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Classification and Comparison of EMI Mitigation Techniques in Switching Power Converters – A Review

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Abstract

Power electronic systems such as switching power supplies are accounted as noise sources for other sensitive circuits. EMI caused by power converters can disturb the normal operation of the converter and other adjacent systems. Major research is concentrated on EMI mitigation for power converters in which the main concern is compliance with EMC standards to ensure proper operation of converters and nearby systems. This paper reviews EMI reduction techniques related to switching power converters with emphasis on the conducted EMI. A comprehensive review of significant research works is performed and various methods are thoroughly discussed and compared. Also, a classification of methods is presented. Moreover, converter prototypes are realized which contain several EMI mitigation techniques and their effects are presented via experimental results.

Key Words: EMC, EMI, Line Impedance Stabilization Network (LISN), Power converter

I. INTRODUCTION

In the design of power electronic systems, many electrical, magnetic, thermal and mechanical parameters are considered. Among these parameters, the electromagnetic interference (EMI) in power electronic circuits is a major aspect which becomes more significant at high powers and high frequencies. The EMI generated by switching power converters interferes with the normal operation of other sensitive equipment and may cause operating faults. Nowadays, international standards on electromagnetic compatibility (EMC) [1] such as those of the FCC (Federal Communications Commission) and the CISPR (International Special Committee on Radio Interference) [2] are more stringent for noise reduction in switching power converters. EMI can be in the form of radiation or conduction [3]. The first form deals with the electromagnetic field radiated from power electronics converters. Conducted EMI passes through supply lines and interconnecting wires and is divided into common mode (CM) and differential mode (DM) which are identified by their noise propagation [4]. Many EMI reduction techniques have been used to reduce common mode noise in the literature because CM has a greater contribution to the generation of radiated emissions [5]. Taking EMI into account in the design stage can ensure electromagnetic compatibility before circuit realization leading to reductions in both time and cost. The selection of effective methods based on converter behavior is necessary for optimum EMI reduction. In this paper, literature related to the EMI mitigation methods of switching power converters is reviewed with focus on the conducted EMI. Also, a classification and a comparison of various methods are presented.

II. EMI REDUCTION METHODS

EMI reduction techniques employ additional elements in the power topology [5]–[7] or different control approaches [**?**], [9]–[18] for switching power converters. Since EMI reduction techniques are mainly applied to the power or control section, these techniques are classified into two categories: methods in the power section and methods in the control section. In addition, popular EMC methods such as grounding and shielding can be employed in both sections. Grounding and shielding are well-known techniques for EMC consideration [1], [3] and are not restated in this paper.

Methods in the control section are mostly implemented using two concepts: 1) varying the switching frequency and 2) improving the gate circuitry. The variable switching frequency

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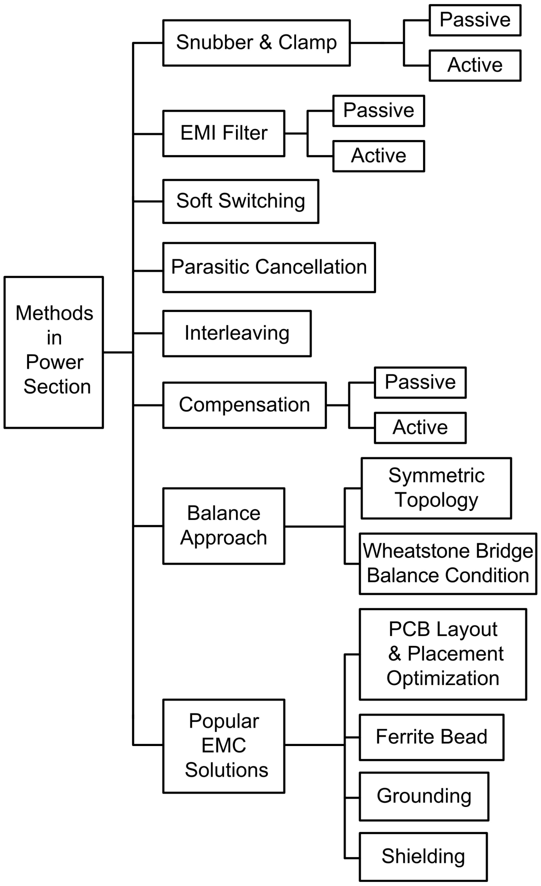


Fig. 1. EMI mitigation methods applied to power section [21]–[68].

[8] method is a well-known approach for spreading the EMI spectrum and consequently, lowering the EMI level. Randomized modulation [13]–[15], frequency modulation [16]–[18] and some other control methods such as chaos control [9], [10] and sigma delta [11], [12] all require a variable switching frequency.

These methods improve EMC, but may result in a non-optimal design of the magnetizing components, a higher THD [18] and a greater complexity. Also, there are passive [19] and active gate circuitry [20] techniques implemented in the control section such as increasing the equivalent gate driver resistance which may result in increasing the switching losses. A more detailed survey of EMI reduction techniques related to the control section is beyond the scope of this paper and will be the subject of a future investigation.

In this paper, the EMI mitigation techniques which are essentially implemented in the power section are reviewed. Fig. 1 shows the EMI reduction methods mainly related to the power aspect.

A. Snubber and clamp

In general, di/dt and dv/dt of the switch should be decreased for EMI mitigation. Traditionally, snubber circuits performed this in the power section. Snubbers can be divided into passive and active circuits.

