and Y.-S. Lai, ''Effective EMI filter design method for three-phase inverter based upon software noise separation,'' *IEEE Trans. Power Electron.*, vol. 25, no. 11, pp. 2797–2806, Nov. 2010.

[18] J. Fukuda, S. Ogasawara, and M. Takemoto, ''A basic study on inverter output filter for radiative noise suppression,'' in *Proc. Int. Power Electron. Conf.-ECCE ASIA*, 2010, pp. 2872–2876.

[19] D. Hamza, M. Sawan, and P. K. Jain, ''Suppression of common-mode input electromagnetic interference noise in DC-DC converters using the active filtering method,'' *IET Power Electron.*, vol. 4, no. 7, pp. 776–784, 2011.

[20] S. Ye, W. Eberle, and Y.-F. Liu, ''A novel EMI filter design method for switching power supplies,'' *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1668–1678, Nov. 2004.

[21] S. Wang, Y. Y. Maillet, F. Wang, R. Lai, F. Luo, and D. Boroyevich, ''Parasitic effects of grounding paths on common-mode EMI filter's performance in power electronics systems,'' *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3050–3059, Sep. 2010.

[22] S. J. Underwood, ''DC-DC converters suppress EMI: Minimizing EMI at its source-higher current demands and higher operational speeds are placing greater demands that switching power supply EMI be suppressed,'' *Power Electron. Technol.*, vol. 28, no. 12, pp. 14–21, 2002.

[23] V. Serrao, A. Lidozzi, L. Solero, and N. A. Di, ''Common and differential mode EMI filters for power electronics,'' in *Proc. Int. Symp. Power Electron., Elect. Drives, Autom. Motion*, 2008, pp. 918–923.

[24] G. A. Latheef, S. Karunakaran, and K. Sridhar, ''Tuned band reject powerline EMI filter,'' in *Proc. Int. Conf. Electromagn. Interference Compat. (INCEMIC)*, 1995, pp. 436–439.

[25] S. Ogasawara, H. Ayano, and H. Akagi, ''An active circuit for cancellation of common-mode voltage generated by a PWM inverter,'' *IEEE Trans. Power Electron.*, vol. 13, no. 5, pp. 835–841, Sep. 1998.

[26] J. Walker, ''Designing practical and effective active filters,'' in *Proc. Int. Conf. Power Syst. Technol.*, Dallas, TX, USA, vols. 1–3, 1998, pp. 1–8.

[27] W. Chen, X. Yang, and Z. Wang, ''An active EMI filtering technique for improving passive filter low-frequency performance,'' *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 1, pp. 172–177, Feb. 2006.

[28] T. Farkas and M. F. Schlecht, ''Viability of active EMI filters for utility applications,'' *IEEE Trans. Power Electron.*, vol. 9, no. 3, pp. 328–337, May 1994.

[29] L. E. LaWhite and M. F. Schlecht, ''Active filters for 1-MHz power circuits with strct input/output ripple requirements,'' *IEEE Trans. Power Electron.*, vol. PE-2, no. 4, pp. 282–290, Oct. 1987.

[30] L. LaWhite and M. F. Schlecht, ''Design of active ripple filters for power circuits operating in the 1-10 MHz range,'' *IEEE Trans. Power Electron.*, vol. 3, no. 3, pp. 310–317, Jul. 1998.

[31] H. K. Patel, ''Critical considerations for EMI filter design in switch mode power supply,'' in *Proc. IEEE Int. Conf. Ind. Technol.*, Dec. 2006, pp. 1843–1848.

[32] C. Bona and F. L. Fiori, ''A new filtering technique that makes power transistors immune to EMI,'' *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2946–2955, Oct. 2011.

[33] D. Hamza, M. Qiu, and P. Jain, ''Interface impedance consideration in the design of an input EMI filter for grid-tied PV micro-inverter,'' in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2011, pp. 1390–1395.

[34] J. Amini, ''High performance shunt active power filter based on flying capacitor multilevel inverter using multi-stage $\Sigma\Delta$ modulator,'' in *Proc. 19th Iranian Conf. Elect. Eng.*, May 2011, pp. 1–6.

