EMI Suppression in High Frequency Half Bridge Converter

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***Abstract*—Electromagnetic effects influence the design of power converters switching in MHz frequency region. In these converters, the high switching frequency in combination with sudden changes in current and voltage levels generate higher order harmonics which causes Electro Magnetic Interference (EMI). To study the effects of increased switching frequency on conducted EMI, the harmonics amplitudes are analyzed by increasing the switching frequency of a two wire input half bridge power converter from 1.32 MHz to 3 MHz. In order to suppress the Common Mode (CM) conducted EMI, different possibilities of connecting the Y - capacitor in a two wire universal input half bridge converter are discussed and the conducted EMI is measured and analyzed by connecting the Y - capacitor at different points. The line filters are designed, characterized and implemented in order to suppress conducted EMI. The effects of increased switching frequency on the line filter design are studied by analysing the EMI spectrum of both the converters. The analysis of results indicates that the filter size is reduced by increasing the switching frequency of the power converter.**

***Index Terms*—Common mode, differential mode, electromagnetic interference, electromagnetic compatibility, line impedance stabilization network.**

I. INTRODUCTION

With the development of emerging semiconductor devices, such as the CoolMOS and GaN power MOSFETs, high frequency multi-layered Printed Circuit Board (PCB) and hybrid (POT +I) core power transformers it is possible to design the high frequency (MHz range) and energy efficient power converters [1]–[4]. Multi-resonant half bridge converters have been designed in the 1 MHz – 4 MHz switching frequency range, up-to a 40 W output power level and with 92 % energy efficiency. Planar power transformers used in these converters are highly energy efficient and ultra-compact [4]. The motivation for designing these high frequency converters is that the majority of the power electronic devices used are surface mounted. These devices have reduced parasitic components as compared to those for the through-hole devices and closer placement of the components has thus become possible. Therefore, surface mounted devices are better from an EMI point of view as compared to through-hole devices.

The energy efficiency of power converters is an important parameter. However, because of very stringent Electromagnetic Compatibility (EMC) regulations such as International Special Committee on Radio Interference (CISPR) and Federal Communication Commission (FCC) etc., it has also become a compulsory requirement and it is as important as the energy efficiency. The EMI produced by the power converters is of a broadband nature (from operating frequency to GHz range). The conducted electromagnetic signals travel within the circuit as well as on power lines [5]. Therefore, careful design of the power stages of these converters is inevitable for the EMI reduction. In addition to soft switching and filtering different spread spectrum techniques are also helpful for the reduction of EMI in the power converters [6].

In isolated power converters, the major sources of Common Mode (CM) noise are charging and discharging of parasitic capacitances, mainly the heat sink and transformer inter-winding capacitance [7], [8]. The inter-winding capacitances of a power transformer reduce the high frequency AC isolation and result in common-mode currents. The return current path at high switching frequency is highly critical with regards to the EMC performance of a power converter.

The leakage inductance of the power transformer is also an extremely critical parasitic element. At higher switching frequencies, it resonates with inter-winding capacitance and provides a low impedance path for the CM EMI. Therefore, this results in high frequency CM noise peaks. The leakage inductance may also resonate with the junction capacitance of the rectifier diode. It can thus become a source of high frequency CM noise on the secondary side [9].

The Differential Mode (DM) noise is mainly caused by the magnetic coupling *Ldi/dt*. The DM current generated at the input of the device under test is measured as an interference voltage across the load impedance of each line with respect to the ground [10].

In [11] the author has performed the initial measurements and analysis of the conducted EMI in DC-DC power converters, switching at 3.45 MHz and at a power level of 6 W. The Line Impedance Stabilization Network (LISN) was designed and implemented for EMI measurements. The

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design, implementation and characterization of the EMI filter and the measurement of the suppressed conducted noise by applying the filter were discussed.