Although, snubbers decrease noise, they may increase power dissipation and yield efficiency reduction. In addition, higher complexity, size and cost are unavoidable which become more significant at higher rated powers [6]. Although lossless snubbers have been introduced [21], [22] to lower power dissipation, extended elements are needed. Additional components would further increase the converter conduction losses [21] and the parasitic contribution in EMI. In addition, passive lossless snubbers usually introduce additional current and voltage stresses. In [22], an active lossless snubber is introduced for a forward converter which uses a capacitor, two diodes and an extra inductor. In this forward converter with the snubber topology, there is no need for a reset transformer winding. Recently, energy regenerative snubbers have been introduced. For instance in [23], a regenerative snubber for the forward converter is proposed, as shown in Fig. 2. This lossless snubber has some advantages such as providing zero voltage switching (ZVS) for the main switch, transferring the recovered energy to the source and load and controlling dv/dt of the switch. As illustrated in Fig. 2, more elements are needed than the Resistance-Capacitance-Diode (RCD) passive snubbers which incorporate only a resistor, a diode, and a capacitor. In addition, the transformer has an extra winding and there is a voltage spike across D_2.

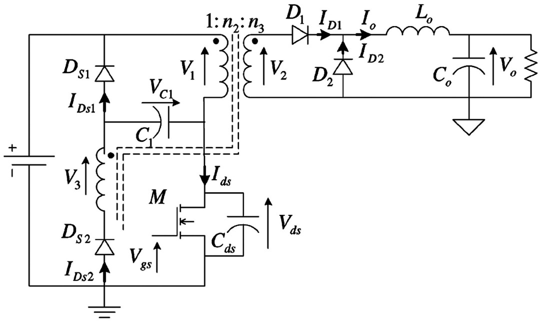


Fig. 2. A typical energy regenerative snubber [23].

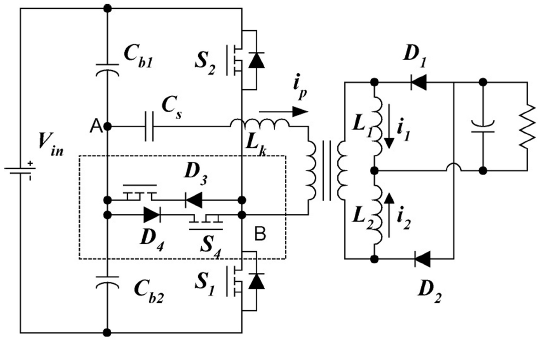
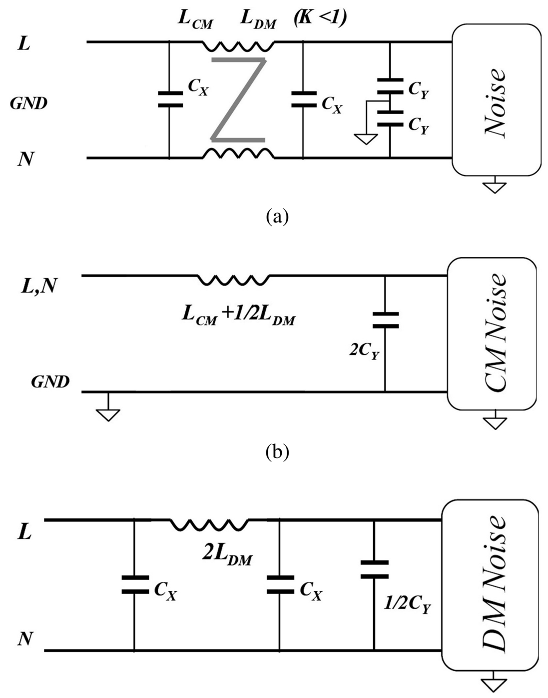


Fig. 3. Half bridge DC-DC converter with an active clamp (dashed- line frame) [25].

Also, active clamp circuits are employed to reduce the voltage spike of the main switch [24], [25]. In [25], an active-clamp snubber, illustrated in Fig. 3, is proposed for half-bridge DC-DC converters. Since the reverse-recovery characteristics of the MOSFET body diode do not have proper performance at high frequencies, the oscillations created at the turn off instant cause EMI. The introduced active-clamp concept reduces EMI by not allowing this diode to conduct. Furthermore, the energy of the transformer leakage inductance, as shown in Fig. 3, is transferred to the snubber capacitor (C_s) during the off-time mode which eliminates ringing.



(a)

(b)

(c)

Fig. 4. (a) Typical EMI filter, (b) CM equivalent circuit. (c) DM equivalent circuit [32].

B. *EMI filter*

The EMI filter is a common solution to meet EMC standards in power converters [26]. The filters often have to be designed and tuned after converter realization which results in a longer design time, a larger size and a higher cost [27]. However, in addition to other EMI suppression methods, filtering is inevitable for achieving the further EMI reductions necessary to satisfy strict EMC regulations. In general, it is desirable to implement cost effective suppression methods in order to reduce the filtering characterization before designing and implementing the filter. Several filtering solutions based on passive and active approaches have been introduced [28]-[34] to attenuate conducted EMI. Since CM and DM filters are typically implemented together [32], discerning between CM and DM noise is necessary. For this reason, the regular filter topology presents different equivalent attenuation paths for CM and DM. Fig. 4 shows a general topology and corresponding CM and DM circuits [32].

Passive EMI filters [26], [28] are mainly in the form of the bulky LC low pass topology used to reduce high frequency noise. In some cases, one LC passive filter may not satisfy the stringent standards leading to the use of a multi-stage filter. This solution results in a higher cost and a larger size of the converter. Active EMI filters [33], [34] can be utilized as an alternative in which the active components are contributed to the configuration in addition to the passive elements. For instance, Fig. 5 shows the active filter proposed in [33]. In this EMI filter, the low frequency attenuation is improved due to the active section topology. The main idea of this filter is based on sensing the noise current through a current transformer (CT), amplifying it and then injecting back a compensation current through an RC branch connected to an op-amp output, as shown in Fig. 5.

