CHAPTER 5

DESIGN PROCEDURE AND ANALYSIS OF EMI FILTER

EMI filter is a significant part of SPC to minimize the CM and DM Conducted emissions in terms of size and cost. This chapter proposes an advanced and easiest method of EMI filter design for SPC. The practical approach of measuring the power converter noise spectrum to calculate the maximum and minimum magnitude of the DM and CM noise source impedances is proposed. The design of EMI filter is based on the noise source impedance values. The practical filters like DM choke with X capacitor on EUT side filter, DM choke with X capacitor on LISN side filter, π filter, complete EMI filter and X2Y filters are investigated.

5.1 INTRODUCTION

The power converters are unable to meet the FCC standards for Conducted EMI. Accordingly, EMI filters for both CM and DM are added at the input of the power converters so as to filter out the switching noise and reduce EMI of other equipments. Mismatch between the EMI source impedance and the EMI filter output impedance causes poor noise attenuation. Hence, an easy and efficient EMI filter design technique is essential. In addition, as the existing EMI filter design techniques do not take into account the noise source impedance of the SPC, the optimum levels of filtering could not be achieved.
The considered method is simple to understand and does not require the phase information of the noise source impedance. Hardware results show that the proposed method is an efficient technique to design EMI filters for AC-DC half-bridge converter. Passive filters have several significant benefits in certain applications, because they use no active elements. Passive filters range is enhanced to large signals where active devices are frequently impossible.

The EMI filter topology and elements are decided under the maximum or minimum value of the CM and DM noise source impedances which provide the smallest attenuation. The input filter on a SPC has two major purposes: (i) to prevent EMI produced in SPC and its effect on the other equipment, (ii) to avoid high frequency voltage from power line passing through the output of the SPC.

5.2 DESIGN OF CM FILTER

The following are required to know the purpose of designing the CM filter: (i) the attenuation needed to construct the CM noise range above the EMI standards at the required frequency range and (ii) the minimum noise source impedance or maximum noise source impedance for the frequency range of interest.

A passive LC filter result attains both the filtering requirements. The objective of the input filter design is to achieve the best balance between filter performance against size and cost. The input filter does not adjust the converter loop gain, if the output impedance is below the input impedance of the converter. To avoid oscillation, it is essential to keep the peak output impedance of the filter must be lower than the input impedance of the converter.
5.2.1 Design Procedure of CM Filter

Procedure for designing CM filter is given below:

STEP 1: CM and DM noise separation using a noise separator.

STEP 2: Using a simple test CM filter, measure the CM noise spectrum with and without filter.

STEP 3: Calculate the required attenuation along with definite regulations.

STEP 4: Calculate the maximum and minimum values of CM noise source impedances for the frequency range of interest.

STEP 5: Design the CM filter using maximum or minimum value of the noise source impedance which provides the least attenuation.

STEP 6: Calculate the spot frequency of the designed CM filter.

STEP 7: Calculate the attenuation of the designed CM filter and if it is satisfactory, CM filter design is completed.

STEP 8: If spot frequency of the designed CM filter is lesser, go to step 6.

STEP 9: If the designed filter does not meet the required attenuation, then a suitable filter topology is to be chosen and proceed from step 5.

STEP 10: Test the completed CM filter.

5.2.2 CM Filter Topology

CM filter consists of CM inductor and $C_Y$ or X capacitor. Regarding filter topology two cases are considered. When the CM inductor faces the
input side of SPC, $Z_{sCM_{max}}$ is used to find CM filter parameters. If X capacitor faces the input side of SPC, then $Z_{sCM_{min}}$ should be used to select the filter components.

**CASE 1:** For this topology, filter inductor’s impedance should be much larger than the noise source impedance for efficient suppression of noise. Noise equivalent circuit with CM inductor at the input of SPC is shown in Figure 5.1. If the maximum magnitude of the noise source impedance, $Z_{sCM_{max}}$ is easily determined, then the EMI filter is effectively designed using the maximum magnitude of the noise source impedance.