In this paper, the conducted EMI analysis of two high frequency half bridge AC DC power converters switching is presented. Both converters have same output power level of 20 W. One converter is switching at 1.32 MHz and the other is switching at 3 MHz. Their conducted EMI is measured using a HAMEG HMS3000 spectrum analyzer and a HAMEG HM6050-2 LISN. Different possibilities for the suppression of conducted EMI are investigated. Two wire input line filters are designed and implemented for both power converters. The EMI spectrum is analyzed with and without the application of filter. The remainder of this paper is organized as follows:

- In Section II, the high frequency half bridge converter used for the conducted EMI measurement is briefly described;
- In Section III, the EMI measurement results without application of filter are discussed;
- In Section IV, the techniques for reducing the conducted EMI in two input off-line power supplies are discussed and the harmonics amplitude after adding CY capacitor between different points is analyzed;
- In Section V, the design, implementation and characterization of the line filter are discussed;
- In Section VI, the measurement results obtained from the application of the EMI filter are discussed and a comparison of the harmonic amplitude with and without filter is presented.

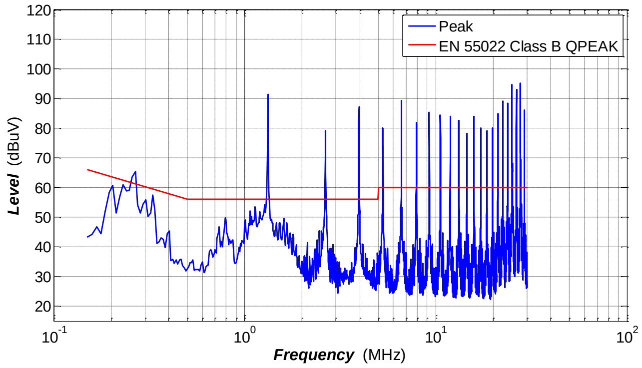
II. HIGH FREQUENCY HALF BRIDGE CONVERTER

A multi-resonant AC-DC half bridge converter is selected for the conducted EMI measurements. In these emerging power converters, Zero Voltage Switching (ZVS) is achieved for the entire load range using a hybrid planar power transformer and GaN power MOSFETs. The energy efficiency, the design details of the converter and the power transformer used for the EMI measurement are given in references [3], [4]. A hybrid core centre tapped planar power transformer with a 0.3 mm air gap in the POT core centre post is used in the half bridge converter [4].

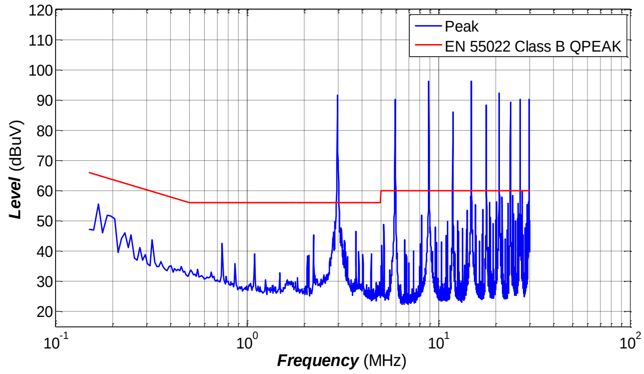
The smaller values of the inter-winding capacitance (i.e, 22.2 pF) and the secondary side leakage inductance (28 nH) [4], of these power transformers are helpful with regards to reduction of the CM noise current flowing through the inter-winding capacitance. These high frequency power transformers are less vulnerable to CM conducted EMI. However, it is important to analyze the radiated EMI due to the resonance of the leakage inductance with the inter-winding capacitance and the junction capacitance of the rectifier diode for these high frequency power converters.

III. EMI MEASUREMENTS OF HALF BRIDGE CONVERTER

The conducted EMI of both the half bridge converters is measured according to CISPR (EN 55022 Class B QPEAK) [10] requirements. The frequency spectrum of conducted EMI, in case of half bridge converter switching at 1.32 MHz, is shown in Fig. 1(a).



a)



b)

Fig. 1. Conducted EMI spectrum: a – 1.32 MHz; b – 3 MHz converter.

The spectrum is comprised of both even and odd order harmonics. The fundamental frequency component is at 91.38 dBμV, which is 35.38 dB above the CISPR limit. The third and fifth order harmonics are at 90 dBμV. The other higher order harmonics are approximately 80 dBμV – 85 dBμV. It is observed that all the harmonics are above the CISPR limit and thus the converter does not meet the regulatory requirement.

