Design and implementation of EMI filter for high frequency (MHz) power converters

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Abstract—**The fabrication of emerging power semiconductor devices and high frequency PCB power transformers has made it possible to design the power converters in MHz switching frequency range. However, the higher switching frequency, di/dt loops and dv/dt nodes in power stages of these converters generate higher order harmonics which causes Electro Magnetic Interference (EMI). It is commonly believed that the EMI has worst affect in the converters switching in MHz frequency range than the converters operating below 150 kHz. Thus, it is important research direction to investigate the consequences of implementing a line filter to suppress the conducted EMI in high frequency power converters. In this paper, the measurements, and analysis of the conducted EMI in emerging power converters, switching in MHz frequency range, and the design of the filter for its suppression is presented. The design of LISN and its PCB implementation for EMI measurements is presented. The measurement of conducted EMI of a half bridge DC-DC converter switching at 3.45 MHz and the analysis of the frequency spectrum is discussed. The design, PCB implementation and characterization of the EMI filter and the measurement of the suppressed conducted noise by applying the filter are also discussed.**

Keywords: - Electro Magnetic Interference, Electro Magnetic Compatibility, Line Impedance Stablization Network, Pulse Width Modulation

I. INTRODUCTION

Power supply is an essential part of almost every electronic device. The miniaturization of electronic devices demands the smaller sized power supplies. The development of emerging semiconductor devices, like Cool MOS, GaN and SiC power MOSFETs, and high frequency multilayered PCB power transformers have made it possible to design the compact, high frequency and power efficient isolated converters. Using these new power MOSFETs and multilayered PCB power transformers the power converters are designed in the switching frequency range of 2-4 MHz and tested output power level up to 40 W [1]-[4]. It is very important to analyze the EMI generated by these converters and develop them according to Electro Magnetic Compatibility (EMC) standards.

In recent years, the EMI considerations have become very important because of very stringent EMC regulations. The EMI produced by power converters is of broadband type and falls within the frequency range from operating frequency to several MHz. It affects EMC of these converters. The careful design of the power stages of the high frequency Pulse Width Modulated (PWM) converters is an important step towards the reduction of EMI. The cause of EMI induction is the coupling between circuit elements due to a magnetic field or an electric field. The conducted EMI is divided two major categories: radiated and conducted.

The radiated EMI is most often a magnetic field, due to low voltages and high currents. Power lines can also radiate EMI, the source of which is the current noise conducted from converters [5].

The conducted EMI consists of both common mode and differential mode noise signals. The frequency range of EMI signals generated by power electronic equipment extends up to 1GHz [6]. There are various standards e.g. CISPR, FCC IEC, VDE and military standards that specify the limit on conducted EMI [7].

The common mode noises are high frequency noises that are in phase with each other having circuit paths through ground. Common mode noise is generally the more difficult noise to deal with. It originates due to charging and discharging of parasitic capacitances, primarily, the heat sink and transformer inter-winding capacitance [8]. The main cause of common-mode EMI is the parasitic capacitances between those points of the system that have high *dv/dt* and ground [9].

The differential mode noise is predominantly caused by the magnetic coupling *L.di/dt* where *L* is the parasitic loop inductance which experiences high switching current slew rate *di/dt* [8]. The parameters such as cable spacing and filtering determine differential mode coupling. The differential mode current generated at the input of the SMPS is measured as an interference voltage across the load impedance of each line with respect to earth at measured point [10].

In this paper, the design and implementation of EMI filter for power converters switching in MHz frequency is presented. The measurement of conducted EMI under a constant condition requires Line Impedance Stabilization Network (LISN) for EMC compliance testing. The LISN is designed and implemented on PCB. Measurements are performed by HAMEG HMS3000 spectrum analyzer using a LISN between input and the converter under test. The frequency spectrum of input conducted noise is analyzed. The filter is designed and implemented on PCB and after application of filter the spectrum is analyzed.

II. MEASUREMENT SETUP AND LISN IMPLEMENTATION

The common mode EMI is measured for a half bridge converter switching at 3.45 MHz. The tested output power level of the converter is 6 W. The common mode EMI is measured across 50 Ω resistor of LISN using HAMEG HMS3000 spectrum analyzer.