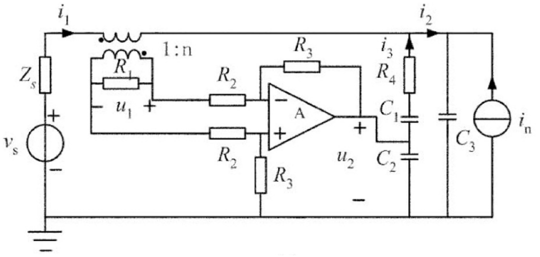


Fig. 5. An active EMI filter introduced in [33].

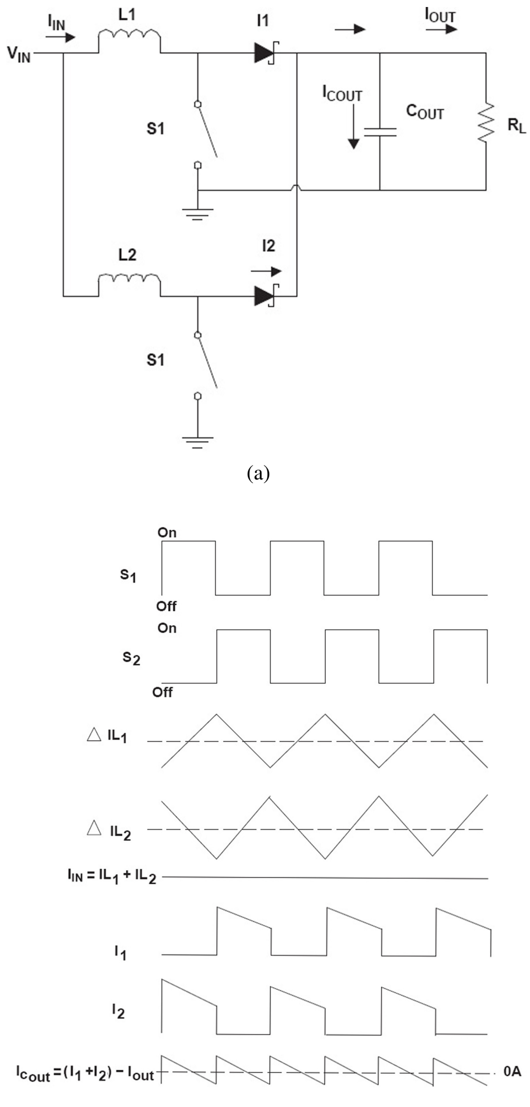
C. *Soft switching*

The soft switching conditions for IGBTs, MOSFETs and diodes as switching devices are able to reduce EMI due to a lower dv/dt and di/dt [4], [5], [35], [36]. Soft switching has also been addressed to reduce the switching losses with respect to hard switching [37]. In some literature, EMI in soft switching converters has been discussed [16], [38] and compared to hard switching converters [4], [35], [36], [39]. However, in some soft switching topologies, there is no significant reduction in EMI. Some practical results indicate that reducing EMI by soft switching is not as simple as it seems [5] due to the increased number of elements, the switching frequency and extra resonances which force the designer to resort to other EMI mitigation techniques. In [36], the EMI emission of a resonant soft switching three-phase inverter is compared with a hard switching inverter. The experimental results show that the EMI levels increase to hard switching in few frequencies. Also in [4], the EMI of a hard switching flyback converter is compared to several resonant converters and the results show that the hard switching converters with snubber circuits are not necessarily noisier than soft switching converters. Usually, soft switching topologies are capable of reducing EMI, but in some topologies this reduction is not considerable or there is not enough of a reduction to satisfy EMC standards. Extra elements employed in soft switching converters lead to more parasitics which can generate more EMI. Thus, despite the other advantages of soft switching converters, the effect of the extra elements from the EMI viewpoint should be evaluated.

D. *Interleaving*

Interleaving is a paralleling strategy in which multi-switching cells are connected in parallel with an equal switching frequency while switching times are phased in sequence. The interleaved method is widely used in high power applications [40]. A conventional interleaved boost converter is illustrated in Fig. 6 [41].

As it can be seen from the current waveforms in Fig. 6, this topology yields to a lower line current ripple [40] and thus reduces the conducted EMI, especially in differential mode [7]. This smaller ripple results in a smaller number of required magnetic components [42], [43]. There are other advantages to working with interleaving such as reductions in both the device stress [43] and the output capacitor ripple [40], [44] as well as a higher reliability [45]. Although the number of



(a)

(b)

Fig. 6. (a) 2-Channel interleaved boost converter and (b) its waveforms [41].

elements increases, due to the current sharing in the interleaved elements, devices with a lower current rating can be used and thus the overall cost does not significantly increase [46]. The main disadvantage of interleaved systems is the increased components count and layout space.

The ripple cancellation effect can reduce both the EMI filter size and its cost [42], [44]. However, this is not true for all cases. In [7], it is shown that the conventional 2-channel interleaving technique (180 degree phase shift) cannot help reducing the EMI filter size for a PFC operating in the 75∼150 kHz frequency range. The filter attenuation is based on the 2nd order harmonic of these frequencies. Thus, this harmonic cannot be significantly confined by using conventional interleaving. As a solution, a 2-channel 90 degree phase shift is used for mitigating the 2nd order harmonic and for reducing the EMI filter size.