In order to analyze the effect of an increased switching frequency on the harmonic amplitude, the switching frequency of the converter is increased from 1.32 MHz to 3 MHz. The conducted EMI spectrum for a 3 MHz converter is shown in Fig. 1(b). From measurement results it is observed that the fundamental frequency component is at 93 BμV, the third and fifth order harmonics is at 96.4 dBμV and other higher order harmonics are at approximately 90 dBμV. The harmonics amplitude (especially fundament, third and fifth harmonics) of this converter are higher than that of 1.32 MHz power converter because of increased switching frequency.

IV. EFFECT OF ADDING C_Y CAPACITOR

In order to suppress the conducted EMI, a commonly used topology is a three pin line filter. These filters consist of CM chokes, C_X and C_Y capacitors as shown in Fig. 2.

The majority of the modern power supplies have two pin input (without safety ground) connectors. In the two wires universal input power supplies, a C_Y capacitor is placed between the primary and secondary ground of the power transformer instead of placing it in the line filter.

With the placement of the C_Y capacitor, most of the displacement currents return back to their sources instead of flowing into the LISN.

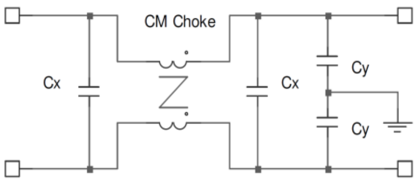


Fig. 2. Three pin line filter.

Therefore, it is helpful in reducing the EMI. Its maximum value is calculated according to (1) [12]

$$C_Y = \frac{I_{Leakage(Max)}}{V_{AC(Max)} \times 2 \times \pi \times f_{Line}}, \quad (1)$$

where $I_{Leakage}$ is the current which flows across the primary to secondary isolation barrier and according to IEC60950 its maximum value is 250 μA [12]. According to (1), the maximum value of C_Y capacitor is 3 nF for maximum input AC voltage $V_{AC(Max)}$ 265 V and line frequency f_{Line} 50 Hz. In order to ensure human safety, the converter is designed with low leakage current (125 μA). Therefore maximum 1.5 nF C_Y capacitor is used between points A-B, as shown in Fig. 3. The harmonic amplitudes are also measured by placing the capacitor between A-C, D-C or D-B and it is observed that the harmonic suppression is similar to that when placing the C_Y capacitor between A-B.

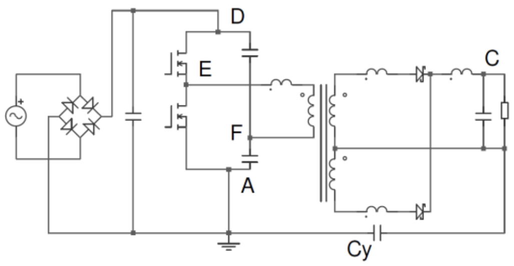


Fig. 3. Connection points for C_Y capacitor in half bridge converter.

The conducted EMI of half bridge converter, switching at 1.32 MHz after placing a 1 nF C_Y capacitor is shown in Fig. 4(a). The amplitudes of all harmonics are reduced significantly. There is approximately 19 dB reduction in the amplitude of the fundamental frequency component. The second order harmonic and all other higher order harmonics are suppressed by more than 20 dB.

The amplitude of conducted EMI is further reduced by increasing the value of C_Y. It is observed from Fig. 4(b) that when the value of the C_Y capacitor from 1 nF to 1.5 nF, the amplitude of the fundamental frequency component is further reduced by approximately 2 dB, while the amplitudes of the third harmonic and other higher order harmonics are reduced by more than 5 dB.

Based on the measurement results of Fig. 4(a) and Fig. 4 (b) it is obvious that in a half bridge converter, the CM EMI is suppressed when the C_Y capacitor is connected between the points A-B, A-C, D-C or D-B (Fig. 3).

The placement of the C_Y capacitor is extremely crucial. The harmonic amplitudes become very high if it is not correctly placed. In [13] it is mentioned from simulated results, that when C_Y is connected between points F-B and F-C (Fig. 3), the harmonics are suppressed. However, from measured results, it is observed that when C_Y is connected between F-C or F-B there is worsening of the harmonics amplitude because the harmonic current flows through the LISN and the EMI increases. The harmonic amplitudes of the converter, when C_Y is connected between points F-C and F-B are shown in Fig. 4(c) and Fig. 4(d).