The block diagram representation of conducted EMI is shown in Figure 1.

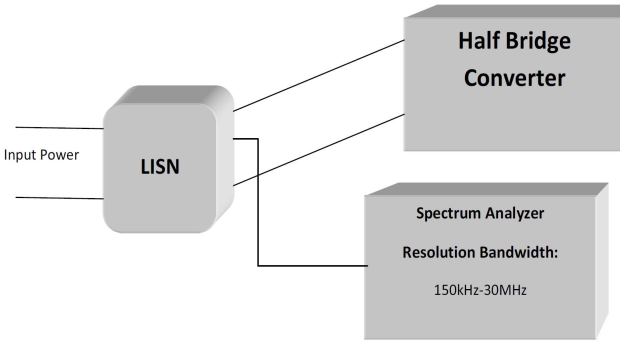

Figure 1 Measurement setup for EMI

The LISN shown in Figure 1 is required for measurements of conducted noise on a power line to separate the high frequency noise signals from the input current. It allows spectrum analyzer to measure the noise current through 50 Ω source impedance. The internal circuit of LISN is a high pass filter. It isolates the measurements from any high frequency shunting which might exists in power distribution network. It ensures that the equipment under test receives the proper dc voltage and current levels and also sees the controlled impedance for the ripple frequencies of interest. The mono cell LISN structure is designed and implemented according to CISPR standards. It is the simplest and commonly used topology [11]. It comprises inductors, capacitors and 50 Ω resistors. The 0.1uF Capacitor and 50 Ω resistor provide a path for the conducted EMI with constant impedance with respect to frequency. This characteristic impedance is defined by standards.

The schematic of LISN designed for EMI measurements is shown in Figure 2 and its prototype is shown in Figure 3 and Figure 4.

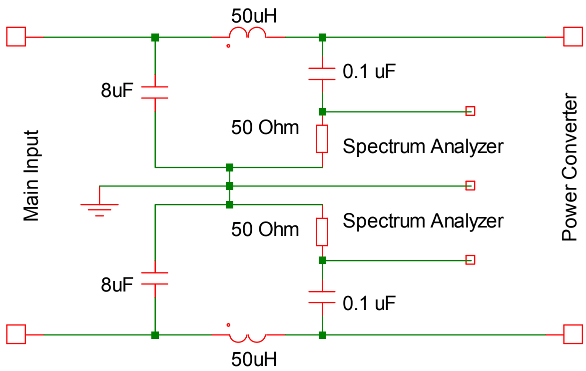

Figure 2 LISN Schematic

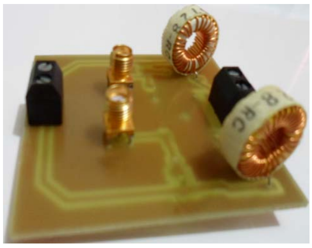

Figure 3 LISN prototype (top side)

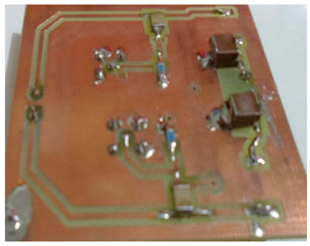

Figure 4 LISN prototype (bottom side)

III. EMI MEASUREMENTS OF HALF BRIDGE CONVERTER WITH OUT FILTER

In DC-DC converters, the differential mode EMI can be reduced by decoupling capacitors [12]. Therefore, only common mode EMI is required to be suppressed. This noise is mainly created by parasitic capacitances to ground. The frequency spectrum of common mode EMI, measured by spectrum analyzer, is shown in Figure 5. It is observed that emission from the half bridge converter does not meet the regulatory requirement. The even and odd order harmonics are present in spectrum. The fundamental frequency component at 3.45 MHz has the highest amplitude of 104 dBμV. Therefore, a filter is required to suppress this noise in the frequency range of 150 kHz to 30 MHz.

