EMI filter design based on the separated electromagnetic interference in switched mode power supplies

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Abstract: Usage of switch mode power supplies (SMPS) has been increased tremendously in recent years due to their advantages compared to conventional ones. In spite of their advantages, SMPSs cause conducted and radiated emissions due to the fact that they switch on and off at specific frequencies. Electromagnetic interference (EMI) filters are mostly preferred equipment for the reduction of conducted emission for coupled circuits. Improved EMI filter in the literature to suppress both common and differential mode noises sourced by ATX (a sample of SMPS) power supply has been proposed. A proposed filter was designed by use of AWR Microwave Office and MATLAB. The power supply was tested according to CISPR22 and it was observed that it has 30 dB higher noise level compared to the limit. A new improvement has also been proposed in order to separate resultant EMI into its common and differential modes for proper EMI filter design. The designed filter, by considering common and differential modes, suppresses those noises by 37 dB.

Key words: Conducted emission, electromagnetic compatibility, electromagnetic interference filter, noise separator, switch mode power supply

1. Introduction

Switching mode power supplies (SMPS) have found a wide range of application area since 1960. SMPSs have both low power dissipation and stepped voltage outputs and so they became the basic parts of the electric and electronic devices [1].

In spite of the advantages, it is known that SMPSs cause conducted and radiated emission at switching frequencies [2–7]. Also, Shin [4] reported that conducted and radiated emissions could result in system malfunctions and electromagnetic interference (EMI) at switching operation. Radiated emissions usually appear above 30 MHz as a result of circuit structure and/or cables. Conducted emissions, which are the main noises, appear between 150 kHz and 30 MHz [8].

Issues related to analysis and attenuation of EMI have been addressed on lots of platforms [9–11]. Electromagnetic shielding (ES) is the most commonly used basic method to attenuate the radiated emission... [12,13], but it is not sufficient for attenuation of conducted emission. In order to suppress the conducted emission, noise components need to be separated first. Separation of components is followed by grounding, shielding, or filtering methods [14].

Measurements show that ATX SMPS units present on computers are emitting above the limits of

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CISPR22, and this is the major part of computer related conduction emissions. This study proposes a new filter to reduce SMPS based electromagnetic interference, and it needs to be used between main and ATX SMPS units.

1.1. Components of conducted emission

Conducted EMI consists of two components called common mode (CM) noise and differential mode (DM) noise according to current direction (Figure 1). Common mode noise is the sum of currents that flow from both phase and neutral to ground. The reason for that noise is inductive impulses during switching on/off or that consist of filter capacitors and MOSFET heat sinks' capacitive impacts. Differential mode noise is the current that results from the difference between phase and neutral voltages. Origin of the differential mode is an interaction between circuit components [15–17].

Voltages (v_{cm}) and currents (i_{cm}) are calculated for common mode noise as indicated in Eq. (1) and Eq. (2).

$$v_{cm} = \frac{v_p + v_n}{2} \tag{1}$$

$$i_{cm} = i_p + i_n \tag{2}$$

Voltages (v_{dm}) and currents (i_{dm}) of differential mode noise are described as indicated in Eq. (1) and Eq. (2) and Figure 1.

$$v_{dm} = v_p - v_n \tag{3}$$

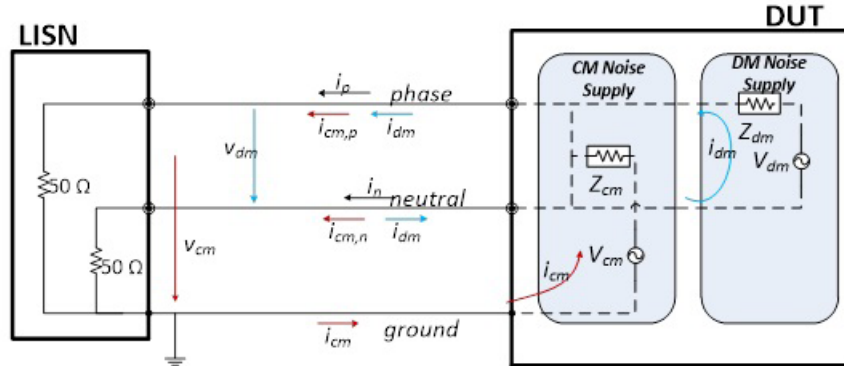$$i_{dm} = \frac{i_p - i_n}{2} \tag{4}$$

Figure 1. Conducted emission components.