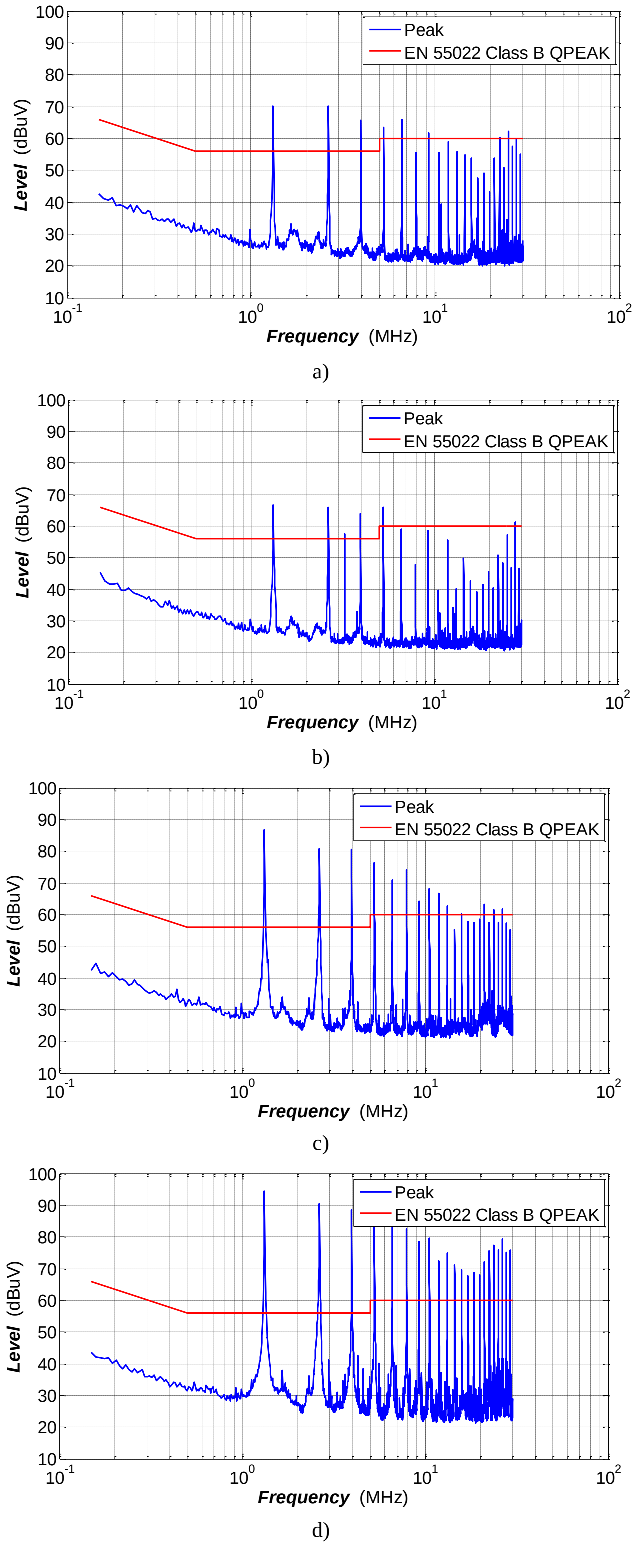


Fig. 4. EMI spectrum with CY: a – 1 nF between A-B; b – 2nF between A-B; c – 1 nF between E-B; d – 1 nF between F-B.

The conducted EMI of the 3 MHz half bridge converter after placing a 1.5 nF C_Y between A-B points is shown in Fig. 5. In this case the fundamental frequency component is suppressed by 26 dB, the second order harmonic is suppressed by 10 dB while other higher order harmonics are suppressed by more than 25 dB.

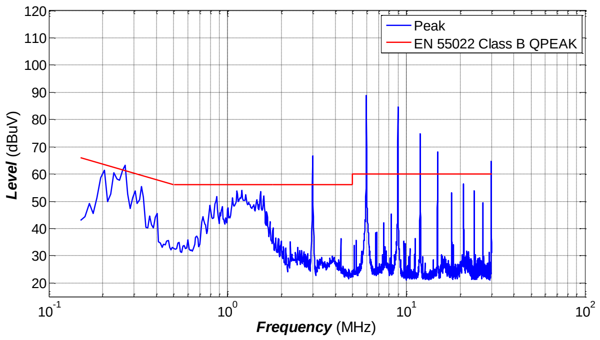


Fig. 5. Frequency spectrum of EMI with the addition of 1.5 nF CY.