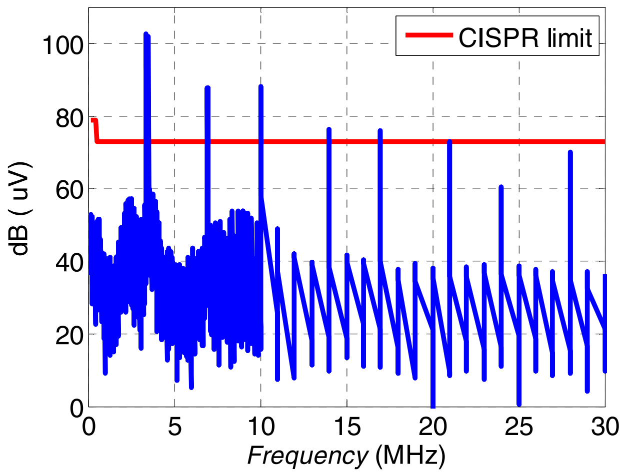

Figure 5 Frequency spectrum of conducted EMI

IV. EMI FILTER DESIGN AND IMPLEMENTATION

The direction of the common mode noise is from load and into the filter. The EMI filters bypass the noise by using shunt capacitors and block it by using series inductors. The common mode inductor becomes high impedance to this noise. It absorbs the noise and then dumps it to ground through low impedance Y capacitors. The commonly used EMI filter topologies used to attenuate the high frequency conducted noise include LC low pass filters. To attenuate a certain frequency, band reject filters can also be used. The single stage EMI filter topology is shown in Figure 6.

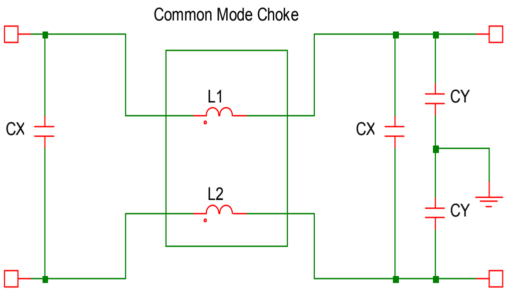

Figure 6 EMI Filter for power converters

The actual size of the filter depends on the design approach, the materials and the components used. However, in general, the size of the filter can be expected to decrease with increasing cutoff frequency and vice versa [13]. A single stage common mode filter is implemented. The value of the common mode choke used in the filter is 80 µH. The self-resonant frequency of common mode choke is about 7 MHz. The capacitors used in the filter determine the attenuation behavior of the filter above the self-resonant frequency of the common mode choke. The values are given in Table 1.

Table 1 Values of passive components for EMI Filter

L_{CM}	C_Y	C_X
80µH	560pF	330nF

The inductors and capacitors used in a filter are complex components. Their effectiveness is dependent on material properties and placement. There exist various parasitic parameters in the filter which cannot be determined by measurements. Therefore two identical filters may behave differently in a given application [14].

The electromagnetic couplings among filter components and circuit layouts play very important roles in the high frequency performance of EMI filters [15]. The layout of EMI filter is very crucial, therefore, it needs special consideration. Following measures are used in the implementation of EMI filters:

- In order to avoid inductive coupling between capacitors and inductors, the common mode choke is soldered on the top side of PCB and capacitors are soldered on bottom side.
- In order to avoid coupling between inductors and ground plan, common mode choke is soldered on the top side of PCB without ground plane. There is ground plane only on the bottom side of PCB.

The filter is implemented on 15mm x 25mm PCB. The prototype filter is shown in Figure 7 and Figure 8.

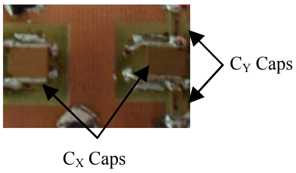

Figure 7 Filter prototype (Bottom Side)

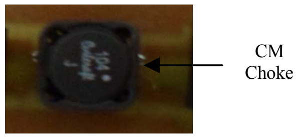

Figure 8 Filter prototype (Top Side)

V. EMI FILTER CHARACTERIZATION

To predict the performance of EMI filters they are characterized by independent network parameters. Scattering parameters are chosen to characterize the EMI filters because they are easy to measure accurately in high frequency range [16]. The reflection coefficients Γ_S and Γ_L are given in Equations 1 and 2, respectively. For EMI filters, insertion voltage gain is defined as the ratio of the port voltage at load side without the filter to that with the filter [17]. For any two-port network with its scattering parameters, the insertion voltage gain with arbitrary source and load impedances can be calculated by using Equation 3 [18].