E. Parasitic cancellation

A suitable approach to controlling EMI is to minimize its generating sources. This can be achieved by cancellation of the parasitic effects which contribute to EMI generation and emissions in the circuit. Parasitcs are caused by the non-ideal effects of active and passive devices or by PCB traces and cables. In [47], an auxiliary circuit is introduced for diodes to suppress the reverse recovery current. Lowering the EMI radiation in an IGBT module via reducing the parasitic capacitances and the circuit loops is shown in [48]. In [49], a negative capacitance method is introduced to cancel the parasitic capacitance of inductors and transformers. The inter-winding capacitance of the transformer can be a path for CM noise. In addition, it forms a resonant circuit with the leakage inductance which results in an unwanted high frequency oscillation [49]. The inter-winding capacitance of the transformer can be reduced by a Faraday shield [1], [50]. Several articles consider the parasitic cancellation in EMI filters to improve the filtration performance, especially for high frequency noise [51], [52]. In [51], cancellation techniques for mutual parasitics, the equivalent series inductance (ESL) of capacitors and the equivalent parallel capacitance (EPC) of CM inductors are proposed. In [52], a single inductance cancellation winding is used with two capacitors to improve filtration performance. A single coupled magnetic winding is built to compensate the effects of the parasitic inductances of two discrete capacitors [52].

F. Compensation

There are number of methods for noise compensation. The basic mechanism behind this is to generate a noise flow adversely. This method is mainly focused on common mode EMI and compensation is achieved by reducing the equivalent earth current (leakage current) [53] or the common mode voltage [54]. Normally, this requires using an auxiliary circuit added to the converter power section. Noise compensation can be achieved by active or passive devices. Passive EMI cancellation techniques can be implemented with simple and cost effective solutions whereas active methods are generally more flexible but also more expensive with respect to passive solutions.

The passive compensation approach can be employed for leakage current reduction [53]. In [53], a CM choke with an additional winding shorted by a resistor, is used. The proper resistance value leads to a reduction of the leakage current. Although this method can cancel the oscillatory ground current, a small amount of ground current still remains [55]. The CM passive cancellation technique in [56] replaces the boost converter inductor with an anti-phase transformer. The primary side acts as a boost converter inductor whereas the secondary winding provides a reverse phase voltage with respect to the CM voltage. The main influence of this technique on the CM EMI spectrum is below 20MHz noise frequencies. Passive compensation implementation for several converters is proposed in [6] by the means of an additional winding (N_C) and a compensation capacitor C_{COMP} to mitigate the common mode noise. This scheme is illustrated in Fig. 7 for a half-bridge isolated DC/DC topology.

The compensation circuit in Fig. 7 generates the anti-noise current for cancelling the parasitic noise current generated by

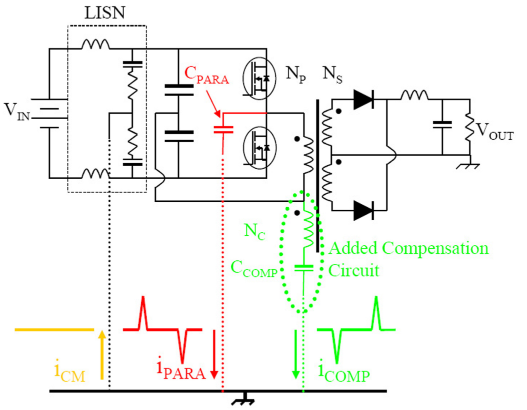


Fig. 7. A passive compensation scheme [6].

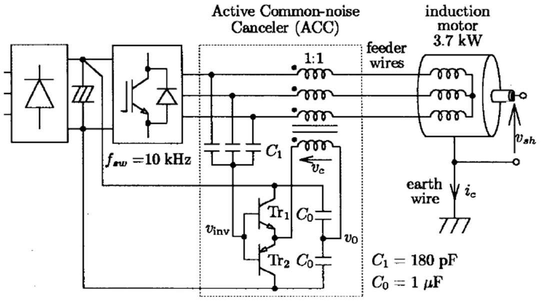


Fig. 8. An active compensation [55].

C_{PARA}. Value of C_{COMP} is determined by the C_{PARA} value which consists of the drain to the heat sink and the heat sink to the earth (chassis) capacitances. If the turns ratio, N_P:N_C is timelstransHour13Minute11:1 then C_{COMP} must be set equal to C_{PARA}. The main drawback of this method is that CM rejection is achieved only if the C_{PARA} current is large enough with respect to the noise current passing through the inter-winding capacitances of the transformer.

As an active cancellation solution, the method in [55] for mitigating the CM voltage of a PWM inverter with a motor load is introduced. The proposed circuit consists of three capacitors on the inverter output to detect the CM noise, a push-pull BJT amplifier and a CM transformer as shown in Fig. 8. To prevent the DC current from flowing into the transformer, two 1μF capacitors are connected as illustrated in Fig. 8. The main drawback of this method is the amplifier power dissipation.

Digital active cancellation applied to the converter input, including CM current detection and active close loop control, is presented in [57]. The closed-loop control is achieved by a DSP, which results in greater complexity and cost. Also the EMI spectrum is affected only up to 10 MHz.

G. *Balance approach*

The compensation solution employs an additional circuit in addition to the main topology. Similarly, the balance approach confines CM EMI, but this is accomplished through topology modifications. In this method, one term of CM noise cancels the another term, instead of minimizing each CM noise term [58]. Balancing can be achieved by a symmetric topology or through the balance condition of a Wheatstone bridge. The balanced switching converter in [59] is proposed based on the symmetric scheme. As shown in Fig. 9, the PFC inductor is equally separated into two windings, and one diode (D_2) is inserted into the topology.

