CONDUCTED EMI REDUCTION USING X2Y FILTER IN SWITCHING POWER CONVERTERS

R.VIMALA[1], K. BASKARAN[2], K.R. ARAVIND BRITTO[3]

This paper presents a filter analysis of conducted Electro-Magnetic Interference (EMI) for switching power converters (SPC) based on noise impedances. EMI filter performance depends on the noise source impedance of the circuit and the noise load impedance at the test site. The noise source impedance is due to the circuit parameters and parasitic elements in the power converter and its environment. The EMI noise is identified by time domain measurements associated with an isolated half-bridge ac–dc converter. The proposed method uses the practical approach of measuring the power converter noise spectrum and using the data to calculate the maximum possible magnitude and minimum possible magnitude of the DM and CM noise impedances. The noise impedance magnitude information aids the design of the EMI filter. The practical filters like Complete EMI filter and X2Y filter are investigated. Experimental results are also included to verify the validity of the proposed method. The results obtained satisfy the Federal Communications Commission (FCC) class A and class B regulations.

Keywords: Common-mode (CM), Differential-mode (DM), X2Y Filter, Conducted EMI, Switching power converters (SPC)

1. Introduction

EMI emission is always a great concern for the modern trends in power electronics by fast switching large amount of current at high voltages and high frequency in switching devices like Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Insulated Gate Bipolar Transistor (IGBT) and Gate Turn Off thyristor (GTO). The frequency range of the conducted emission limit is from 450 kHz to 30 MHz for the FCC class A and class B regulations and 150 kHz to 30 MHz for the German Verband Deutscher Elektroniker (VDE) regulations. Radiated emissions are generally measured at much higher frequencies, namely beyond 30 MHz up to several GHz. The process of EMI mitigation normally involves filter designing. Traditional cut-and-try approach has been abandoned by engineers for its time-consuming and inefficient defects. Therefore, the effective solutions for conducted EMI noise analysis and suppression have become great concerns.

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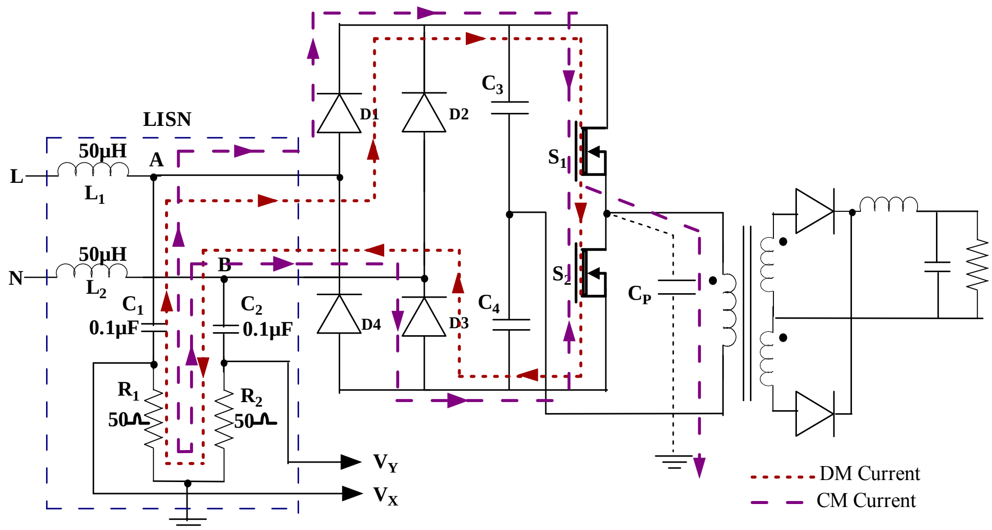

Fig. 1. Conducted EMI coupling path of Half-bridge isolated ac–dc converter

Fig.1 shows the configuration of the conducted EMI measurement for an isolated half-bridge ac–dc converter. The power source is provided through a Line Impedance Stabilizing Network (LISN), which is required by the conducted EMI measurement and contains two 50 μH inductors, two 0.1 μF capacitors, and two 50 Ω resistors. The conducted EMI noise is caused by two mechanisms: Differential Mode (DM) noise and Common Mode (CM) noise. The EMI filter should be designed for CM and DM noises, respectively. So, the first step in designing the EMI filter is to separate the CM and DM noise. A two way 0˚ combiner (ZFSC-2-6-75) and a two way 180˚ power combiner (ZFSCJ-2-1) are used to measure the total, DM and CM noise via selection of a three way built-in switch. In order to suppress the conducted EMI noise, proper design of EMI filter is necessary.

In general, the DM noise is related to switching current and the CM noise is related to capacitive coupling of switching voltage with LISN, which is used in standard conducted EMI measurement. The effective EMI prediction often relies on the engineer's experience or extensive numerical simulation models [1]–[3]. CM and DM noise is dealt with the respective section of an EMI filter [4]. New techniques for designing EMI filters have been developed recently by the use of a noise separator, which can be used to separate DM and CM noise [5].