V. EMI Filter Design and Implementation

From the measurement results shown in Section IV, it can be observed that a significant reduction in the conducted EMI is achieved by the placement of the C_Y capacitor. The amplitudes of the harmonics are still higher than the CISPR limit. Therefore, in order to further reduce the conducted EMI of the power converter, a line filter is required to suppress fundamental frequency component as well as higher order harmonics up to 30 MHz.

In relation to the design for a line filter, the requirement is that no undesired signal should reach the external 100 Ω radiation impedance. Therefore, the series components (CM choke in this design) must have an impedance which is significantly higher than 100 Ω and that the parallel components (*X* capacitors in this design) must have an impedance which is significantly less than 100 Ω over the desired frequency range [14].

In two wire input offline power supplies, the line filter consists of only line and neutral connections and does not have safety ground connection. The filter circuit is comprised of CM chokes and *X* capacitors. The commonly used EMI filter topologies are designed to attenuate the high frequency conducted noise and include LC low pass filters. To attenuate a particular frequency, band reject filters may also be used.

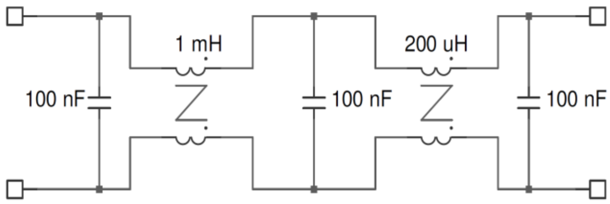
Various parasitic elements exist in the filter such as parasitic inductance of capacitors, the parasitic capacitance of inductors and the parasitic parameters of the PCB trace, which cannot be determined by means of measurements. Therefore the real high frequency characteristic of the EM1 filter will be much different from its expected value and the two identical filters may behave differently [15]. The electromagnetic couplings among the filter components and circuit layouts also affect the high frequency performance of the EMI filters [16].

With regards to the selection of filter components, it is important to consider the CM chokes core material, DC resistance and the capacitors dielectric material. The CM choke with a higher DC resistance has a deleterious effect on the energy efficiency of the power converter. The effect of the DC resistance on the energy efficiency of the input filter is analyzed by taking measurements with an AC input voltage of 100 V and different output power levels. A summary of the measurements is given in Table I.

The schematic diagrams of the filter designed for the 1.32 MHz and 3 MHz converters are shown in Fig. 6(a) and Fig. 6(b) respectively. The fundamental frequency component in the 3 MHz converter is at a frequency which is approximately 2.3 times higher than that for 1.32 MHz converter and, thus the size of the filter components is reduced.

TABLE I. POWER CONVERSION EFFICIENCY OF THE INPUT FILTER.

Input Power (W)	**Energy efficiency (Percentage)**			
	Bridge Rectifier and hold-up capacitors	**Bridge Rectifier, hold-up capacitors and Line Filter**		
		CM choke DCR 50 mΩ	**CM choke DCR 540 mΩ**	**CM choke DCR 700 mΩ**
20	98.0	97.4	97.3	97.0
30	97.9	97.4	96.9	96.7
40	97.7	97.3	96.7	96.4
50	97.6	97.1	96.4	96.2



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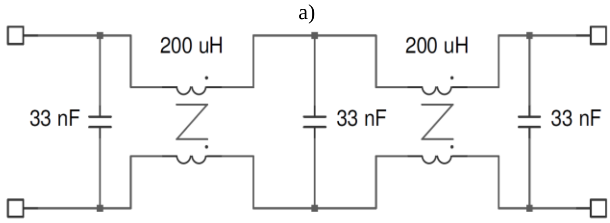


b)

Fig. 6. Filter schematic for: a – 1.3 MHz; b – 3 MHz converter.