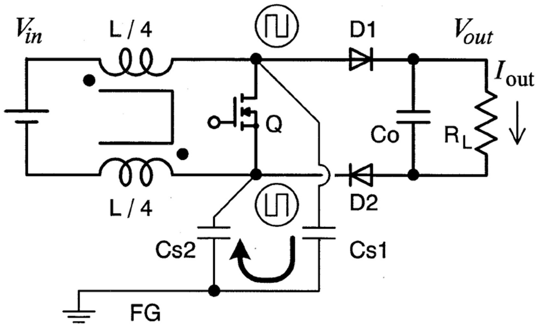


Fig. 9. A balance approach for boost converter [59].

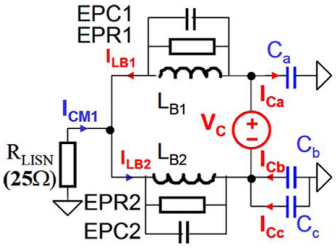


Fig. 10. Boost EMI model applying the balance condition of Wheatstone bridge [58].

Consequently, the drain and source voltages represent an equal amplitude but with a 180 degree phase difference that results in a reduction of the CM noise flowing to the earth. However, the extra diode raises the conduction loss. Also, if the parasitic capacitances Cs_1 and Cs_2 are not equal, an extra capacitance is needed to equalize their values for eliminating the noise current to the earth.

The balance condition of a Wheatstone bridge has been applied in [58]. In this paper, first a boost EMI model for CM noise is established based on network theory. By splitting the boost inductor, the converter satisfies the balance condition for the Wheatstone bridge. The resultant circuit is illustrated in Fig. 10, where L_{B1} and L_{B2} are the separated boost inductors, C_a is the drain-earth capacitance, C_b is the capacitance through the diode cathode net to the earth, C_c is the capacitance between the return load bus to the earth, and V_C is the switching voltage of the MOSFET. The balance condition is as following [58]:

$$\frac{Z_{LB1}}{Z_{Ca}} = \frac{Z_{LB2}}{Z_{Cb+Cc}}. \tag{1}$$

When the above condition is satisfied, the CM noise current in the LISNs is zero.

In [60], the symmetrical topology and the balance conditions of a Wheatstone bridge are achieved and analyzed in a bridgeless PFC converter. The symmetrical topology is obtained by placing two diodes in the return path of the load bus. The current path is through additional diodes instead of the MOSFET body diode. Thus, the conduction loss does not significantly increase with respect to a conventional bridgeless PFC [60]. However, the parasitic capacitance between the primary-secondary sides of the gate drive transformer (C_g)

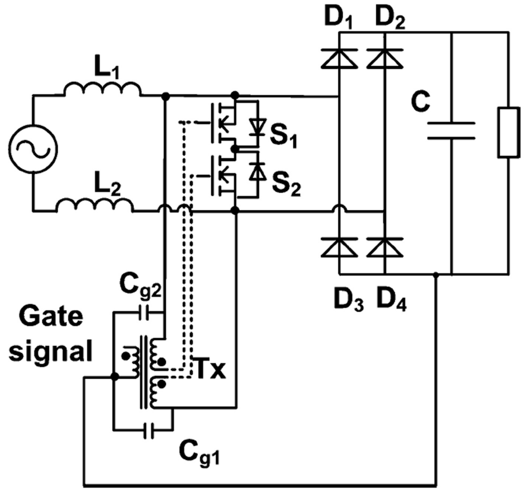


Fig. 11. Improved symmetric bridgeless PFC with gate drive transformer [60].

causes an asymmetrical mode. To resolve this problem, the improved symmetrical topology shown in Fig. 11, is proposed. Two MOSFETs are in series with their drains connected to each other instead of their sources. Furthermore, C_{g1} and C_{g2} are established symmetrically. Experimental results show that the improved symmetry has better CM EMI suppression.

H. PCB layout and placement optimization

PCB layout and placement significantly influence both conducted and radiated EMI. In other word, the PCB tracks, the layers and the component placement must be optimized for better EMC performance [61], [62]. The general EMC rules are well-known for designing an optimum PCB [63]. A proper layout can decrease most EMI [5]. In [5], [64] several EMI/EMC studies on PCBs are reviewed. Also, in recent years, CAD tools for simulating signal integrity (Hyperlynx from Mentor Graphics) and PCB parasitic extraction (Maxwell Q3D from Ansoft) have been developed which can help power electronic system designers to deal with EMC in the PCB design stage instead of by trial and error methods.

Achieving EMC requires minimizing the electric and magnetic fields around the PCB traces. Traces with high voltage transients are more critical because they emit a strong electric field. The traces connected to MOSFET drains exhibit this situation in power converters and cause electric field coupling. In [62], the E-field emissions from the traces of a flyback converter are discussed. Then the PCB layout is optimized with a larger separation between the drain trace and the input lines. Also, the placement of the switch and the transformer is changed to decrease the trace length and for better separation. Experimental results indicate that the optimized layout has a proper CM EMI reduction. In [65], the effects of different concepts for optimizing layout are evaluated for a PFC boost converter. In this paper, the radiated EMI is reduced by lessening the high di/dt (Fig. 12) and by shielding the drain track with two constant voltage tracks.

In [66], an additional layer as a damping layer is proposed to attenuate the unwanted oscillations at switching transients. Fig. 13 shows a PCB layer stack containing two layers and the damping layer which is inserted between the two main layers.

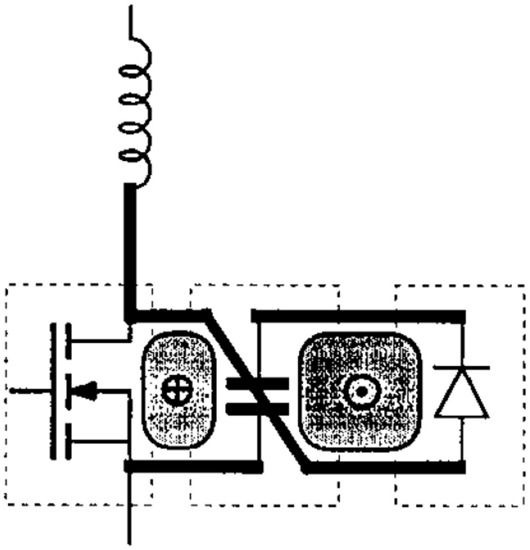


Fig. 12. PCB layout optimization to reduce radiated EMI [65].