[35] F. Luo, X. Zhang, D. Boroyevich, P. Mattevelli, J. Xue, F. Wang, and N. Gazel, ''On discussion of AC and DC side EMI filters design for conducted noise suppression in DC-fed three phase motor drive system,'' in *Proc. 26th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2011, pp. 667–672.

[36] D. Hamza, M. Qiu, and P. K. Jain, ''Application and stability analysis of a novel digital active EMI filter used in a grid-tied PV microinverter module,'' *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2867–2874, Jun. 2013.

[37] M. Ali, E. Laboure, F. Costa, B. Revol, and C. Gautier, ''Hybrid integrated EMC filter for CM and DM EMC suppression in a DC-DC power converter,'' in *Proc. 7th Int. Conf. Integr. Power Electron. Syst. (CIPS)*, Mar. 2012, pp. 1–6.

[38] M. Danilovic, F. Luo, L. Xue, R. Wang, P. Mattavelli, and D. Boroyevich, ''Size and weight dependence of the single stage input EMI filter on switching frequency for low voltage bus aircraft applications,'' in *Proc. 15th Int. Power Electron. Motion Control Conf. (EPE/PEMC)*, Sep. 2012, p. LS4a-4.

[39] Y.-T. Chou and H.-C. Lu, ''Magnetic near-field probes with high-pass and notch filters for electric field suppression,'' *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 6, pp. 2460–2470, Jun. 2013.

[40] C. Xu and S. Wang, ''Effects of mix-mode noise emissions on the design method of planar EMI filter,'' in *Proc. IEEE 8th Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2013, pp. 696–699.

[41] F. de Paulis, M. H. Nisanci, A. Orlandi, X. Gu, R. Rimolo-Donadio, C. Baks, Y. Kwark, B. Archambeault, and S. Connor, ''Experimental validation of an 8 GHz EBG based common mode filter and impact of manufacturing uncertainties,'' in *Proc. IEEE Int. Symp. Electromagn. Compat.*, Aug. 2013, pp. 27–32.

[42] S. Wang and C. Xu, ''Design theory and implementation of a planar EMI filter based on annular integrated inductor–capacitor unit,'' *IEEE Trans. Power Electron.*, vol. 28, no. 3, pp. 1167–1176, Mar. 2013.

[43] S. Natarajan and R. Natarajan, ''An FPGA chaos-based PWM technique combined with simple passive filter for effective EMI spectral peak reduction in DC-DC converter,'' *Adv. Power Electron.*, vol. 2014, pp. 1–11, Feb. 2014.

[44] C.-Y. Hsiao, Y.-C. Huang, and T.-L. Wu, ''An ultra-compact common-mode bandstop filter with modified-T circuits in integrated passive device (IPD) process,'' *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 11, pp. 3624–3631, Nov. 2015.

[45] H. Chen, Z. Qian, Z. Zeng, and C. Wolf, ''Modeling of parasitic inductive couplings in a Pi-shaped common mode EMI filter,'' *IEEE Trans. Electromagn. Compat.*, vol. 50, no. 1, pp. 71–79, Feb. 2008.

[46] P. K. Astaneh, J. Javidan, K. Valipour, and A. Akbarimajd, ''A bidirectional high step-up multi-input DC-DC converter with soft switching,'' *Int. Trans. Elect. Energy Syst.*, vol. 29, no. 1, p. e2699, 2019.

[47] V. V. S. K. Bhajana, P. Drabek, and P. K. Aylapogu, ''Design and implementation of a zero voltage transition bidirectional DC-DC converter for DC traction vehicles,'' *Int. Trans. Elect. Energy Syst.*, vol. 29, no. 5, pp. 1–14, Feb. 2019.

[48] H. Ogiwara, M. Itoi, and M. Nakaoka, ''PWM-controlled soft-switching SEPP high-frequency inverter for induction-heating applications,'' *IEE Proc.-Electr. Power Appl.*, vol. 151, no. 4, pp. 404–413, Jul. 2004.