During separation (measurement) 50 Ω loads of the line impedance stabilization network (LISN) are connected as parallel in common mode and as serial in differential mode. Thus Eqs. (1) and (3) produce Eq. (5), and Eqs. (2) and (4) produce Eq. (6) [18,19]:

$$v_{cm} = \frac{v_p + v_n}{2} = \frac{50\Omega \cdot i_p + 50\Omega \cdot i_n}{2} = \frac{50\Omega}{2} \cdot (i_p + i_n) = 25\Omega \cdot i_{cm} \tag{5}$$

$$v_{dm} = v_p - v_n = 50\Omega \cdot i_p - 50\Omega \cdot i_n = 2 \cdot 50\Omega \cdot (i_p - i_n) = 100\Omega \cdot i_{dm}, \tag{6}$$

where v_p is phase voltage, v_n is neutral voltage, i_p is phase current, and i_n is neutral current. Eqs. (5) and (6) show the equation between CM-DM noise voltages and currents. CM noise currents flow in the same direction. Thus, as shown in Eq. (5), LISN's resistors are considered parallel. Conversely, DM noise currents flow in the opposite direction. For that reason, LISN's resistors are considered as serial in Eq. (6). Conducted emission is assayed by military or civil standards. If the noise exceeds the limits, it will have to be separated into noise components by current probes or separation methods. The importance of noise separation is underlined in the literature to achieve an appropriate filter design [20–23]. Obtained noise components allow us to determine EMI filter components both for common and differential modes.

2. Conducted emission measurements

2.1. CISPR 22 measurement

CISPR 22 is addressed to determine conducted emission of the device under test (DUT) between 150 kHz and 30 MHz under certain conditions. This standard divides equipment, devices, and apparatus into two classes. Class A equipment are not intended to be used in the domestic environment, and Class B equipment are intended to be used in the domestic environment. In this paper, the chosen SMPS under test was assumed as in Class B [24].

Figure 2 is a screenshot of the spectrum analyzer [25] that shows CISPR 22 limits, as well as both conducted emissions, come from phase and neutral lines. Observed signals need to be separated in order to suppress exceeded levels.

(a)   (b)
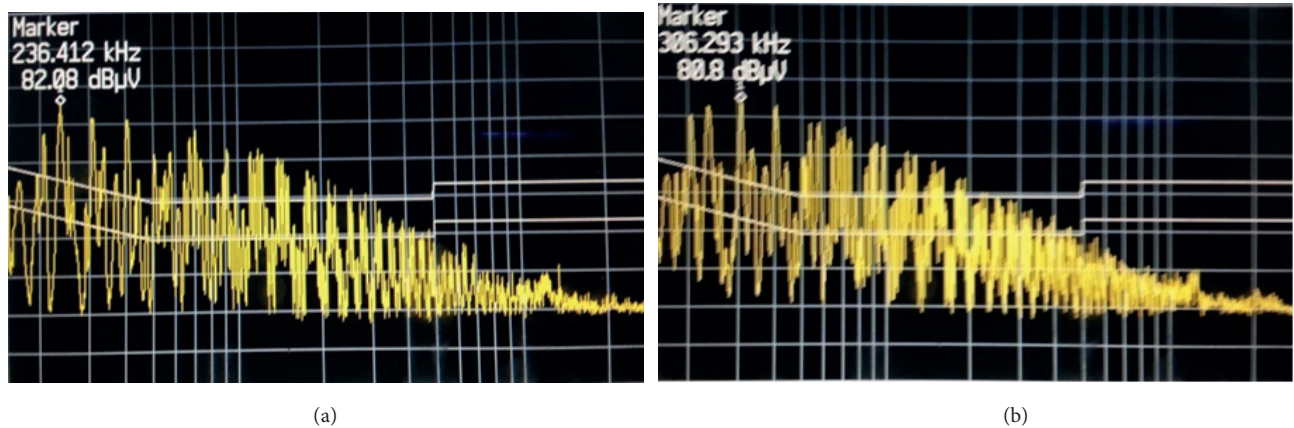
Figure 2. Conducted emission results of (a) phase and (b) neutral lines.