2. EMI Noise Separator

The noise separator is built using the principle of noise rejection accomplished by using power combiners. Fig.2 (a) shows the diagram depicting the basic concept of a noise separator in which the two signals derived from the

LISN, consist of both CM and DM noises. One of the signals is the vector sum of the two modes of noise (CM+DM) and the other signal is the vector difference of the two modes of noise (CM-DM). The CM current is evenly divided between the two input terminals. There are four parameters defined to evaluate a noise separating network, that is, the Common-Mode Insertion Loss (CMIL), Differential-Mode Insertion Loss (DMIL), Common-Mode Rejection Ratio (CMRR) and Differential-Mode Rejection Ratio (DMRR). The transmission coefficient of noise separating network are defined as

$$S_{21}= 20 \log (V2/V1) \text{ (dB)} \quad (1)$$

where V1 and V2 are the input and output of the network. As the transmission coefficient S_{21} is CMIL/DMIL, the V1 and V2 represent the same mode signals, and as S_{21} is CMRR/ DMRR, V1 and V2 represent different mode signals [6]. It should be mentioned that the insertion loss should be not more than 5dB and the rejection ratio should be not less than 40 dB. A spectrum analyzer and $0^o/180^o$ combiners are used to measure the characterization parameters of noise separating network [7].

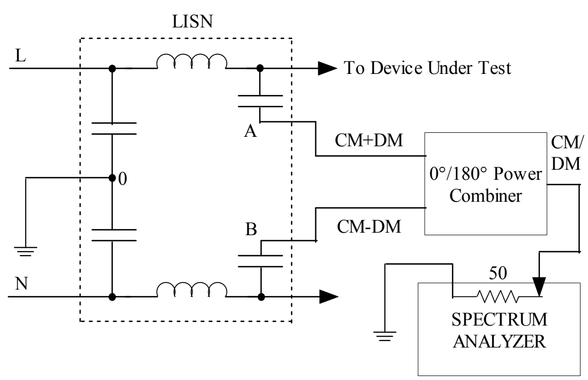

Fig.2 (a) 0°/180° Power Combiner

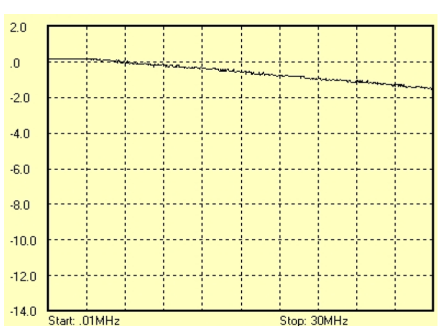

Fig.2(b) CMIL of noise separating network

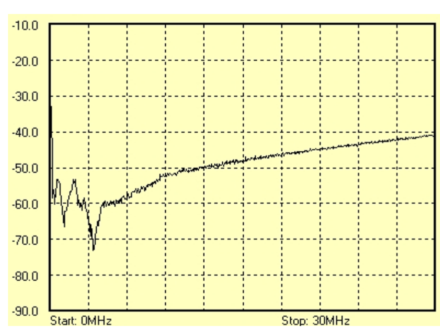

Fig.2(c) DMRR of noise separating network

The CMIL result of the high-performance noise separating network is shown in Fig.2 (b). As the frequency goes up, the CMIL declines slightly but remains above -2dB. The DMRR result of the high-performance noise separating network is shown with a good performance in Fig.2(c). The DMRR rises with increasing frequency, and at 30MHz, the maximum frequency for conducted EMI noise measurement, the DMRR successful remains below -40dB. The measurement results prove that the noise separating network can separate the conducted EMI noise efficiently.

3. Noise Source Impedance Measurement

Insertion loss method is used to measure the noise source impedance of SPC. The information obtained through this method enables the prediction of EMI filter performance and the design of a suitable filter for a SPC. The impedance of the inserted component must be much larger than the noise source impedance. If these conditions are not fulfilled, accuracy deteriorates. In the basic theory of insertion loss method, the noise source is modeled as voltage source V_s in series with noise source impedance Z_s as shown in Fig.3. If a piece of filter element (Z_{series} or Z_{shunt}) is inserted between Z_s and R_{load}, the noise voltage across R_{load} will change. This change is measured by insertion loss or attenuation Equation (2) which is defined as the ratio of voltage across R_{load} before and after the filter element is inserted.

$$IL = 20 \log\left(\frac{V_{LISN} \text{ without filter}}{V_{LISN} \text{ with filter}}\right) \tag{2}$$