![Figure 5.1 Noise Equivalent Circuit with Inductor at the Input of SPC](image)

**CASE 2:** Similarly for the second topology, Y capacitor’s impedance should be much smaller than the noise source impedance for efficient attenuation. In these cases, phase angle of the noise source impedance is ignored and the design procedure is carried out easily. Noise equivalent circuit with Y capacitor at the input of SPC is shown in Figure 5.2. The CM noise spectrum of the unfiltered SPC operating at full load is illustrated in Figure 5.3.
CM noise voltage is measured across $R_{\text{loadCM}}$ with the equivalent circuits while the filter is inserted. Figure 5.4 shows the noise spectrum with CM inductor at the input of the SPC. Noise spectrum with Y capacitor at the input of the SPC is shown in Figure 5.5. Two types of CM filter topologies are analyzed. For this analysis, the CM inductance value is $100\mu\text{H}$ and the Y capacitor value is $1\mu\text{F}$. Furthermore, this result highlights the reality that the noise source impedance has an important consequence on the presentation of the EMI filter.
Figure 5.4 Noise Spectrum of CM Inductor at the Input of the SPC

Figure 5.5 Noise Spectrum of Y Capacitor at the Input of the SPC
With the experimental setup, the noise voltage values obtained at 0.5 MHz are tabulated in Table 5.1. From the results, it is concluded that the CM inductor at the input of the SPC topology should be used because it provides more attenuation at high frequencies than the X capacitor at the input of the SPC topology.

### 5.2.3 SELECTION OF CM FILTER COMPONENTS

The required lowest spot frequency for CM filter is determined using Equation (5.1).

\[
f_s = \frac{F_0}{\sqrt{A_{TCMreq}}}
\]

\(f_s\) is the spot frequency of the CM filter and \(A_{TCMreq}\) is the required attenuation at frequency \(F_0\). The CM attenuation required for the SPC to pass the FCC Class B standards is plotted as shown in Figure 5.6. Spot frequency value is calculated at each point for the value obtained from Figure 5.6 using Equation (5.1). The spot frequency required for the CM noise spectrum to pass FCC Class B standards is shown in Figure 5.7.
Figure 5.6 Required Attenuation of the CM Noise Spectrum

Figure 5.7 Spot Frequency Required for the CM Noise Spectrum

The lowest spot frequency calculated for CM filter is \( f_s = 110 \text{ KHz} \), using \( F_0 = 500 \text{ KHz} \) at \( A_{TCMreq} = 14 \). The CM inductor value is selected by the maximum noise source impedance value since it offers the least attenuation for the CM inductor at the input of the SPC filter.
The noise voltage without CM filter at 0.5 MHz is measured to be 54 dBµV as shown in Figure 5.3 and with CM test filter is 30 dBµV as shown in Figure 5.4. With these values, attenuation is found to be 15.85. From Equation (4.16), the maximum value of $Z_{sCM}$ is found to be 168 Ω by series insertion method. With the experimental setup, the noise source impedance values obtained at 0.5 MHz are tabulated in Table 5.2.

**Table 5.2 CM Noise Source Impedance Value**

<table>
<thead>
<tr>
<th>Attenuation</th>
<th>CM Noise Source Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.85</td>
<td>168 Ω</td>
</tr>
</tbody>
</table>

CM inductor impedance $Z_{LCM}$ must be twice the maximum CM noise source voltage.

$$Z_{LCM} >> 2 \times |Z_{sCM}|_{Max}$$

$$>> 2 \times 168$$

$$>> 336 \Omega$$

CM inductor impedance value must be greater than 336 Ω. From this value $L_{CM}$ is calculated as 106.9 µH. The inductance selected is any practical value above 106.9 µH. In order to leave some margin, a 110 µH inductor is selected. The impedance of this CM inductor at 500 KHz is 346 Ω which is greater than two times the maximum value of the CM noise source impedance.
Considering the CM noise source impedance as purely resistive, the attenuation of the topology in Figure 5.1 is stated by Equation (5.2) where $V_1$ and $V_2$ are known by Equations (5.3) and (5.4), respectively. Factors $Z_1$ and $Z_2$ are provided by Equations (5.5) and (5.6), respectively.

$$|A_{TCM}| = \frac{V_2}{V_1}$$  \hspace{1cm} (5.2)

where,

$$V_1 = \frac{Z_1 Z_2}{Z_{LCM} + Z_1} \text{ IsCM}$$  \hspace{1cm} (5.3)

$$V_2 = \frac{R_{load} Z_{sCM}}{R_{load} + Z_{sCM}} \text{ IsCM}$$  \hspace{1cm} (5.4)

$$Z_1 = \frac{R_{load} Z_{CY}}{R_{load} + Z_{CY}}$$  \hspace{1cm} (5.5)

$$Z_2 = (Z_{LCM} + Z_1) \left( \frac{Z_{sCM}}{Z_{sCM} + Z_1 + Z_{LCM}} \right)$$  \hspace{1cm} (5.6)

$Z_{LCM}$ is the impedance of the CM inductor. $Z_{CY}$ is the impedance of the Y capacitor. $V_2$ is the voltage across the LISN equivalent resistor shown in Figure 5.1 and $V_1$ is the noise voltage across the LISN resistor without the CM filter. The final step in the filter design is to select the capacitance. A capacitance of 94 nF is selected using two $C_Y$ capacitors of 47nF each in parallel. Using this capacitance and Equation (5.2), the calculated attenuation of the filter at 500 KHz is 15.45 which is greater than the required attenuation 14. Experimental waveform obtained after placing the designed CM filter is given in Figure 5.8.
The SPC with CM filter passed the FCC 15 Class B requirements over the required frequency range and the attenuation achieved is greater than the 3-dB margin over most of the frequency range.

