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

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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

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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 fly-back 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.

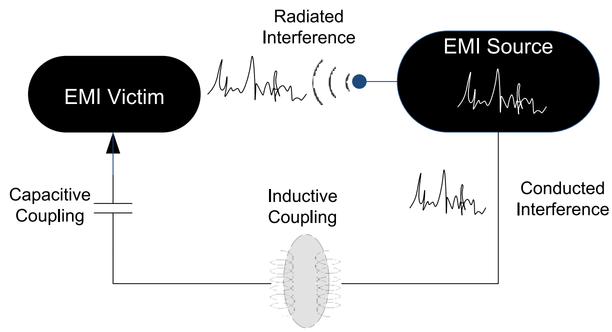

FIGURE 2. Schematic block diagram of electromagnetic interference (EMI) coupling path.

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.

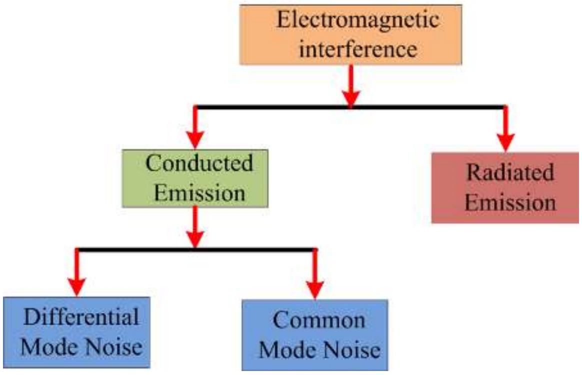

FIGURE 3. Classification of electromagnetic interference in an electrical circuit.

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

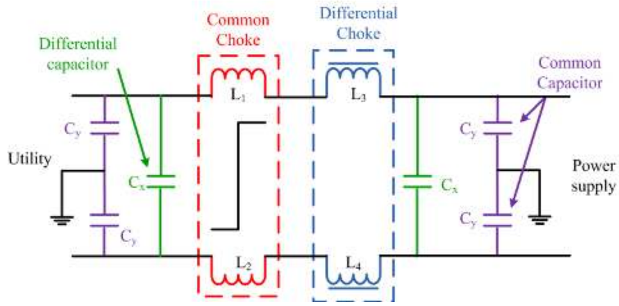

FIGURE 4. Schematic circuit diagram of passive EMI filter.

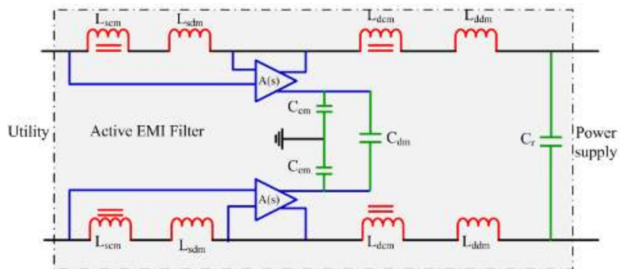

FIGURE 5. Schematic circuit diagram of active EMI filter.

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

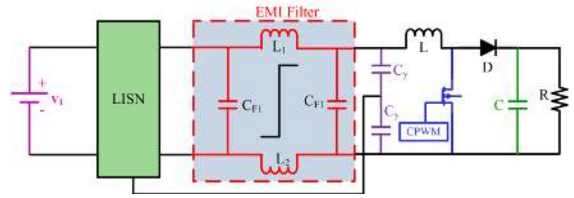

FIGURE 6. General block diagram of EMI filtering.

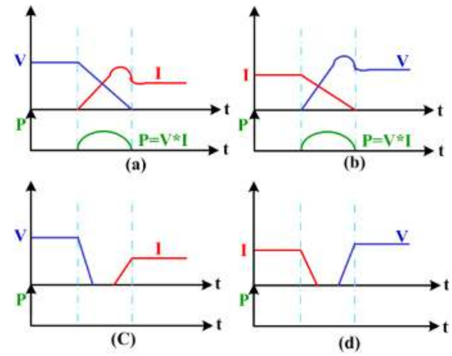

FIGURE 7. Switching sequences of power MOSFET.

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.

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.

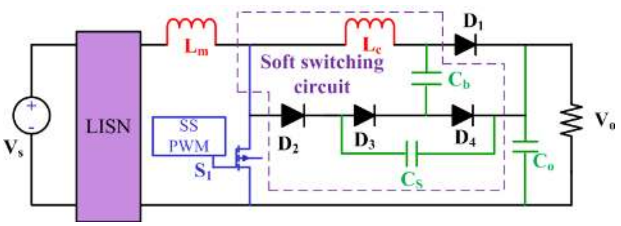

FIGURE 8. **General block diagram of boost converter with soft switching for EMI suppression.**

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.

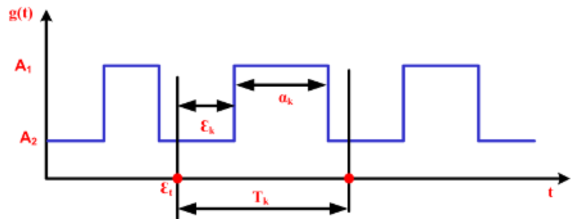

FIGURE 9. Switching signal for randomization of parameters.

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. ahin 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.

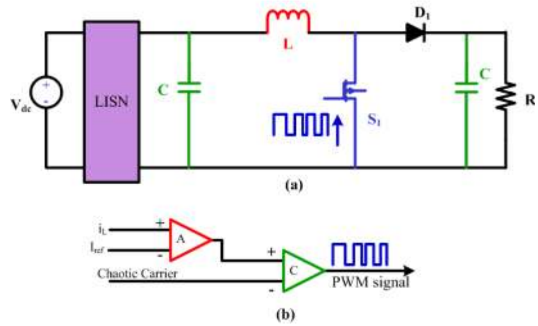

FIGURE 10. (a) Schematic circuit diagram of chaotic PWM boost converter, (b) block diagram for chaotic PWM pulse generation.

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.

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