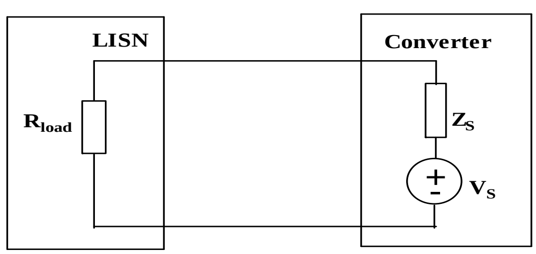

Fig. 3. Conducted Emission Model

Insertion loss is a complex number, but usually only magnitude is measured. Now insertion loss and CM filter impedance is a known quantity, from which Z_{sCM} is calculated. In order to obtain noise source impedance $|Z_s|$ accurately, any one of the two methods series insertion or shunt insertion can be used, depending on the relative magnitude of either $|Z_s|$ Vs $R_{load.}$

The major components of the CM noise source impedance are the unintentional capacitance between the switching devices and its heat sink, parasitic capacitances between other devices or wires, which carry pulsating voltage waveform and the grounded chassis. The charging and discharging of insulator capacitance is the main cause for common mode EMI. The major components of DM noise source impedance are the diode on state resistance and the Equivalent Series Resistance (ESR), Equivalent Series Inductance (ESL) of the bulk capacitor. Other factors, such as the PCB layout, component placement and wiring layout also influence the noise source impedance.

3.1 Series Insertion Method

Series insertion as shown in Fig.4 is used in case of $|Z_s| >> R_{load}$ for better accuracy. By using a series component with assumption $|Z_{series}| >> |Z_s|$, it is used for measuring only CM input impedance. The expression for attenuation can be simplified using Equations (3) to (5).

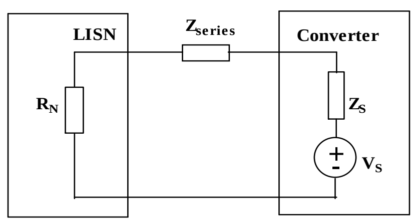

Fig. 4. Series Insertion Method

$$IL = \frac{\frac{R_{load}}{R_{load} + Z_S} \times V_S}{\frac{R_{load}}{R_{load} + Z_S + Z_{series}} \times V_S} \tag{3}$$

$$= 1 + \frac{Z_{series}}{R_{load} + Z_S} \approx 1 + \frac{Z_{series}}{Z_S} \tag{4}$$

Since |IL| is normally much greater than 1, then

$$|Z_S| \approx \frac{|Z_{series}|}{|IL|} \tag{5}$$

where $|Z_{series}|$ is given, and |A| is obtained by insertion loss measurement. In General, larger the insertion loss, the more accurate $|Z_s|$ will be obtained. When $|R_{load}+ Z_s|$ value turns out to be much greater than R_{load}, series insertion method can be used. To measure the CM noise source impedance test setup in Fig.5 is used. In order to measure the maximum and minimum possible value of noise source impedance, a test inductor of value 100μH is added at the input side of SPC. Above circuit can be simplified to its equivalent circuit as shown in Fig.6. This equivalent circuit helps to derive the expression for attenuation.

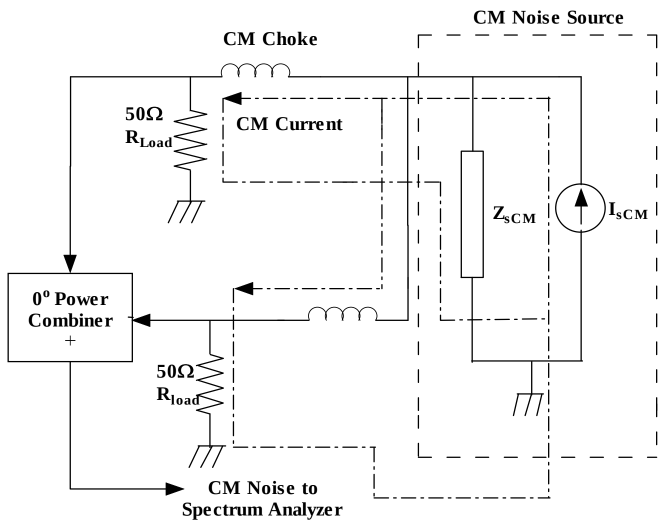

Fig. 5. CM Noise Impedance Measurement Test Setup

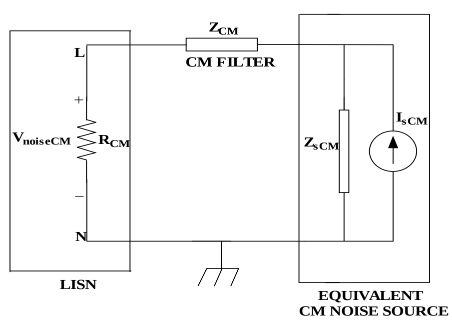

Fig. 6. CM Equivalent Circuit

From Fig.6 attenuation can be calculated using Equation (6).

$$A_{TCM} = \frac{\dfrac{R_{CM} Z_{sCM}}{R_{CM} + Z_{sCM}} I_{sCM}}{\dfrac{Z_{sCM}}{R_{CM} + Z_{sCM} + Z_{CM}} I_{sCM} R_{CM}} \tag{6}$$