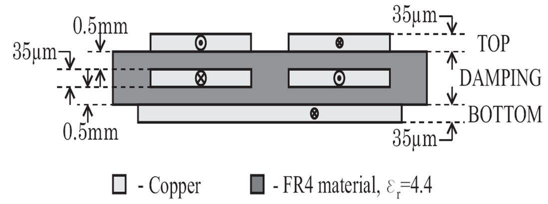


Fig. 13. PCB layer stack with a damping layer [66].

By terminating the copper trace of the damping layer with a proper RC network, the current induced in this layer reduces the undesired oscillations in the main layers.

I. Ferrite bead

The use of ferrite beads is another technique for minimizing unwanted transients [64] and noise radiation [67], [68] in a power board. Ferrite beads are well known magnetic components [3] that act as a high impedances for high frequency noises while presenting negligible impedance at the switching frequency.

The proper selection and placement of ferrite beads results in a significant noise reduction. It is beneficial to place ferrite beads in series with the power trace. In [68], a ferrite bead is placed between the boost converter diode and the output positive bus. The high frequency ringing related to the diode characteristics, is attenuated. This has lowered the radiated EMI as shown by the experimental results in [68].

III. EXAMINATION OF EMI REDUCTION METHODS

Several of the methods classified in the previous sections are examined to verify their represented characterization in section II. Simple and cost-effective reduction methods are selected in addition to the EMI filter as a common solution. These methods are shown in Table I.

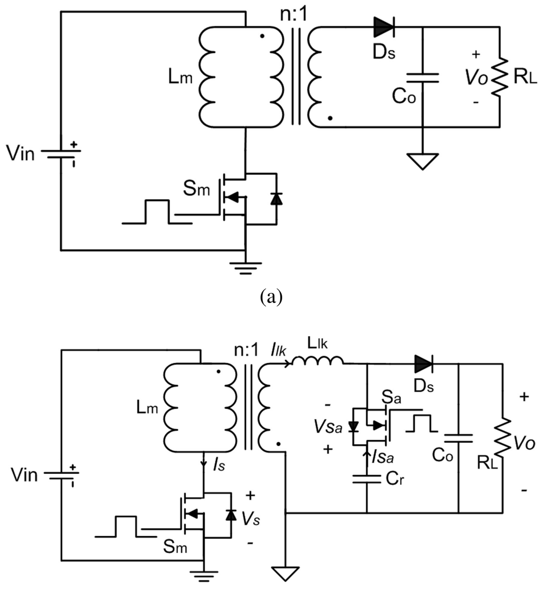
Two PWM switching converters are selected from the boost and buck types for evaluating the mentioned techniques in Table I. A flyback converter, due to its extensive use in isolated converters especially PFC applications, and a half

TABLE I
SELECTED CASES FOR EVALUATION OF EMI REDUCTION METHODS

Case	*Category*	*Description*
1	Soft Switching	ZCT introduced in [70]
2	Parasitic Cancellation	Faraday Shield for transformer
3	Compensation	Passive compensation of C_{CM} current [6]
4	Ferrite Bead	On input lines & transformer sec.
5	EMI Filter	Passive filter (Fig.4) L=2.9mH,C_X=0.1μF,C_Y=3.3nF

TABLE II
MAIN COMPONENTS OF ZCT FLYBACK PROTOTYPE

Main switch (S_m)	IRF840
Auxiliary switch (S_a)	IRF460
Diode	MUR860
$L_{Pri.}$, $R_{Pri.}$	0.95mH, 0.3Ω
$L_{Sec.}$, $R_{Sec.}$	130μH, 0.05Ω
Transformer inter-winding capacitances	$\sim$ 50pF
Output capacitor	100μF
Resonant capacitor (C_r)	22nF



(a)

(b)

Fig. 14. (a) Regular switching flyback converter[69] and (b) ZCT flyback converter [70].

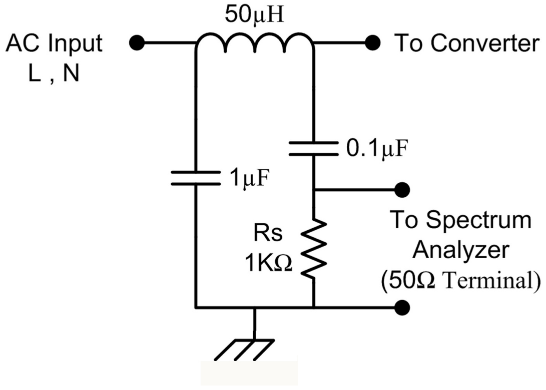


Fig. 15. CISPR22 LISN for conducted EMI measurement.

bridge converter, due to its widespread use as switching power supply up to 500W, [69] have also been selected. The flyback converter is used to evaluate the EMI at the input lines whereas the half bridge type is used to examine its impact on the output noise.