2.2. Conducted noise separation

There are a few methods to determine both common and differential mode noise components emitted by the DUT by measuring voltage [21,26–28]. One of these methods is the noise separator circuit offered by Wang in 2005 [26]. Resistance of 50 Ω present in the circuit given in Figure 3 has parallel connection for common mode and serial connection for differential mode such that those connections satisfy resistance response of Heinz electrodynamic designs (HEDD) for either common or differential modes. Binding of T1 transformers' windings allows us to block parasitic capacitances that may appear between them. These aforementioned advantages are new capabilities according to previous designs present in the literature. The results of offered design are: –50 dB for S11, –50 to –90 dB for S21, constant –6 dB for S31 and S41 (Figure 4).
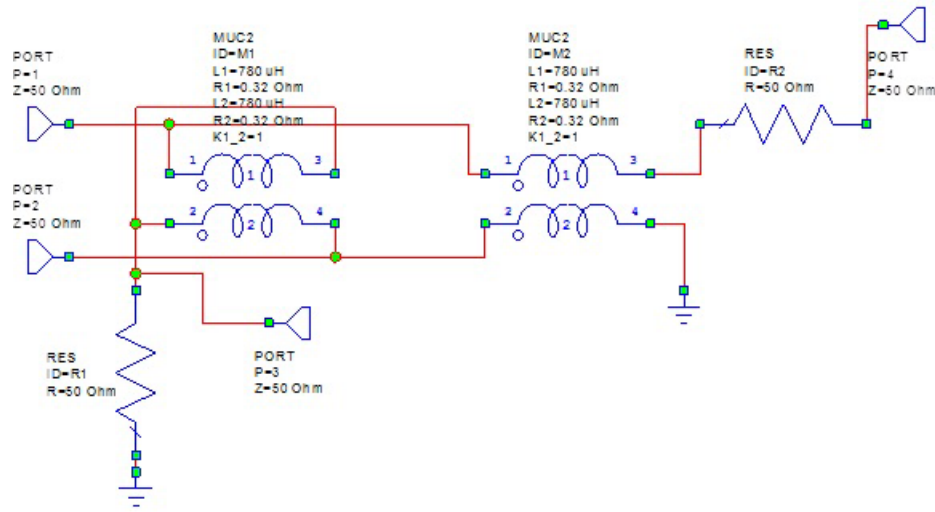
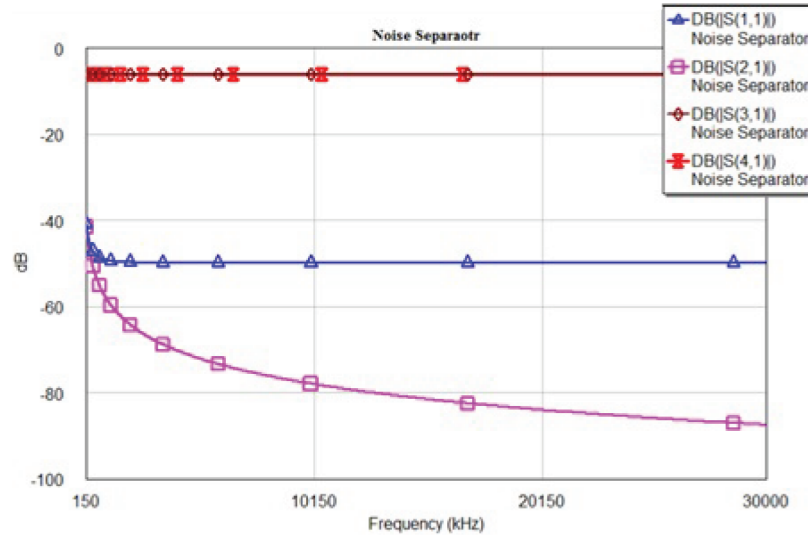**Figure 3**. Scheme of noise separator.

Figure 4. Noise separator schematic results.

In order to improve the previously proposed circuit, larger ground and narrower gap between the circuit components have been applied. Making the circuit's paths' shape as curvature instead of sharp is another solution that we also applied. S-parameters of the improved noise separator were measured by network analyzer [29].

Figure 5 indicates both Wang's results and the proposed circuits' response. Instead of the emitted noise from the DUT exceeding the limits between 150 kHz and 4 MHz bands, the proposed circuit has a capability to suppress them at the same band interval.