From the above relationship, Equation (7) can be obtained.

$$\left|R_{CM} + Z_{sCM}\right| = \frac{\left|Z_{CM}\right|}{\left|A_{TCM} - 1\right|} \tag{7}$$

For $A_{TCM} >> 1$, $$\left|R_{CM} + Z_{sCM}\right| = \frac{\left|Z_{CM}\right|}{\left|A_{TCM}\right|} \tag{8}$$

In the Equation (8) A_{TCM} and Z_{CM} are known values and so CM noise source impedance Z_{sCM} can be easily calculated. A_{TCM} is 1.24.

$$\left|Z_{sCM}\right|_{Max} \approx \left|R_{CM} + \left|\frac{\left|Z_{CM}\right|}{\left|A_{TCM}\right| - 1}\right|\right| \tag{9}$$

$$\left|Z_{sCM}\right|_{Min} \approx \left|R_{CM} - \left|\frac{\left|Z_{CM}\right|}{\left|A_{TCM}\right| + 1}\right|\right| \tag{10}$$

CM noise impedance values vary with frequency, so some points in frequency range of interest is selected and then the maximum and minimum possible value of the CM noise impedance is calculated at these frequency points using (9) and (10). As the test filter is placed on the input side of the SPC.

$$\left|Z_{sCM}\right|_{Max} = 39.92\ \Omega, \quad \left|Z_{sCM}\right|_{Min} = 17.69\ \Omega$$

3.2. Shunt Insertion Method

Shunt insertion as shown in Fig.7 is used in case of $|Z_s| << R_{load}$ for better accuracy. By using a shunt component with assumption $|Z_{shunt}| << |Z_s|$, it is used for measuring only DM input impedance. The expression for attenuation can be simplified using Equations (11) and (12).

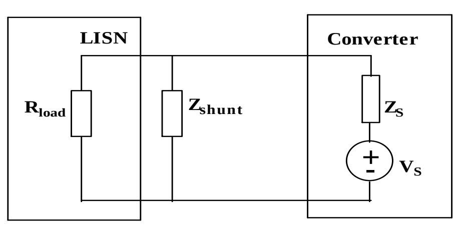

Fig. 7. Shunt Insertion Method

$$IL = \frac{\dfrac{R_{load}}{R_{load} + Z_S} \times V_S}{\dfrac{R_{load} // Z_{Shunt}}{R_{load} // Z_{Shunt} + Z_S} \times V_S} \tag{11}$$

$$= 1 + \frac{R_{load} // Z_S}{Z_{shunt}} \approx 1 + \frac{Z_S}{Z_{shunt}} \tag{12}$$

Since |IL| is normally much greater than 1, $|Z_s|$ can be approximated as Equation (13).

$$\left|Z_S\right| \approx \left|Z_{shunt}\right| \times \left|IL\right| \tag{13}$$

where $|Z_{shunt}|$ is given, and |IL| is obtained by insertion loss measurement. In general, the larger the insertion loss, the more accurate will be attenuation. When $|R_{load}//Z_{shunt}|$ value is much less than R_{load}, then shunt insertion loss method is used. To measure the DM noise source impedance, test setup in Fig.8 is used. C_X is the DM test capacitor added at the input side of SPC. In order to calculate the attenuation, A_{TDM} simplified equivalent circuit given in Fig.9 is used. Z_{DM} is the filter impedance which is chosen to be less than noise source impedance.

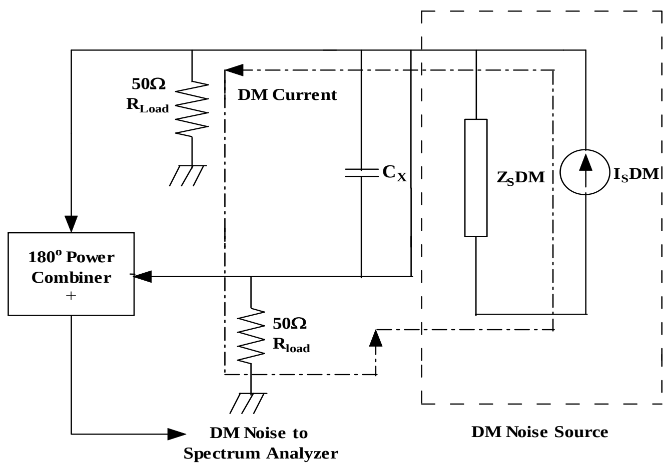

Fig. 8. DM Noise Impedance Measurement Test Setup

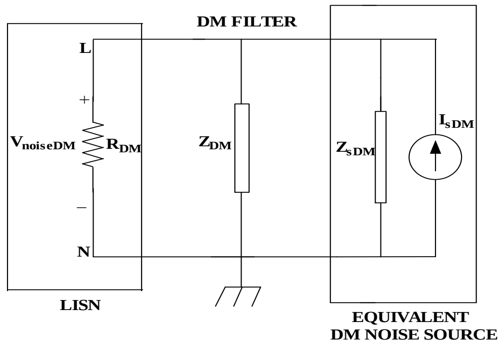

Fig. 9. DM Equivalent Circuit

From the equivalent circuit attenuation expression can be derived as follows:

$$|A_{TDM}| = \left|1+\frac{R_{DM}Z_{sDM}}{(R_{DM}+Z_{sDM})Z_{DM}}\right|$$

$$|A_{TDM}| \approx \left|1+\frac{Z_{sDM}}{Z_{DM}}\right| \tag{14}$$

In the above Equation (14), A_{TDM} and Z_{DM} are known from which Z_{sDM} can be calculated. A_{TDM} is 1.36.The expression to find minimum possible and maximum possible noise source impedance is shown in Equations (15) and (16).

$$|Z_{sDM}|_{Min} = |Z_{DM}|\,\big||A_{TDM}|-1\big| \tag{15}$$

$$|Z_{sDM}|_{Max} = |Z_{DM}|\,\big||A_{TDM}|+1\big| \tag{16}$$

$$|Z_{sDM}|_{Min} = 1.93 \text{ x } 0.36 = 0.694\Omega$$

$$|Z_{sDM}|_{Max} = 1.93 \text{ x } 2.36 = 4.554\Omega$$

4. Analysis Filters for Noise Suppression

After the filter circuit has been selected, the component values in that circuit must be determined. The Y-capacitors can easily be determined from the leakage current limit, which is given in the safety standards applicable to the particular equipment. With known Y-capacitors, the CM inductance can be calculated from:

$$L = \frac{1}{4\pi^2 f_c^2 C} \tag{17}$$

where *fc* should be the corner frequency, which can be defined as the intersection between the 0 dB line and a line with slope 40 dB/decade that is tangent to the required CM Insertion loss. Similarly, the DM corner frequency is determined from the required DM Insertion loss. When the CM inductance is being calculated, the capacitance C in (17) should be twice the C_Y value. The CM inductance consists of the CM choke's inductance and half of the inductance of the DM inductors, if these are decoupled inductors. If the DM inductors are coupled, they have negligible CM inductance and then the CM inductor should have an inductance, equal to the required CM inductance, obtained by (17). The L_{DM} is a DM choke C_X is a DM capacitor or (called "X" capacitor). When filtering DM noise, an X capacitor is used to shunt noise from one line to the other through the low impedance of the capacitor, thus returning the noise to the EMI source.

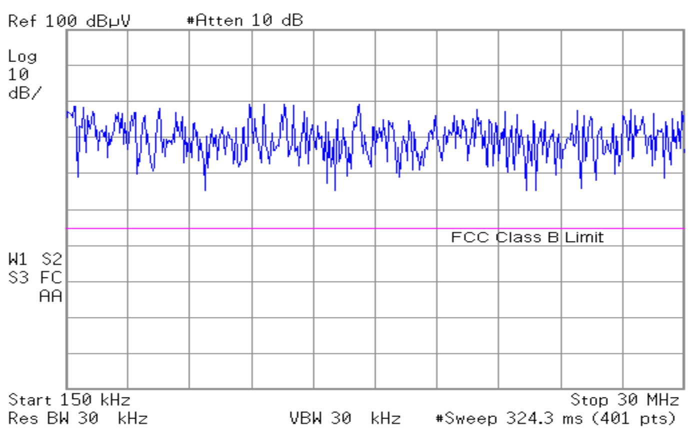

Fig. 10. Total noise spectrum of the ac–dc SPC without filter

For DM noise, DM choke should have suppressing effect when the two paths are unbalanced. Even though current flow is unbalanced, the magnitude of each current is attenuated already by the DM choke and therefore the DM noise is suppressed. To suppress the DM noise effectively, the capacitor is always used together with the DM chokes. After considering the measure bandwidth of 10 kHz and normalized in dBµV [8], the spectra of total EMI is given in Fig.10. The fluctuation of EMI at a particular frequency can be displayed by using the zero span mode of a spectrum analyzer. Using this mode, a magnitude of the selected noise frequency is displayed with respect to time. Another important issue is that the insertion of the filter should not affect the stability of the SPC. The EMI filter will not affect the power converter's stability and dynamics only if the output impedance of the filter part is much less than the input impedance of the converter from dc to the gain crossover frequency of converter's control loop [9]–[12].