[49] K. Taniguchi, T. Morizane, N. Kimura, and M. Ogawa, ''OSAKA converter—Large scale three-phase soft-switching power factor corrected converter,'' in *Proc. 4th Int. Power Electron. Motion Control Conf.*, vol. 2, Aug. 2004, pp. 913–918.

[50] P. Kongsakorn and A. Jangwanitlert, "A two-output high frequency series-resonant induction heater," in *Proc. ECTI Int. Conf. Elect. Eng./Electron., Comput., Telecommun. Inf. Technol. (ECTI-CON)*, 2010, pp. 842–845.

[51] N. Sudhakar, N. Rajasekar, V. T. Rohit, E. Rakesh, and J. Jacob, "EMI mitigation in closed loop boost converter using soft switching combined with chaotic mapping," in *Proc. Int. Conf. Adv. Electr. Eng. (ICAEE)*, 2014, pp. 1–6.

[52] T.-F. Wu and S.-A. Liang, "A systematic approach to developing single-stage soft switching PWM converters," *IEEE Trans. Power Electron.*, vol. 16, no. 5, pp. 581–593, Sep. 2001.

[53] R. Monteiro, B. Borges, and V. Anunciada, "EMI reduction by optimizing the output voltage rise time and fail time in high-frequency soft-switching converters," in *Proc. IEEE 35th Annu. Power Electron. Spec. Conf.*, vol. 2, 2004, pp. 1127–1132.

[54] R. J. Wai, C. Y. Lin, L. W. Liu, and R. Y. Duan, "Voltage-clamped forward quasi-resonant converter with soft switching and reduced switch stress," *IEE Proc.-Electr. Power Appl.*, vol. 152, no. 3, pp. 558–564, May 2005.

[55] W. Li and X. He, "High step-up soft switching interleaved boost converters with cross-winding-coupled inductors and reduced auxiliary switch number," *IET Power Electron.*, vol. 2, no. 2, pp. 125–133, Mar. 2009.

[56] T. Morimoto, K. Saito, M. Nakamura, and M. Nakaoka, "A novel voltage source PWM DC-DC converter using transformer parasitic inductive components-assisted soft-commutation scheme," in *Proc. 8th Int. Conf. Power Electron. Variable Speed Drives*, Sep. 2000, pp. 97–102.

[57] Z. Lu, Z. Qian, and T. C. Green, "Limitation of soft-switching technique in AC/DC power converter's efficiency improvement," *J. Electron.*, vol. 17, no. 4, pp. 363–369, 2000.

[58] R. Iijima, T. Isobe, and H. Tadano, "Loss comparison of Z-source inverter from the perspective of short-through mode implementation and type of switching device," in *Proc. IEEE 2nd Int. Future Energy Electron. Conf. (IFEEC)*, Nov. 2015, pp. 1–6.

[59] M. R. Yazdani and H. Farzanehfard, "Conducted electromagnetic interference analysis and mitigation using zero-current transition soft switching and spread spectrum techniques," *IET Power Electron.*, vol. 5, no. 7, pp. 1034–1041, 2012.

[60] N. Hoshi and A. Matsui, "Improvement of power conversion efficiency of soft-switching inverter in range of low output power by adjustable dead time control," *Elect. Eng. Jpn.*, vol. 180, no. 1, pp. 57–64, 2012.

[61] K. J. Lee, B.-G. Park, R.-Y. Kim, and D.-S. Hyun, "Nonisolated ZVT two-inductor boost converter with a single resonant inductor for high step-up applications," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 1966–1973, Apr. 2012.

[62] A. Charalambous, X. Yuan, N. McNeill, Q. Yan, N. Oswald, and P. Mellor, "EMI reduction with a soft-switched auxiliary commutated pole inverter," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 2650–2657.

[63] K. K. Tse, H. S.-H. Chung, S. Y. R. Hui, and H. C. So, "A comparative study of carrier-frequency modulation techniques for conducted EMI suppression in PWM converters," *IEEE Trans. Ind. Electron.*, vol. 49, no. 3, pp. 618–627, Jun. 2002.

[64] Y. Ma and H. Kawakami, "Control of bifurcation in DC/DC PWM switching converters," in *Proc. 8th Control, Autom., Robot. Vis. Conf. (ICARCV)*, vol. 2, Dec. 2004, pp. 1421–1426.