3. EMI filter design

Figure 6 shows both common and differential modes separated from emitted noise by SMPS exceeded limits. The common mode noise points are 20.7 dBµV, 27.55 dBµV, and 27.75 dBµV at 168 kHz, 235 kHz, and 305 kHz. The differential mode noise points are 22.26 dBµV and 30.55 dBµV at 202 kHz and 404 kHz, respectively.
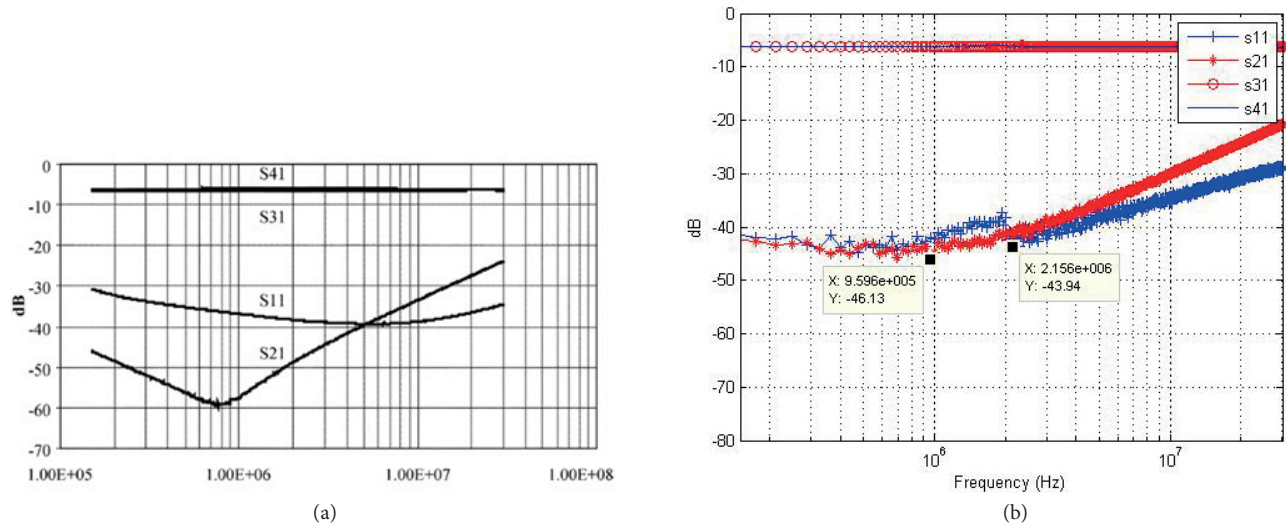
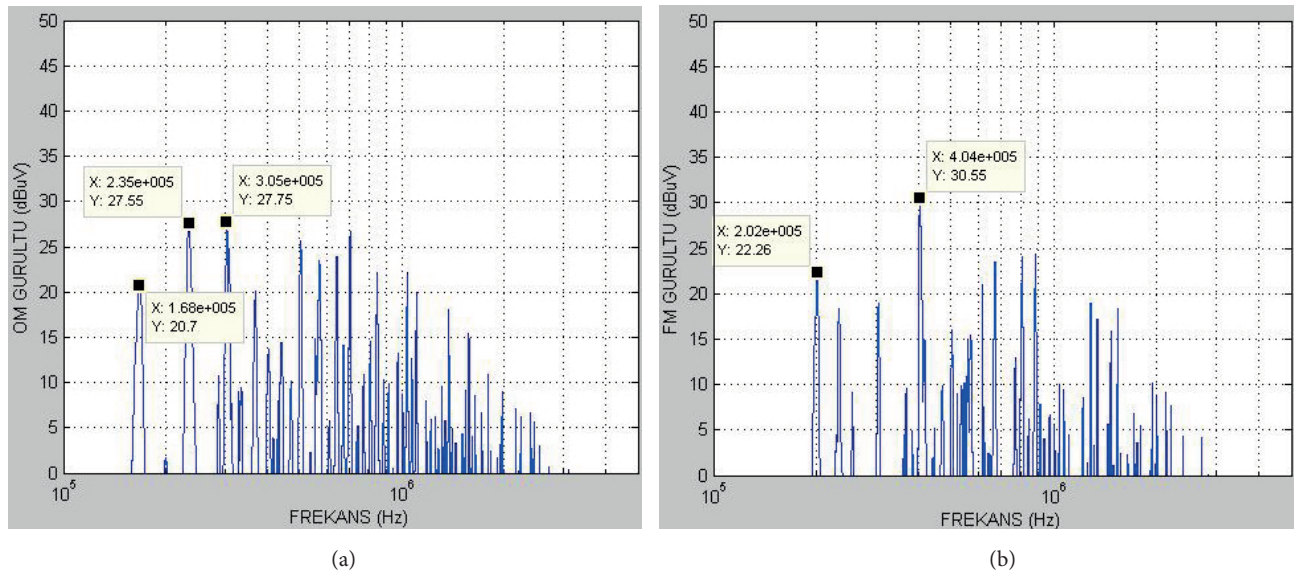**Figure 5**. (a) Designed and (b) improved noise separator's results.