This requires that the DM filter should be well damped to avoid impedance peaking and consequent possible violation of this criterion. To effectively suppress the conducted EMI noise, the balancing capacitor should provide balanced impedance such that the currents flowing through the two LISN resistors R1 and R2 are the same, irrespective of C_p's charged condition. Under this condition, the choice of C_x value depends on the frequency and the filter topology. The value of C_x can be calculated by using the following formula.

$$X_c = 1/(2\pi f C_x) \; ; \; X_c << 50\ \Omega \qquad (18)$$

f = starting frequency of EMI noise;
(150 KHz for VDE and 450 KHz for FCC)
The filter attenuation is defined as

$$A_{filter} = \frac{V_{noise}(without filter)}{V_{noise}(with filter)} \qquad (19)$$

V_{noise} without filter is measured at the LISN output, when no EMI filter element is added. V_{noise} with filter is measured at the LISN output when a filter is added. The topology should be selected according to the source and load impedances. The selection of the filter components involves not just the calculation of suitable capacitance and inductance values, but also other considerations, such as inductor core material, the dielectric of the capacitor, voltage, and current ratings, the voltage drop at line frequency, size, weight, etc. Their approach considered filter topology only but not mentioned the relationship of noise source impedance (Zs) and noise load impedance (LISN), which determine the EMI filter performance significantly [13].

5. EMI Filter Design Procedure

In this section, a method to design an EMI filter using the maximum and minimum CM and DM noise impedances is introduced. The objective is to design an EMI filter, so that the SPC would pass the FCC 15 Class B regulations for conducted EMI. The CM and DM filters were designed separately. The maximum or minimum worst case noise impedance was considered for each filter. After completion of the CM and DM filters, they were put together to make the complete filter [14].

The procedure to design the EMI filter is summarized as follows.

(i) Separate the CM and DM noise spectrum of the SPC.

(ii) Measure the noise voltage, V_{noise}, with and without a simple filter

(iii) Design the EMI filter using the maximum magnitude, or minimum magnitude of the noise impedance, which ever yields the least attenuation.

(iv) Test the completed EMI filter.

The CM and DM noise spectra of the unfiltered ac-dc SPC, operating at full load, are illustrated in Fig.11 and Fig.12 respectively. The impedance of the CM inductor is Z_{fCM}. R_{loadCM} is the equivalent resistance of the LISN. I_{sCM} represents the SPC noise source and Z_{sCM} represents the noise source impedance. Calculations were made at different frequency points using measurements of the noise voltage $V_{noiseCM}$ along with (19) and (20)–(23).

1) When $A_{TCM} \geq 10$

$$\left|Z_{sCM}\right|_{Max} \approx \left|R_{loadCM} + \frac{\left|Z_{fCM}\right|}{\left|A_{TCM}\right|}\right| \tag{20}$$

$$\left|Z_{sCM}\right|_{Min} \approx \left|R_{loadCM} - \frac{\left|Z_{fCM}\right|}{\left|A_{TCM}\right|}\right| \tag{21}$$

2) When $A_{TCM} < 10$

$$\left|Z_{sCM}\right|_{Max} \approx \left|R_{loadCM} + \frac{\left|Z_{fCM}\right|}{\left|A_{TCM} - 1\right|}\right| \tag{22}$$

$$\left|Z_{sCM}\right|_{Min} \approx \left|R_{loadCM} - \frac{\left|Z_{fCM}\right|}{\left|A_{TCM} + 1\right|}\right| \tag{23}$$

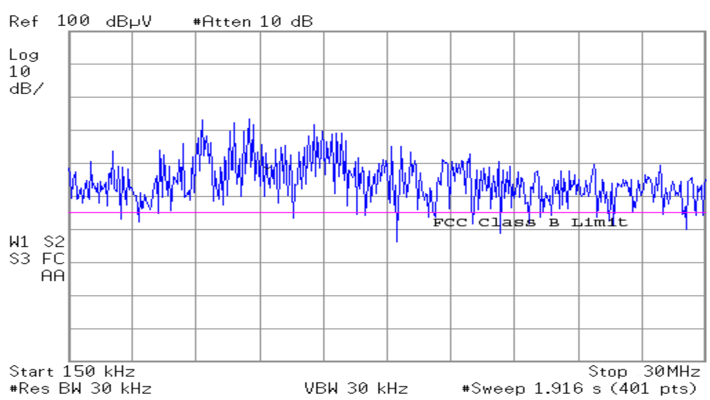

Fig.11 CM noise spectrum without filter

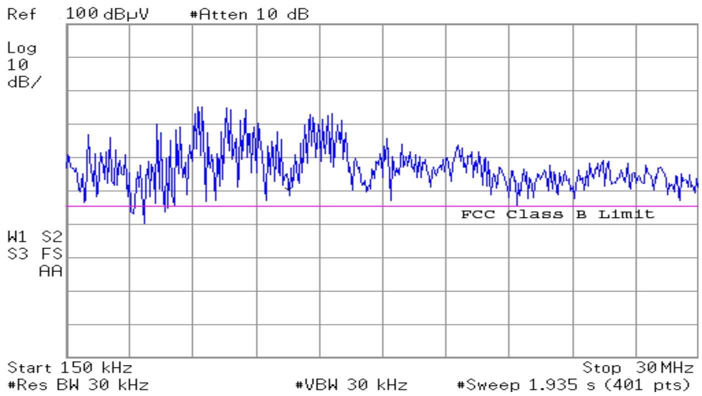

Fig.12 DM noise spectrum without filter

From the test results, it is noted that the CM noise was the dominant factor. The maximum possible value and minimum possible value of the DM noise impedance from 0.15 to 2.5 MHz were calculated at different frequency points using measurements of the noise voltage $V_{noiseDM}$ along with (19), (24), and (25). Z_{sDM} is the DM noise impedance of the SPC and Z_{fDM} is X capacitor's impedance.