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0} \tag{1}$$

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{2}$$

Where:

Z_S is the impedance of the noise source (device under test) and Z_L is the impedance of LISN. For common mode filter the insertion loss is calculated by using arbitrary values of Z_S = 1MΩ and Z_L=50Ω [18].

$$A_V = \frac{S_{12}(1-\Gamma_L\Gamma_S)}{(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-S_{12}\Gamma_S S_{21}\Gamma_L} \tag{3}$$

The scattering parameters, S_{11} and S_{22} are called reflection coefficients while S_{12} and S_{21} are called transmission coefficients. These scattering parameters are measured by network analyzer for common mode EMI filter. The insertion voltage gain of the common mode filter is calculated by Matlab according to Equation 3 using scattering parameters and reflection coefficients. The insertion voltage gain plot is shown in Figure 9.

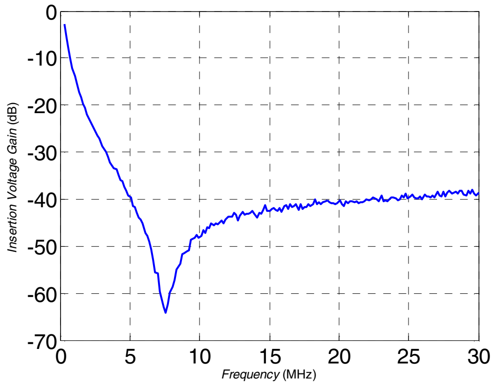

Figure 9 Insertion voltage gain of the common mode filter

VI. EMI MEASUREMENTS AFTER APPLICATION OF FILTER

It is observed that by using this filter the input noise of the converter is suppressed according to CISPR 22 class-A limits. The fundamental frequency component is at 64 dBμV and it is attenuated by 40 dBμV. The EMI plot after the application of the filter is shown in Figure 10.

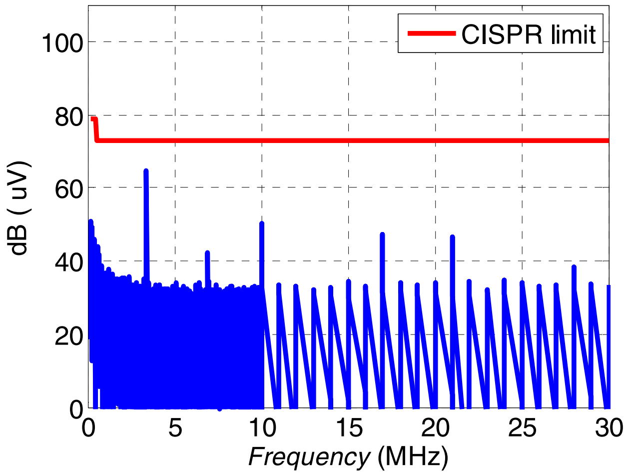

Figure 10 EMI plot after using filter

From the measurement results of the converter circuits, it is observed that the converter switching at higher frequency needs smaller EMI filter. Therefore, the overall size of the converter can be reduced by increasing the switching frequency of the converter.

VII. CONCLUSION

The focus of this paper is to measure and analyze the conducted EMI of the emerging power converters switching in MHz frequency range and to design the filter to keep the noise within regulatory limits.

In order to measure the noise spectrum a LISN is designed and implemented. The frequency spectrum of common mode input noise of the converter is plotted and it is observed that the fundamental frequency components as well as other higher order harmonics are not within regulatory limit. A single stage compact common mode EMI filter is designed and implemented on PCB. It is observed that the size of the converters as well as the EMI filter, required for these converters, is reduced by increasing their switching frequency.

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