Figure 6. SMPS's (a) common mode and (b) differential mode noises.

3.1. Determination of the cut-off frequencies

Selection of two-level filter structure to have 40 dB/decade suppression ratios was followed by determination of cutoff frequencies to suppress noises to aimed level. Moreover, the noise attenuation must be 6 dB more than the exceeded noise given in Eq. (7).

$$(V_{att})_{dB} = (V_{exc})_{dB} + 6dB \tag{7}$$

V_{att} is noise attenuation, V_{axc} is exceeded noise, and 6 dB is the correction factor [30]. The correction factor is added to the exceeded noise in order to ensure that noise is fully suppressed.

By using Eq. (7), suppression values are 26.7 dBµV, 33.55 dBµV, and 33.75 dBµV at 168 kHz, 235 kHz, and 305 kHz for common mode, and 28.26 dBµV and 36.55 dBµV at 202 kHz and 404 kHz for differential

mode. Cutoff frequencies that would allow us to suppress noises were calculated by using MATLAB, and they are presented in Figure 7. Here, 34 kHz for common mode and 39 kHz for differential modes are determined as cutoff frequencies, respectively.
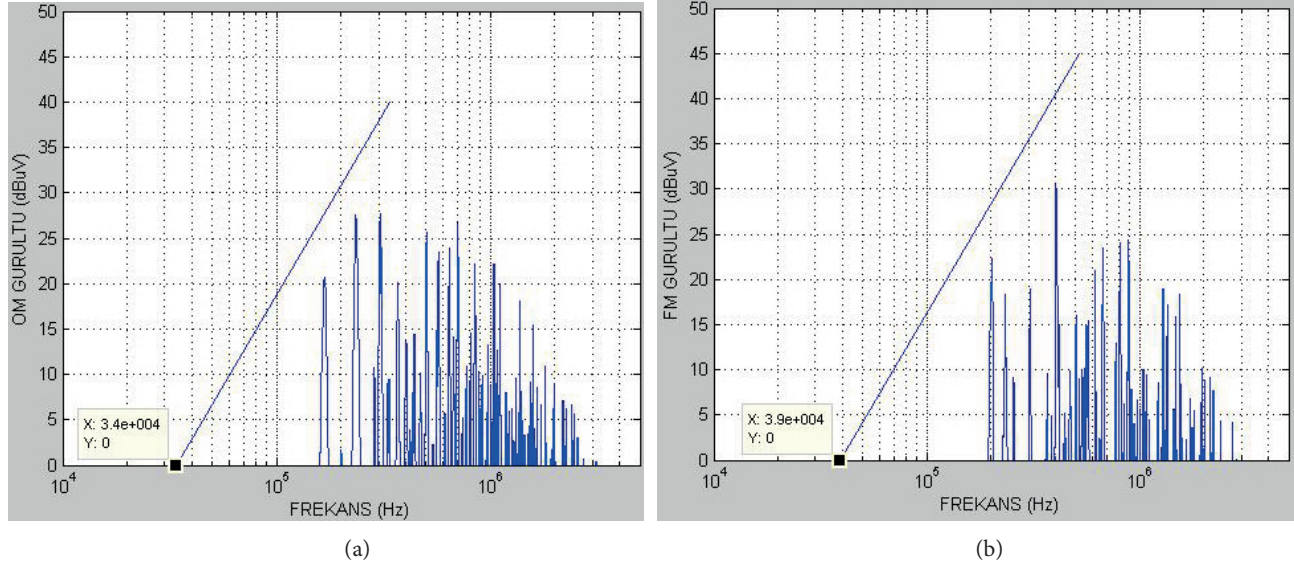
Figure 7. (a) Common mode and (b) differential mode cutoff frequencies.

3.2. Calculation of EMI filter components' values

It is well known in EMC point of view that a capacitor in any filter may behave like a parasitic inductor and an inductor in any circuit may behave like a parasitic capacitor in certain cases. For that reason, a low pass filter may behave as a band reject filter in some cases. This behavior forces engineers to determine first cutoff frequency, middle frequency, and second cutoff frequency of that filter [31]. Second cutoff frequency is usually about 20 MHz. The noise to be suppressed ends at 4 MHz in this paper. Thus, the middle frequency and the second cutoff frequency might be ignored for the designed EMI filter, as we did.