A. Flyback converter

Fig. 14(a) shows a regular hard switching flyback converter [69]. Since the number of extra components to achieve the soft switching condition is important from the EMI viewpoint, the zero current transition (ZCT) flyback converter introduced in [70] is considered to evaluate the soft switching method for case 1. As illustrated in Fig. 14(b), the proposed converter in [70] has only one auxiliary switch and one capacitor. Thus, soft switching is performed with a minimum number of elements to avoid further parasitics, unwanted noise loops and cost increases with respect to other complex soft switching converters. Also, the transformer leakage inductance (L_{lk}), which is modeled in the secondary and the auxiliary capacitor (C_r), is used as the resonant tank. This converter has other advantages such as better efficiency and a switch stress equal to that of an ideal flyback converter.

A 70W ZCT flyback converter and its 70W hard switching counterpart prototype are realized at a rectified input voltage of 110V_{rms} and at a 100 kHz switching frequency. The main components of the ZCT prototype are summarized in Table II. The regular flyback converter is implemented with similar conditions and component values except for the auxiliary circuit (S_a and C_r) of the ZCT converter.

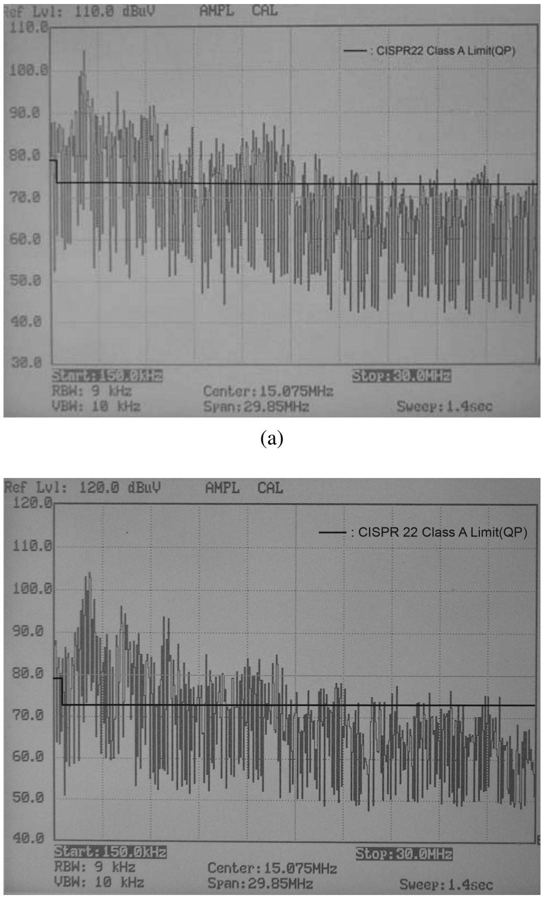
To measure the EMI of the two converters, LISNs according to CISPR22 are realized [2] by the means of air core inductors and metallized polyester film capacitors. An air core inductor is chosen and only one layer of winding on a 1mm thick PVC pipe is used to make 50μH inductances for better performance [71]. The LISNs are connected between the 110V_{ac} line and the input of the prototypes as shown in Fig. 15.

The measurement setup is accomplished according to CISPR22 [2]. The measured conducted EMI on the line terminal of regular and ZCT flyback converters are shown in Fig.16 using peak the detection mode of a GSP827 spectrum analyzer from GW-Instek. The resolution bandwidth (RBW) of the spectrum analyzer is set to 9 kHz for the frequency range of 150 kHz to 30MHz for CISPR22.

According to Fig. 16, although the soft switching technique has a lower EMI in a few frequencies such as above 25MHz, it presents conducted EMI levels similar to the regular flyback converter in other frequencies. Therefore, for case 1, it confirms that a soft switching converter may contribute to EMI levels similar to its hard switching counterpart.

To study case 2, as a parasitic cancellation method, an Aluminum Faraday shield is inserted between the primary and secondary windings to reduce the parasitic inter-winding capacitances of the transformer. The measured EMI of a regular flyback converter after using a Faraday shield is illustrated in Fig. 17 which shows a significant EMI reduction.

For case 3, the compensation method introduced in [6] is applied to a regular flyback converter. As explained in section II.f, this technique compensates the CM noise current generated by the parasitic capacitor (C_{PARA}) between the drain and the earth which consists of the drain to the heat sink and the heat sink to the earth capacitors. The total measured C_{PS} is around 50pF. Since the heat sink is not connected to the



(a)

(b)

Fig. 16. Total conducted EMI of a) regular and b) ZCT flyback converters (Scales: vertical: 10dBμV/div, horizontal: $\sim$3MHz/div).

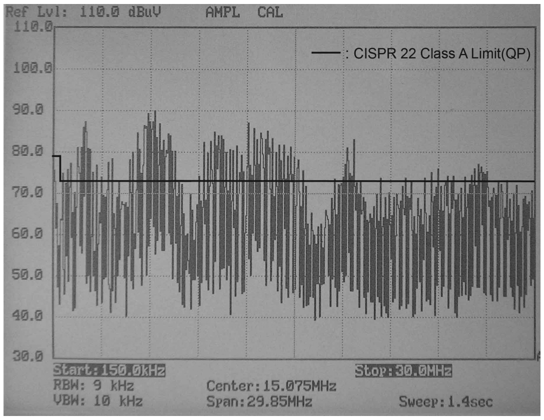


Fig. 17. Total conducted EMI after using Faraday shield (Scales: vertical: 10dBμV/div, horizontal: $\sim$3MHz/div).

chassis, the value of C_{PARA} is comparatively small and equal to 17pF. Therefore, the noise path to the earth is through the transformer primary to secondary instead of passing through the compensating winding due to the lower impedance of the primary to secondary path.

The experimental results show this phenomenon and confirm that the passive cancellation does not work in this circuit. In other words, the proposed technique is useful only if the C_{PARA} parasitic capacitor is large enough with respect to the capacitance between the primary and secondary (C_{PS}).