In the line filter datasheets, the attenuation plots are given by assuming that both noise source and load have 50 Ω impedances. However, in the actual circuit measurements, the noise source impedance (device under test) deviates from the noise load impedance (LISN). When the impedance difference of the noise source and the noise load is more significant, then the attenuation of the 50 Ω and non 50 Ω system becomes significant. Therefore, it is necessary to characterize the filter for its performance prediction [17]. The parasitic extraction and insertion loss of EMI filters can be calculated by using scattering parameters (S-parameters).

The insertion voltage gain, with measured S-parameters (S_{11}, S_{12}, S_{21} and S_{22}), arbitrary source impedance Z_S and load impedance Z_L is calculated by using (2) [18]. The scattering parameters are measured both for the CM and DM EMI filters using a network analyzer.

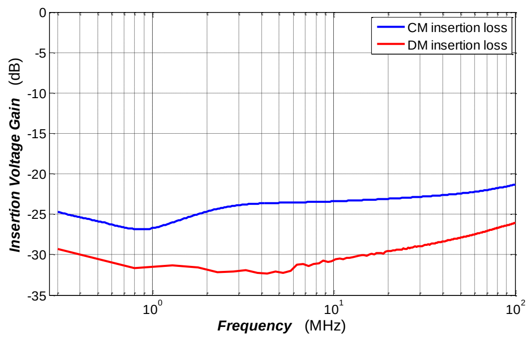
$$A_V = \frac{S_{12}(1-\Gamma_L \Gamma_S)}{(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-S_{12}\Gamma_S S_{21}\Gamma_L}, \qquad (2)$$

where Γ_S is source side reflection coefficient and Γ_L is load side reflection coefficient as given in (3) and (4) respectively. Z_0 is the characteristic impedance, which is usually 50 Ω:

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0}, \tag{3}$$

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}. \tag{4}$$

For the CM filter, the insertion loss is calculated by using the arbitrary values, Z_S = 1 MΩ and Z_L = 25 Ω and for the DM filter by using the arbitrary values of Z_S = 1 MΩ and Z_L = 100 Ω [18]. The insertion voltage gain for the filter shown in Fig. 6(a) is plotted in Fig. 7(a) and for the filter shown in Fig. 6(b) is plotted in Fig. 7(b).



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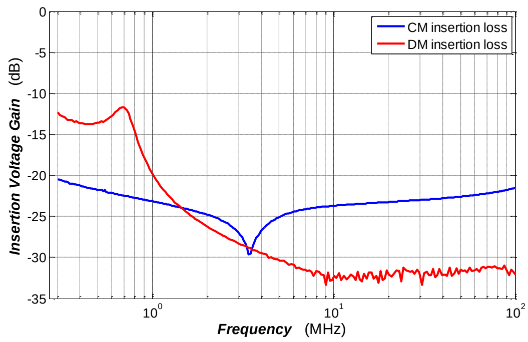
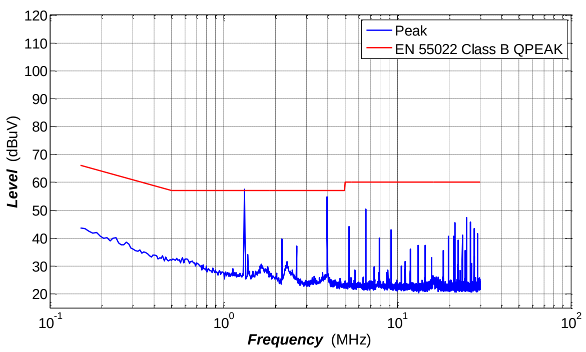


b)

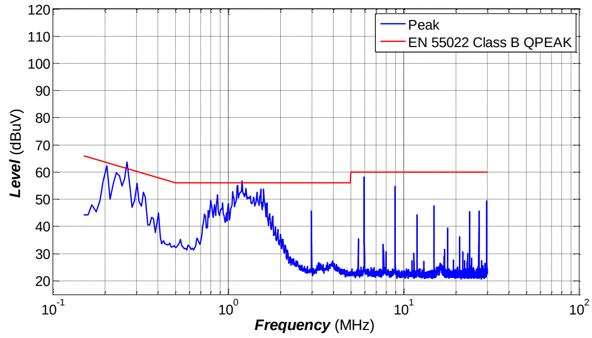
Fig. 7. Line filter insertion loss: a – 1.32 MHz; b – 3 MHz power converter.