[65] F. Mihalic and D. Kos, "Conductive EMI reduction in DC-DC converters by using the randomized PWM," in *Proc. IEEE Int. Symp. Ind. Electron. (ISIE)*, vol. 2, Jun. 2005, pp. 809–814.

[66] A. Knitter, J. Łuszcz, and P. J. Chrzan, "Conducted EMI mitigation in switched mode DC-DC converters by spread spectrum techniques," *Elect. Power Qual. Utilisation J.*, vol. 11, no. 2, pp. 49–55, 2005.

[67] T.-L. Lee and S.-H. Hu, "Discrete frequency-tuning active filter to suppress harmonic resonances of closed-loop distribution power systems," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 137–148, Jan. 2011.

[68] J. Yang, J.-Y. Lee, S.-J. Lim, and H.-M. Bae, "Phase-rotator-based all-digital phase-locked loop for a spread-spectrum clock generator," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 61, no. 11, pp. 880–884, Nov. 2014.

[69] J. Ko, S. Lee, D. Kim, K. Kim, and K. E. Chang, "Spread spectrum clock generator for reducing electro-magnetic interference (EMI) noise in LCD driver IC," in *Proc. 50th Midwest Symp. Circuits Syst.*, 2007, pp. 1106–1109.

[70] S. Kaboli, J. Mahdavi, and A. Agah, "Application of random PWM technique for reducing the conducted electromagnetic emissions in active filters," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2333–2343, Aug. 2007.

[71] M. Kurtoğlu, F. Eroğlu, A. O. Arslan, and A. M. Vural, "Recent contributions and future prospects of the modular multilevel converters: A comprehensive review," *Int. Trans. Elect. Energy Syst.*, vol. 29, no. 3, p. e2763, 2019.

[72] H. Guo, Z. Li, B. Zhang, and Z. Li, "Conducted EMI suppression by random carrier frequency modulation techniques," in *Proc. Int. Conf. Commun., Circuits Syst.*, 2009, pp. 693–696.

[73] K. S. Kim, Y. G. Jung, and Y. C. Lim, "A new hybrid random PWM scheme," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 192–200, Jan. 2009.

[74] J.-C. Wu, C.-W. Mu, C.-H. Yang, and C.-H. Tsai, "Digitally controlled low-EMI switching converter with random pulse position modulation," in *Proc. IEEE Asian Solid-State Circuits Conf.*, Nov. 2009, pp. 341–344.

[75] A. M. Trzynadlowski, K. Borisov, Y. Li, and L. Qin, "A novel random PWM technique with low computational overhead and constant sampling frequency for high-volume, low-cost applications," *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 116–122, Jan. 2005.

[76] K. Mainali and R. Oruganti, "Conducted EMI mitigation techniques for switch-mode power converters: A survey," *IEEE Trans. Power Electron.*, vol. 25, no. 9, pp. 2344–2356, Sep. 2010.

[77] Y.-C. Lim, S.-O. Wi, J.-N. Kim, and Y.-G. Jung, "A pseudorandom carrier modulation scheme," *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 797–805, Apr. 2010.

[78] S. Şahin and C. Güzelis, "'Chaotification' of real systems by dynamic state feedback," *IEEE Antennas Propag. Mag.*, vol. 52, no. 6, pp. 222–233, Dec. 2010.

[79] X. Ming, Z. Chen, Z.-K. Zhou, and B. Zhang, "An advanced spread spectrum architecture using pseudorandom modulation to improve EMI in class D amplifier," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 638–646, Feb. 2011.

[80] H. Li, Z. Li, W. A. Halang, and W. K. S. Tang, "A chaotic soft switching PWM boost converter for EMI reduction," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jun./Jul. 2008, pp. 341–346.

[81] A. Boudouda, N. Boudjerda, M. Melit, B. Nekhoul, K. E. K. Drissi, and K. Kerroum, "Optimized RPWM technique for a variable speed drive using induction motor," in *Proc. Int. Symp. Electromagn. Compat.-EMC Eur.*, 2012, pp. 1–6.