$$Z_{sDM}\Big|_{Min} = Z_{fDM}\Big|A_{TDM} - 1 \qquad (24)$$

$$Z_{sDM}\Big|_{Max} = Z_{fDM}\Big|A_{TDM} + 1 \qquad (25)$$

5.1 Complete EMI Filter Design

EMI filter is designed based on the maximum and the minimum possible values of noise source impedance. The main objective is to design a filter for switching power converters so that it would pass the FCC class B regulations for conducted EMI. Design of EMI filter is trivial, because very little is known about the EMI source and also the system designers to know the details of the power module circuits [15]. While designing EMI filter, noise source impedance should not be ignored because it leads to either over design or the system requirements not being met with.

Interaction between EMI source impedance and EMI filter impedance is also considered. By matching the filter parameters with that of noise source impedance, an efficient filter design method is obtained [16]. After separately designing CM and DM filter, they are integrated together to get the complete EMI filter. The complete filter topology is shown in Fig.13. Inductor used as filter has a value of 0.9mH and current rating of 3 A. The number of windings is 79. Similarly the capacitance has a voltage rating of 400V and ESR requirements are

1.2Ω. X capacitance has a value of 0.1μF and each Y capacitance has a value of 0.01μF.

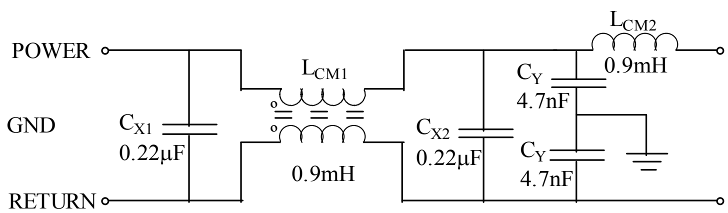

Fig. 13 Complete EMI Filter

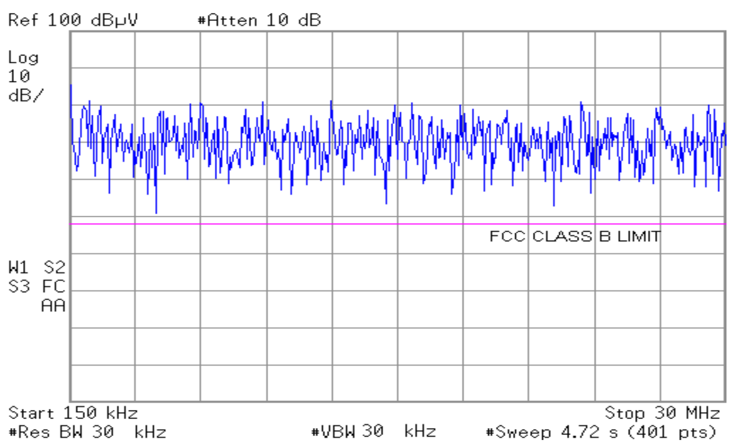

Fig.14 Noise Spectra without EMI Filter

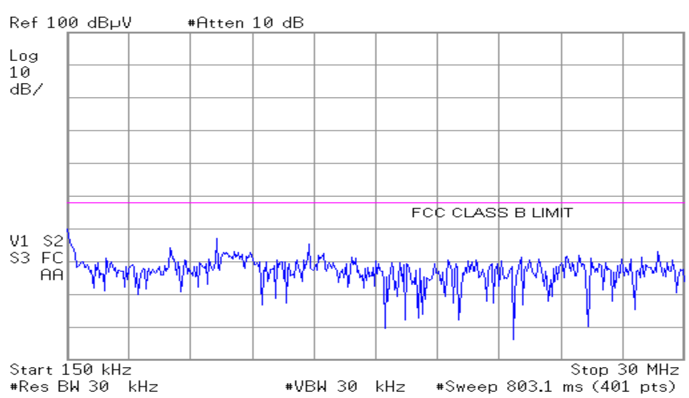

Fig.15 Noise Spectra with EMI Filter

Experimental waveform obtained before and after placing the EMI filter is given in Figs 14 and 15 respectively. Table I gives the values of noise voltages before and after placing the EMI filter at 10 MHz frequency is observed.

Table I

EMI Noise Voltages

Topology	Noise Voltage
Without EMI filter	79 dBμV
With EMI filter	26 dBμV

FCC class B standards recommend conducted noise emission limits as 48dBμV. Conducted noise emission before placing the EMI filter is 79 dBμV and after placing the EMI filter is 26 dBμV which is very much below the limit of the FCC class A and class B standard. So the standard regulation is well satisfied. Thus by matching the filter parameters with noise source impedance, an efficient EMI filter can be designed. Experimental results are presented for an isolated ac–dc power converter with a nominal input voltage of 220 V / 50 Hz, and an output voltage of 12 V_{DC} at a full load current of 5 A.