VI. EMI Measurements after Filter Application

The two stage filter explained in Section V is designed and implemented to suppress the conducted EMI of both power converters. The EMI plot of 1.32 MHz half bridge converter after the application of a line filter is shown in Fig. 8(a).

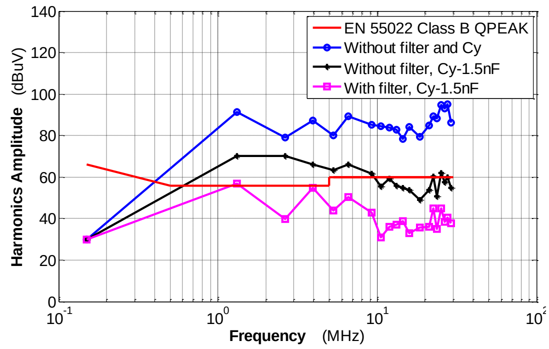


a)

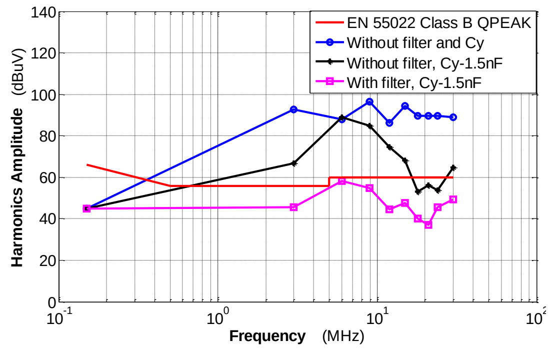


b)

Fig. 8. EMI plot after using filter: a – 1.32 MHz; b – 3 MHz converter.



a)



b)

Fig. 9. Harmonic amplitude comparison: a – 1.32 MHz, b – 3 MHz converter.

It is obvious from the plot that the fundamental frequency component is further reduced by 15 dB after the application of the filter. The fundamental frequency component and the third harmonic fall below the CISPR limit, while all other harmonics are more than 10 dB below the limit (more suppressed than the fundamental frequency component and third harmonic). The comparison of the harmonic amplitudes for 1.32 MHz half bridge converter without filter, with addition of C_Y and with two stage input line filter shown in Fig. 6(a) is plotted in Fig. 9(a). Form the harmonics comparison plot it is obvious that the proper placement of a C_Y capacitor and a two stage line filter are required to suppress the conducted EMI below the CISPR limit.

In order to keep the harmonics amplitudes in the 3 MHz power converter, below CISPR limit a two stage filter, as shown in Fig. 6(b) is applied and the measurement results are shown in Fig. 8(b). It is observed that the fundamental frequency component is further suppressed by 21 dB with the addition of the line filter. The comparison of the harmonic amplitudes for the half bridge converter switching at 3 MHz, before after the application of the line filter, is plotted in Fig. 9(b). It is observed that after the application of the line filter, all the harmonics fall below the CISPR limit.

From the measurement results of both the converter circuits, it is observed that although the harmonics amplitudes of 3 MHz half bridge converter are slightly higher than that of 1.32 MHz converter but the 3 MHz converter requires smaller EMI filter. Therefore, the overall size of the converter can be reduced by increasing the switching frequency.

VII. CONCLUSIONS

The focus of this paper is to measure, analyze and suppress the conducted EMI for emerging power converters switching in the MHz frequency range and to observe the effects of this increased switching frequency on the filter design. The conducted EMI is measured by connecting a C_Y capacitor at various points in the half bridge converter. Based on measurement results, the proper connection points for Y capacitor in a half bridge converter are suggested and it is concluded that a properly connected Y capacitor is useful for the suppression of CM conducted EMI, while the improperly connected Y capacitor results in increased EMI.

The energy efficiency of the input filter is measured for different output power levels and it is observed that if DC resistance of common modes changes from 50 mΩ to 700 mΩ, then the energy efficiency of the input filter is degraded by approximately 1 %. It is concluded that the size of the filter components is reduced for converter switching at 3 MHz. This is a motivating factor for designing the power converters at higher switching frequencies.

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