[82] C. H. Tsai, C. H. Yang, and J. C. Wu, "A digitally controlled switching regulator with reduced conductive EMI spectra," *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 3938–3947, Sep. 2013.

[83] D. Gonzalez, J. Balcells, A. Santolaria, J.-C. Le Bunetel, J. Gago, D. Magnon, and S. Brehaut, "Conducted EMI reduction in power converters by means of periodic switching frequency modulation," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2271–2281, Nov. 2007.

[84] A. Santolaria, J. Balcells, D. Gonzalez, and J. Gago, "Evaluation of switching frequency modulation in EMI emissions reduction applied to power converters," in *Proc. 29th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, vol. 3, Nov. 2003, pp. 2306–2311.

[85] G. Chen, Z. Wu, Y. Zhu, and J. Zhao, "Simulation and analysis of random switching frequency space vector pulse width modulation," *Inf. Technol. J.*, vol. 12, no. 10, pp. 2009–2015, 2013.

[86] Y. Sato, M. Nomura, H. Matsumoto, and M. Iioka, "Steam temperature prediction control for thermal power plant," *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 9, pp. 2382–2387, Sep. 1984.

[87] W. Xuesong, Z. Zhengming, and Y. Liqiang, "Conducted EMI reduction in IGBT-based converters," in *Proc. Asia–Pacific Int. Symp. Electromagn. Compat.*, 2010, pp. 230–234.

[88] G. Poddar, K. Chakrabarty, and S. Banerjee, "Control of chaos in the boost converter," *Electron. Lett.*, vol. 31, no. 11, pp. 841–842, May 1995.

[89] J. B. Wang, "Reduction in conducted EMI noises of a switching power supply after thermal management design," *IEE Proc.-Electr. Power Appl.*, vol. 150, no. 3, pp. 301–310, May 2003.

[90] K. Chakrabarty, G. Podder, and S. Banerjee, "Bifurcation behavior of the buck converter," *IEEE Trans. Power Electron.*, vol. 11, no. 3, pp. 439–447, May 1996.

[91] S. Callegari, R. Rovatti, and G. Setti, "Chaotic modulations can outperform random ones in electromagnetic interference reduction tasks," *Electron. Lett.*, vol. 38, no. 12, pp. 543–544, Jun. 2002.