The designed EMI filter's differential mode equivalent circuit is shown in Figure 8. The values of those circuit components are calculated using Eq. (8). Values of C_x and C_y are selected as 4.7 nF to prevent leakage currents more efficiently [31].
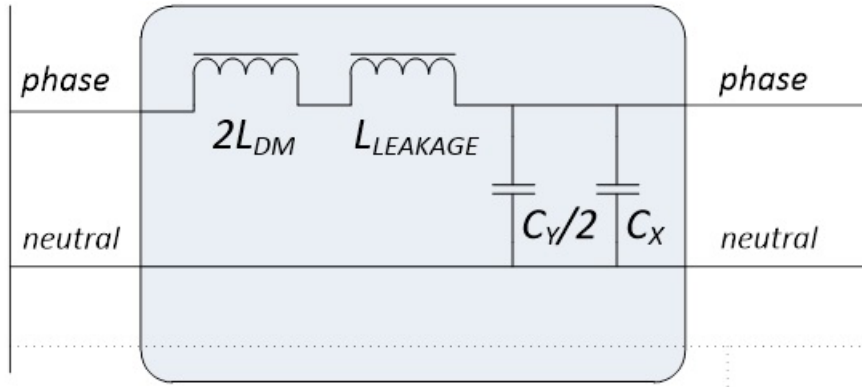
$$f_{c,DM} = \frac{1}{2\pi\sqrt{2L_{DM} \cdot (C_X + \frac{C_Y}{2})}}[Hz] \tag{8}$$

$f_{c,DM}$ is differential mode cutoff frequency and calculated as 39 kHz, and C_x and C_y are 4.7 nF. So if the differential mode inductor (L_{DM}) is taken from Eq. (8),
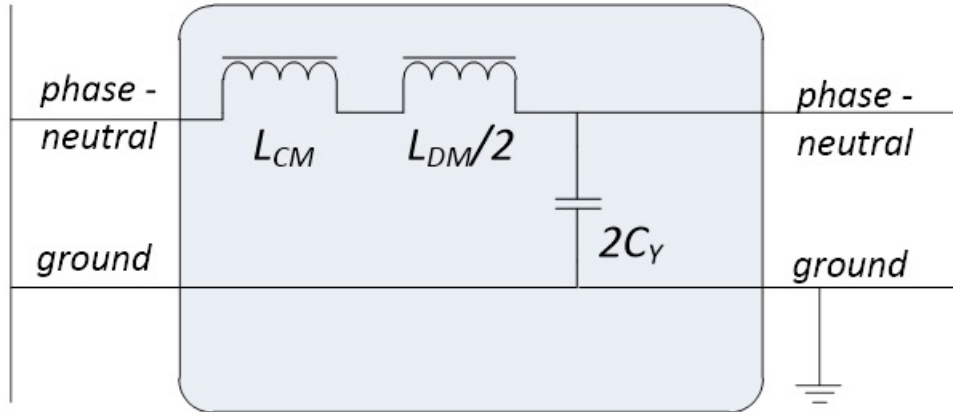
$$L_{DM} = \frac{1}{2 \cdot (2\pi \cdot 39 \times 10^3)^2 \cdot 4,7 \cdot 10^{-9} \cdot \frac{3}{2}}[H]$$

then L_{DM} is equal to 1200 µH.

The designed EMI filter's common mode equivalent circuit is shown in Figure 9. L_{CM} value of the circuit is calculated by using Eq. (9).

Figure 8. Filter's differential mode equivalent circuit.

Figure 9. Filter's common mode equivalent circuit.

$$f_{c,CM} = \frac{1}{2\pi\sqrt{(L_{CM} + \frac{L_{DM}}{2}) \cdot 2C_Y}}[Hz] \tag{9}$$

According to Eq. (9), common mode cutoff frequency ($f_{c,CM}$) is calculated as 34 kHz, where L_{DM} is differential mode inductor (1200 µH) and L_{CM} is common mode choke. Therefore, if L_{DM} is taken from the Eq. (9),

$$L_{CM} = (\frac{1}{(2\pi \cdot 34 \times 10^3)^2 \cdot 9, 4 \cdot 10^{-9}} - \frac{1, 2 \times 10^{-3}}{2})[H]$$

L_{CM} is 1800 µH. The structure of the EMI filter is shown in Figure 10.

