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 modula-|
| CAFM      | chaotically amplitude frequency modula-|
| 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 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.

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

\[
f_r = f_{pk} 10^{-\frac{\Delta A_s}{10}} \tag{2}
\]

where \( f_{pk} \) 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.

\[
f_{r,CM} = \frac{1}{2\pi \sqrt{L_1 C_y}} \tag{3}
\]

\[
f_{r,DM} = \frac{1}{2\pi \sqrt{(2L_3 + L_4)C_x}} \tag{4}
\]

\( L_1 \) 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.
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 FIGURE 8.

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

**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% (3rd) and 45% (5th) 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 Damilovic [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 | Planer EMI Filter | 150 kHz | - | Flyback Converter | 40 dBµA |
| 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 | 40 dBµV |
| 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 | - |

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

Fig 8. Ogiwara et al. [48] presents a novel quasi resonant high frequency inverter for mitigation of EMI.

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   | 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. | 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 10dBuV                         |
| Jun-Ho Kim [61]       | 2012 | ZVT               | 40 kHz              |             | Interleaved Boost Converter                    | -                                       |
| Apollo Charalambous   | 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 Farzanehfar [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.
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.

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 [86], [87] 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 logic 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 Back)  | PWM Feedback Control                 | 10 W        | Voltage mode-controlled Buck Converter & Current mode control Boost Converter |
|                      |      | 1000 kHz (for Boost)|                                     |             |                                                     |                                                       |
| 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 20dBpV                                           |
| 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 18dBpV                                           |
| 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 (Psuedo Random Modulation)       | -           | Class-D Amplifier                                   |                                                       |
| A. Boudouida [81]    | 2012 | 3 kHz               | ORPWM (Optimal RPWM)                 | 1.5 kw      | VSD                                                 | 15dBpV                                               |
| 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 10dBpV is obtained   |
| Jaehyuk Yang [68]    | 2014 | 100 Hz              | Random Modulation                    | 15.8 mW     | Phase Rotor based digital PLL                       | Achieved upto 43 dBpV                                 |

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 (CAF), 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    | -                |
| G Poddar [88]   | 1995 | 1 kHz               | -                                          | -           | Current controlled Boost    | -                |
| 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         |
| Shantuna Kapat [100] | 2011 | 33 kHz              | FSM (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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