[92] S. Banerjee, D. Kastha, and S. SenGupta, "Minimising EMI problems with chaos," in *Proc. Int. Conf. Electromagn. Interference Compat.*, Feb. 2002, pp. 162–167.
[93] A. M. Stankovic, G. C. Verghese, and D. J. Perreault, "Analysis and synthesis of randomized modulation schemes for power converters," *IEEE Trans. Power Electron.*, vol. 10, no. 6, pp. 680–693, Nov. 1995.
[94] K.-S. Tan, I. Hinberg, and J. Wadhwani, "Electromagnetic interference in medical devices: Health Canada's past and current perspectives and activities," in *Proc. IEEE EMC Int. Symp. Rec. Electromagn. Compat.*, vol. 2, Aug. 2001, pp. 1283–1288.
[95] J. Chen, D. Maksimovic, and R. Erickson, "Buck-boost PWM converters having two independently controlled switches," in *Proc. PESC*, Jun. 2001, pp. 736–741.
[96] Z. Wang, K. T. Chau, and C. Liu, "Improvement of electromagnetic compatibility of motor drives using chaotic PWM," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2612–2614, Jun. 2007.
[97] Q. Li, R. Xiong, and O. He, "Reduction in electromagnetic interference of switching converters using self-excitation-chaos," in *Proc. 3rd IEEE Conf. Ind. Electron. Appl.*, Jun. 2008, pp. 879–884.
[98] R. Mukherjee, A. Patra, and S. Banerjee, "Chaos-modulated ramp IC for EMI reduction in PWM buck converters design and analysis of critical issues," in *Proc. 21st Int. Conf. VLSI Design (VLSID)*, Jan. 2008, pp. 305–310.
[99] H. Li, F. Lin, Z. Li, W. A. Halang, and B. Zhang, "Chaotic SVPWM control and its application in EMI suppression for PV inverters," in *Proc. IEEE-APS Top. Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2012, pp. 1213–1216.
[100] S. Kapat, A. Patra, and S. Banerjee, "Achieving monotonic variation of spectral composition in DC–DC converters using pulse skipping modulation," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 58, no. 8, pp. 1958–1966, Aug. 2011.
[101] Z. Zhang, T. W. Ching, C. Liu, and C. H. Lee, "Comparison of chaotic PWM algorithms for electric vehicle motor drives," in *Proc. 38th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2012, pp. 4087–4092.
[102] G. M. Dousoky, M. Shoyama, and T. Ninomiya, "FPGA-based spread-spectrum schemes for conducted-noise mitigation in DC–DC power converters: Design, implementation, and experimental investigation," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 429–435, Feb. 2011.
[103] P. Aruna and L. Premalatha, "Investigation of EMI reduction in buck converter by using external chaos generator," in *Proc. Int. Conf. Recent Advancement Elect., Electron. Control Eng.*, Dec. 2011, pp. 520–525.
[104] F. C. Chen and P. N. Shen, "Suppression of electromagnetic interference of DC-DC power converters by chaos generators," in *Proc. 20th Australas. Univ. Power Eng. Conf.*, 2010, pp. 1–6.
[105] Y. Zhao, G. Tan, L. Zhang, and Y. Zhang, "Supression of electromagnetic interference (EMI) in PWM voltage source rectifier (VSR) based on chaotic SVPWM," in *Proc. IEEE Power Eng. Automat. Conf.*, Sep. 2011, pp. 99–102, doi: 10.1109/PEAM.2011.6134917.
[106] H. Li, T. Q. Zheng, Z. Li, and F. Wang, "EMI suppression for single-phase grid-connected inverter based on chaotic SPWM control," in *Proc. Asia–Pacific Symp. Electromagn. Compat.*, 2012, pp. 125–128.
[107] Y. Zhao, G. Tan, L. Zhang, and Y. Zhang, "Supression of electromagnetic interference (EMI) in PWM voltage source rectifier (VSR) based on chaotic SVPWM," in *Proc. IEEE Power Eng. Autom. Conf.*, vol. 2, Sep. 2011, pp. 99–102.
[108] K. T. Chau and C. C. Chan, "Emerging energy-efficient technologies for hybrid electric vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 821–835, Apr. 2007.
[109] H. Li, Y. Liu, J. Lu, T. Zheng, and X. Yu, "Suppressing EMI in power converters via chaotic SPWM control based on spectrum analysis approach," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 6128–6137, Nov. 2014.