Interaction between different circuit levels designed for different noise components has been shown. It has to be noted that the DUT connected to the filter's output has high impedance and meanwhile the LISN connected to the filter has low impedance level. Therefore, when the filter is designed, capacitors and then inductors are placed for impedance matching. The CM and DM equivalent circuits of the filter are shown in Figure 11 with determined components simulated in Microwave Office.
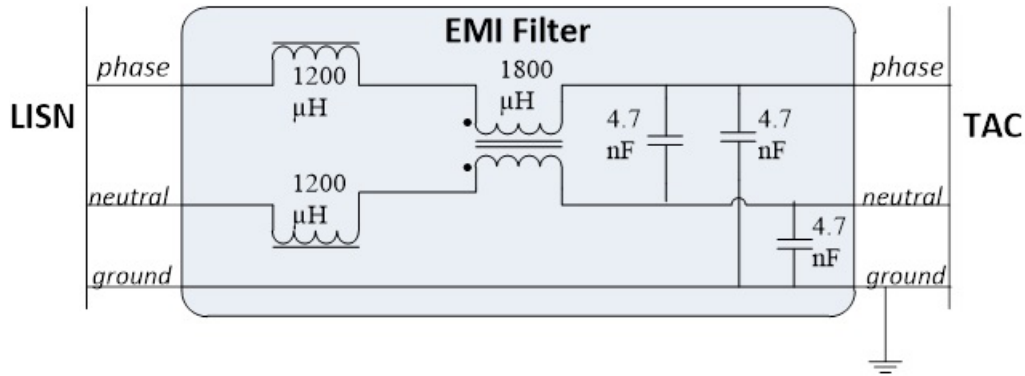
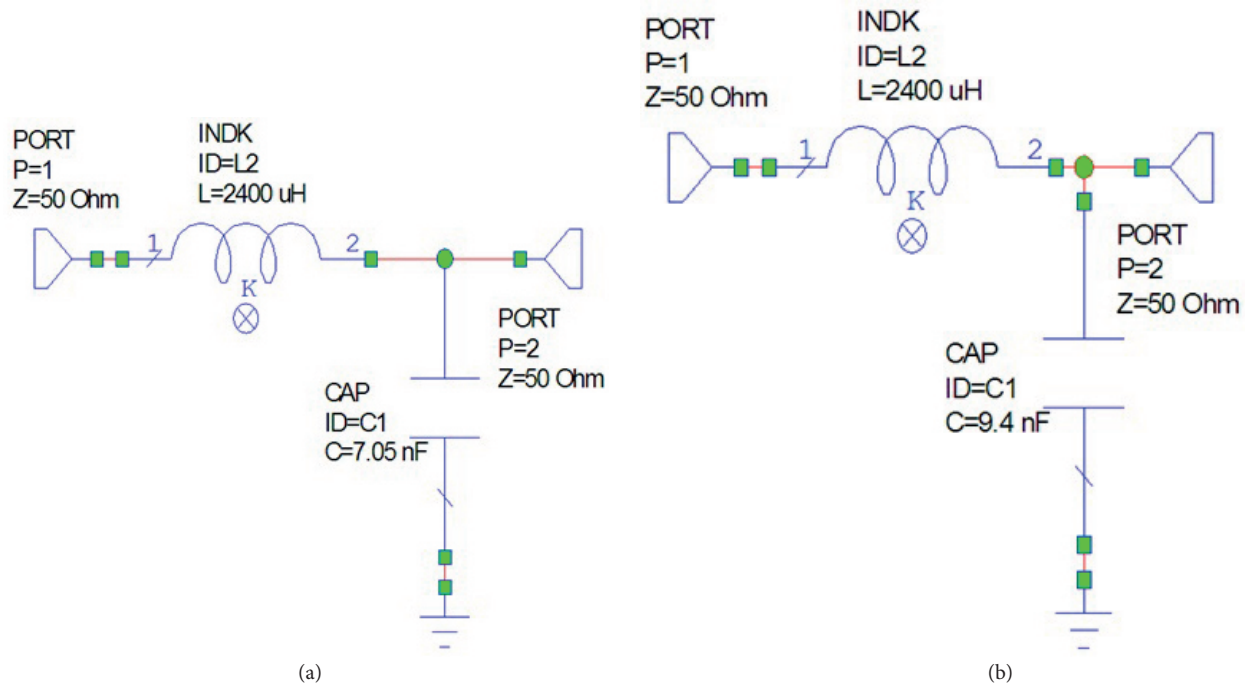**Figure 10**. Structure of the EMI filter.