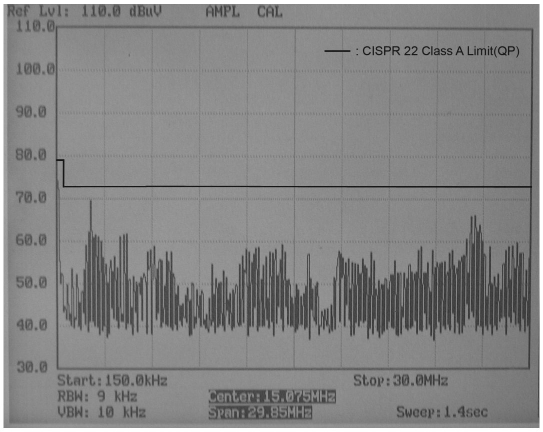


Fig. 18. Total conducted EMI after using EMI filter (Scales: vertical: 10dBμV/div, horizontal: $\sim$3MHz/div).

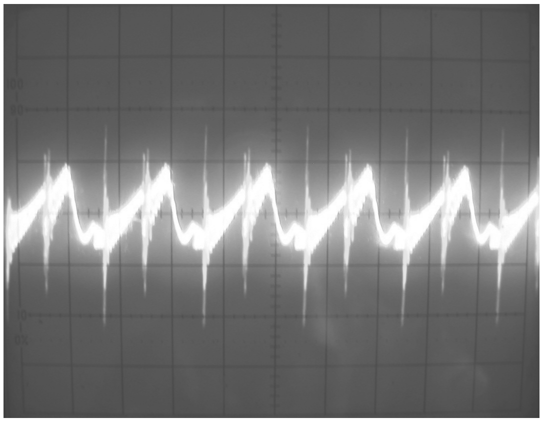


Fig. 19. Output noise of a half bridge converter (vertical scale: 5mV/div, time scale: 10μs/div, Probe: ×10).

In Case 4, two ferrite beads are placed in the ac input line path. A 2.5dBμV reduction is achieved for the main peak at $\sim$2MHz. A greater reduction of around 4dBμV is achieved in the frequencies between 10MHz and 20MHz.

A comparison of these cases indicates that the Faraday shield has a greater impact on EMI. For example, this method decreases the upper EMI level from 105 dBμV to 90 dBμV as shown in Fig. 17.

Finally, an EMI filter is placed at the converter input as case 5. The use of a filter results in a large mitigation of the EMI spectrum at the cost of increasing the volume and price. Fig.18 illustrates that the converter satisfies CISPR 22 class A (QP). As an optimum solution, the previous cases can be implemented before filtering. Then a filter with lower requirements could be employed to satisfy CISPR22 or other EMC regulations.

B. *Half bridge converter*

The half bridge prototype converter in [69] is considered to evaluate the influence of some reduction techniques on the output noise of the converter. The converter operates at a 25 kHz switching frequency and an isolated 15V output voltage with an input voltage of 220V_{rms}. The original output noise is measured at nearly 190mV_{P-P} by a modified probe and a Leader-1043 oscilloscope as shown in Fig. 19.

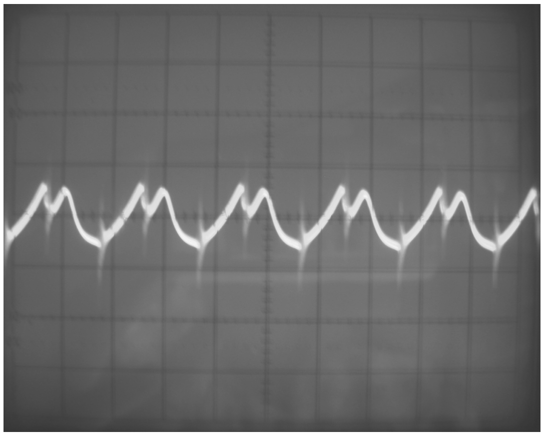


Fig. 20. Output noise after using Faraday shield and ferrite bead (vertical scale: 5mV/div, time scale: 10μs/div, Probe: ×10).

As in case 2, the transformer is modified and a Faraday shield is used. Similar to the previous flyback converter, applying the compensation method from case 3 does not provide a proper reduction of the output noise due to the larger contribution of C_{PS} than C_{PARA}.

Also, the effect of ferrite beads is examined. As mentioned in section III.i, the proper placement of a ferrite bead is important. The best impact is achieved by placing it on the transformer secondary winding which is connected to the ground. The result is a reduction of approximately $20mV_{P-P}$. Fig. 20 illustrates the output noise after applying cases 2 and 4. The total reduction in peak to peak is approximately 30%. According to Fig. 19 and Fig. 20, the amplitude reduction of the output noise components, such as spikes in the time domain, yields to the reduced EMI level in the frequency domain.

IV. CONCLUSION

EMI mitigation techniques are widely used in power electronic systems to satisfy EMC standards. Designers should consider both the EMI phenomena and the optimal mitigation approaches in the design stage and before system realization in order to eliminate the additional costs which would occur otherwise. Therefore, a proper classification is needed to determine which method can efficiently mitigate EMI for a specific converter. This review provides a suitable background for designers in order to select proper techniques based on the available methods. The EMI mitigation techniques are classified with an emphasis on the techniques applied to the power section. Also, a characterization of each technique is presented. Major concerns for proposing new topologies, especially soft switching topologies, are improving efficiency and decreasing switch stress. However, improving these criteria may not necessarily result in a lower EMI to satisfy EMC compliance. In section III, several techniques are implemented from a cost-effective viewpoint. The impact of the mitigation techniques, behavior verification and evaluations are discussed. It is shown that the effectiveness of some techniques is not valid for all conditions and topologies and thus, must be precisely studied for each case.

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