[110] S. Natarajan and R. Natarajan, "Effective suppression of conducted electro magnetic interference in DC-DC boost converter using field programmable gate array based chaotic pulse width modulation switching," *Elect. Power Compon. Syst.*, vol. 42, no. 5, pp. 471–480, 2014.
[111] A. S. Sundari, S. Natarajan, P. Kaliannan, and U. Subramaniam, "Conducted EMI suppression in DC-DC boost converter using labview," *Int. J. Appl. Eng. Res.*, vol. 9, no. 21, pp. 9353–9364, Feb. 2014.
[112] Z. Yang, H. Li, F. Lin, B. Zhang, and J. Lü, "Common-mode electromagnetic interference calculation method for a PV inverter with chaotic SPWM," *IEEE Trans. Magn.*, vol. 51, no. 11, Nov. 2015, Art. no. 8600204.
[113] N. X. Quyen, Y. V. Van, and T. M. Hoang, "Chaotic modulation based on the combination of CPPM and CPWM," in *Proc. Joint INDS ISTET*, Jun. 2011, pp. 1–6.
[114] L. B. Gravelle and P. F. Wilson, "EMI/EMC in printed circuit boards-a literature review," *IEEE Trans. Electromagn. Compat.*, vol. 34, no. 2, pp. 109–116, May 1992.
[115] R. J. Hill and P. Pozzobon, "Fuzzy identification of rail track parameters," in *Proc. IEEE/ASME Joint Railroad Conf.*, Mar. 1997, pp. 11–20.
[116] K. Y. See, "Network for conducted EMI diagnosis," *Electron. Lett.*, vol. 35, no. 17, pp. 1446–1447, Aug. 1999.
[117] Y. H. Lim and D. C. Hamill, "Chaos in spacecraft power systems," *Electron. Lett.*, vol. 35, no. 6, pp. 510–511, Mar. 1999.
[118] C. K. Tse, O. Dranga, and H. C. C. Iu, "Bifurcation analysis of a power-factor-correction boost converter: Uncovering fast-scale instability," in *Proc. Int. Symp. Circuits Syst. (ISCAS)*, vol. 3, May 2003, p. 3.
[119] J.-M. Redoute and M. Steyaert, "Current mirror structure insensitive to conducted EMI," *Electron. Lett.*, vol. 41, no. 21, pp. 1145–1146, Oct. 2005.
[120] S. P. Rea, D. Linton, E. Orr, and J. McConnell, "EMI suppression in an aircraft cooling vent," *IEE Proc.-Microw., Antennas Propag.*, vol. 152, no. 2, pp. 57–62, Apr. 2005.
[121] A. Richelli, "EMI susceptibility issue in analog front-end for sensor applications," *J. Sensors*, vol. 2016, pp. 1–9, Jan. 2016.
[122] Y. Poire, M. Meyer, M. Ramdani, R. Perdriau, and M. Drissi, "Design approach for EMI filters in power supplies," *Electron. Lett.*, vol. 44, no. 3, pp. 235–236, 2008.
[123] K. A. Britto, R. Dhanasekaran, R. Vimala, and B. Saranya, "EMI analysis and evaluation of an improved flyback converter," in *Proc. Int. Conf. Comput. Commun. Informat.*, 2012, pp. 1–7.
[124] J. Ji, W. Chen, X. Yang, and J. Lu, "Delay and decoupling analysis of a digital active EMI filter used in arc welding inverter," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 6710–6722, Aug. 2018.
[125] H. A. Huynh, Y. Han, S. Park, J. Hwang, E. Song, and S. Kim, "Design and analysis of the DC–DC converter with a frequency hopping technique for EMI reduction," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 8, no. 4, pp. 546–553, Apr. 2018.
[126] L. Zhai, L. Lin, X. Zhang, and C. Song, "The effect of distributed parameters on conducted EMI from dc-fed motor drive systems in electric vehicles," *Energies*, vol. 10, no. 1, p. 1, 2017.
[127] H. Zhang, S. Wang, Y. Li, Q. Wang, and D. Fu, "Two-capacitor transformer winding capacitance models for common-mode EMI noise analysis in isolated DC–DC converters," *IEEE Trans. Power Electron.*, vol. 32, no. 11, pp. 8458–8469, Nov. 2017.
[128] Y. Liu, S. Yin, X. Pan, H. Wang, G. Wang, and J. Peng, "Effects of nonlinearity in input filter on the dynamic behavior of an interleaved boost PFC converter," *Energies*, vol. 10, no. 10, p. 1530, 2017.
[129] L. Turos and G. Csernáth, "DPWM techniques in digitally controlled, EMI compliant DC-DC converters," *Procedia Manuf.*, vol. 22, pp. 436–443, Apr. 2018.
[130] D. Mezghani, H. Othmani, and A. Mami, "Bond graph modeling and robust control of a photovoltaic generator that powered an induction motor pump via SEPIC converter," *Int. Trans. Elect. Energy Syst.*, vol. 29, no. 3, p. 2746, 2019.