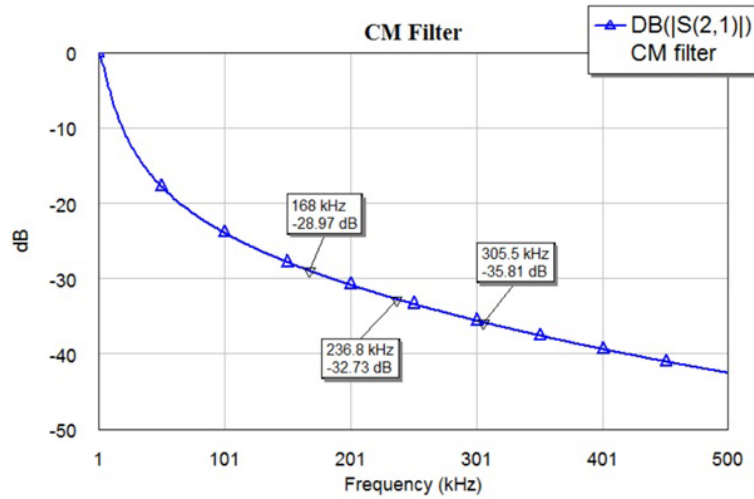**Figure 11**. (a) Differential mode and (b) common mode equivalent circuits simulation of EMI filter.

4. Experimental results

The response of the filter designed to suppress CM and DM noises produced by ATX power supply was performed and analyzed using the Microwave Office platform. Besides the filter's common mode and differential mode simulation, s-parameter results are indicated in Figure 12 and Figure 13, respectively. According to the results, the EMI filter is able to suppress common mode noises by 28.56, 32.54, and 35.46 dBμV at 168, 235, and 305 kHz, and to suppress differential mode noises by 30.46 and 38.25 dBμV at 202 and 404 kHz, respectively.
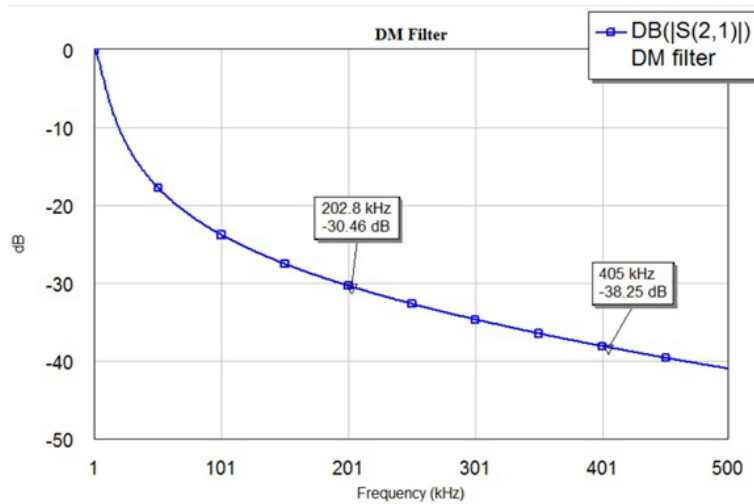
5. Conclusion

In this paper, a newly designed EMI filter based on separated noise components for common and differential mode interference of ATX power supply (a sample of SMPS) has been proposed. For this purpose, the noise

Figure 12. Common mode simulation frequency response of EMI filter.

Figure 13. Differential mode simulation frequency response of EMI filter.

separator circuit previously designed by Wang in 2005 has been improved. Both S11 and S21 for improved noise separator vary between –46 dB and –37 dB at the bandwidth where the noise exceeds the limits. The performance of the designed filter has been proved to be sufficient to reduce the interference sourced by CM and DM, and equivalent circuit simulations were carried out in Microwave Office and MATLAB. During the improvement of noise separator design, the effect of both LISN and SMPSs on filter design has also been discussed. It was shown that the proposed improvement is good enough to suppress CM and DM noises sourced by SMPSs type ATX power supplies. Comparison of active and passive EMI filter performances on SMPSs type ATX power supply based interference suppression is our future goal.

ATX SMPS units present on computers are emitting above the limits of CISPR22, and this is the major part of computer emissions. We may certainly conclude that the proposed filters need to be used between main and computer SMPS units to get rid of electromagnetic interference.

Acknowledgments

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