5.2 X2Y Filter

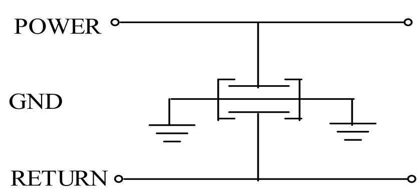

Fig.16 X2Y Circuit ACJX07X474KF4T

The complete EMI filter using X2Y is illustrated in Fig.16. The X2Y filter used is the Johnson Dielectrics catalogue no. ACJX07X474KF4T. X2Y replaces five to seven standard passive elements used for the purpose of noise canceling. Standard two termination capacitors are made up of two opposing electrodes that are screened onto layers of dielectric material in an alternating fashion during the fabrication process. The layers are repeated to increase capacitance value, C=ε.Area/Distance between plates. X2Y components use this standard structure and add an additional reference layer between the opposing electrodes. A single X2Y component can provide the needed filtering to meet less stringent FCC EMC compliance at a lower cost than conventional EMI filter measures.

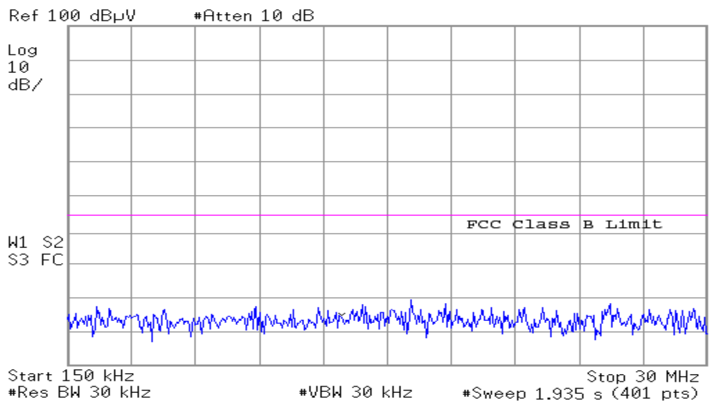

Fig.17 Noise spectrum after the X2Y filter was added

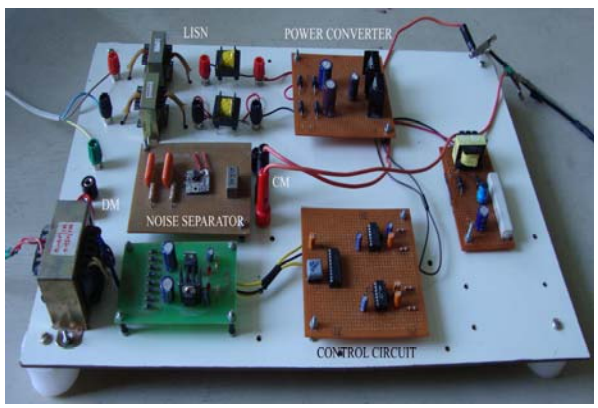

Fig.18 Photograph of the measurement arrangement

The test result for the X2Y filter is shown in Fig.17. Common mode noise is filtered to ground by the two Y capacitors. Because X2Y is a balanced circuit that is tightly matched in both phase and magnitude with respect to ground, common to differential mode noise conversion is minimized and any differential mode noise is cancelled within the device. The method presented is not only limited to single power converter, it can be used to design EMI filters for paralleled switching power converter modules and multiple power converters. Table II shows the comparison of hardware results for various frequency ranges using filters. Fig.18 shows the Photograph of the measurement arrangement. As expected, the Half-bridge isolated ac–dc converter with the designed filter meets the requirements set in the standard.

Table I1

Comparison of Filter waveform results

Frequency in MHz	Without Filter (dBμV)			With Filter (dBμV)	
	Total	CM	DM	Passive components filter	X2Y Filter
10	79	65	67	30	13
20	78	62	62	24	12
30	76	58	55	23	10

6. Conclusions

An improved method of filter design based on measuring the noise source impedance is proposed. This approach considers filter topology only but does not mention the relationship of noise source impedance and noise load impedance, which determines the EMI filter performance significantly. The Complete EMI filter using standard passive components and X2Y filters are analyzed. From the Table II, it is well understood that the waveforms with filters have below the FCC class B level. The analysis and results proposed here can provide a guideline for future effectiveness of filtering schemes in switching power converters. The estimation of parameters for the model can be done by measurement or analytical calculation based on the geometry of the circuit. Experimental Results have shown that the proposed method is very effective and accurate in identifying and capturing EMI features in switching power converters. The method presented is not only limited to half-bridge converters, but it can be applied to many different converter topologies, such as buck, flyback, boost, with single-phase diode bridge front-end.

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