SUDHAKAR NATARAJAN (Member, IEEE) received the B.E. degree in electrical and electronics engineering from Bharathiyar University, in 2000, the M.Tech. degree in electrical drives and control from Pondicherry University, in 2005, and the Ph.D. degree from the Vellore Institute of Technology, Vellore. He is currently working as an Associate Professor with the School of Electrical Engineering, Vellore Institute of Technology. He has more than 18 years of experience in teaching and research. His research work focused in the area of EMI/EMC in power converters, fuel cell application in electric vehicles, driver circuits for LED lighting applications, nonlinear phenomena in power electronics and chaos control.

THANIKANTI SUDHAKAR BABU (Member, IEEE) received the B.Tech. degree from Jawaharlal Nehru Technological University, Ananthapur, India, in 2009, the M.Tech. degree in power electronics and industrial drives from Anna University, Chennai, India, in 2011, and the Ph.D. degree from VIT University, Vellore, India, in 2017.

He is currently a Postdoctoral Researcher with the Department of Electrical Power Engineering, Institute of Power Engineering, Universiti Tenaga Nasional (UNITEN), Malaysia. He has published more than 30 research articles in various reputed international journals. His areas of interests include design and implementation of solar PV systems, renewable energy resources, power management for hybrid energy systems, fuel cell technologies, electric vehicle, and smart grid. He has been acting as an Editorial Board Member and a Reviewer of various reputed journals, such as the IEEE and IEEE ACCESS, IET, Elsevier, and Taylor and Francis.

KARTHIK BALASUBRAMANIAN received the B.Tech. degree in electrical and electronics engineering with minor in industrial automation from the Vellore Institute of Technology (VIT), Vellore, India, in 2014, and the M.Sc. degree in power engineering from Nanyang Technological University (NTU), Singapore.

Prior to pursuing his master's degree, he was working as an Electrical, Instrumentation Control and Telecommunication Engineer at Saipem, Chennai, India, from July 2014 to May 2017. Prior to joining OTD, he was working at Micron Semiconductor Asia Operations Private Limited, Singapore as a Process and Equipment Engineer, from Aug 2018 to Nov 2019. He is currently working as an Electrical/Automation Engineer at Offshore Technology Development (OTD) Private Ltd., Keppel Offshore and Marine Ltd., Singapore. He has published many research articles in highly reputed national and international journals. His research interests are fuel cell system design, PV system design, power systems, automation, the IoT, semiconductors and applications of power electronics in renewable energy systems. He has served as a Reviewer for various reputed national and international journals. He was the President of Toastmasters International–VIT University Chapter. He has received multiple High-Performance leadership awards from Toastmasters International, USA.

UMASHANKAR SUBRAMANIAM (Senior Member, IEEE) has more than 15 years of teaching, research, and industrial research and development experience. He was an Associate Professor and the Head of VIT Vellore and a Senior Research and Development and a Senior Application Engineer in the fields of power electronics, renewable energy, and electrical drives. He is currently an Associate Professor with the Renewable Energy Laboratory, College of Engineering, Prince Sultan University, Saudi Arabia. He has published more than 250 research articles in national and international journals and conferences. He has also authored/coauthored/contributed 12 books/chapters and 12 technical articles on power electronics applications in renewable energy and allied areas. He is also a member of IACSIT, IDES, and ISTE. He was an Executive Member, from 2014 to 2016. He is also an Editor of *Heliyon* (Elsevier). He has received the Danfoss Innovator Award-Mentor, from 2014 to 2015 and 2017 to 2018, and the Research Award from VIT University, from 2013 to 2018. He also received the INAE Summer Research Fellowship for the year 2014. Under his guidance, 24 P.G. students and more than 25 U.G. students completed the senior design project work, and also, six Ph.D. scholars completed Ph.D. thesis, as a Research Associate. He is also involved in collaborative research projects with various international- and national-level organizations and research institutions. He has taken charge as the Vice Chair of the IEEE Madras Section and the Chair of the IEEE Student Activities, in 2018. He has been the Vice Chair of the IEEE MAS Young Professional of the IEEE Madras Section, since 2017.

DHAFER J. ALMAKHLES (Member, IEEE) received the B.E. degree in electrical engineering from the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in 2006, and the master's (Hons.) and Ph.D. degrees from The University of Auckland, New Zealand, in 2011 and 2016, respectively. Since 2016, he has been with Prince Sultan University, Saudi Arabia, where he is currently an Assistant Professor with the Department of Communications and Networks Engineering and the Director of the Science and Technology Unit. He is also the Leader for the Renewable Energy Research Team and Laboratory, Prince Sultan University. His research interests include the hardware implementation of control theory, signal processing, networked control systems, and sliding mode.