If the capacitance is selected based on an ideal LC filter design, the calculated capacitance required would be 21nF using Equation (5.7). The closest available capacitance is 22 nF.

\[ f_c = \frac{F_0}{2\pi \sqrt{L_{CM} C_Y}} \]  

(5.7)

Using Equation (5.2) with the parameters \( C_Y = 22\text{nF}, R_{\text{loadCM}} = 25\Omega, L_{CM} = 100\mu\text{H}, \) and \( Z_{\text{SCM}} = 132\Omega, \) the calculated attenuation is 7.9 at 500 KHz which is less than the required attenuation, \( A_{\text{TreqCM}} = 14. \) It is obvious that this filter does not meet the FCC Class B requirements at approximately 500 KHz.

From the above analysis, it is clear that neglecting the noise source impedance directs a designer to design a filter that will not meet the
requirements. Neglecting the noise source impedance, the selected Y capacitance is 22 nF, but when the noise source impedance is taken into account, the selected capacitance of 94 nF is four times larger. The experiment results also verified this conclusion.

5.3 DESIGN OF DM FILTER

The following are required to know for the purpose of designing the DM filter: 1) the attenuation needed to construct the DM noise spectrum passes the EMI standards at the interested frequency range and 2) the maximum value and minimum value of the noise source impedance for the frequencies of interest.

5.3.1 Design Procedure of DM Filter

STEP 1: CM and DM noise separation using a noise separator.

STEP 2: Using a simple test DM filter, measure the DM noise spectrum with and without filter.

STEP 3: Calculate the required attenuation along with definite regulations.

STEP 4: Calculate the maximum and minimum values of DM noise source impedances for the frequency range of interest.

STEP 5: Design the DM filter using maximum or minimum value of the noise source impedance which has the least attenuation.

STEP 6: Calculate spot frequency of the designed DM filter.
STEP 7: Calculate attenuation of the designed DM filter and if it is satisfactory, DM filter design is completed.

STEP 8: If spot frequency of the designed DM filter is lesser, go to step 6.

STEP 9: If still the design does not meet the required attenuation then a suitable filter topology is to be chosen and proceed from step 5.

STEP 10: Test the completed DM filter.

5.3.2 DM Filter Topology

For DM filter, \( \pi \) topology is selected. \( \pi \) filter is a combination of capacitive and inductive filters which effectively reduces the high frequency noise currents where the low-frequency AC is bypassed. The DM filter topology is shown in Figure 5.9. Experimental result of DM noise spectrum without DM filter is shown in Figure 5.10.

![Figure 5.9 \( \pi \) Filter Topology](image-url)
DM test filter comprises a DM inductor 33\(\mu\)H and two \(C_X\) capacitors of value 12nF each. Result of DM noise spectrum with DM test filter is shown in Figure 5.11. The noise voltage without DM filter is 65dB\(\mu\)V and with a test DM filter at 0.5 MHz, it is 37 dB\(\mu\)V. With these two values, the attenuation is found to be 25. Using Equation (4.24) the minimum value of DM noise source impedance, \(Z_{sDM}\) is found to be 0.128 \(\Omega\) by shunt insertion method. For DM filter design, the minimum noise source impedance is used to calculate the filter components as the capacitor at the input side of the SPC. DM inductor impedance \(Z_{LDM}\) must be at least double the maximum magnitude of the DM noise source impedance.

\[
Z_{LDM} \gg 2 \times |Z_{sDM}|_{\text{Min}}
\]

\[
\gg 2 \times 0.128
\]

\[
\gg 0.256 \Omega
\]
The DM inductor impedance value must be greater than $0.256 \Omega$. From this value, $L_{DM}$ is calculated as $81.5 \text{nH}$. Similarly two $C_X$ capacitors each of value $1.2 \mu\text{F}$ is used as DM filter components. Experimental results showing minimum and maximum values of DM noise source impedances are shown in Table 5.3.

![Figure 5.11 Noise Spectrum with Test DM Filter](image)

**Figure 5.11 Noise Spectrum with Test DM Filter**

**Table 5.3 DM Noise Source Impedance Values**

<table>
<thead>
<tr>
<th>Attenuation</th>
<th>Noise Source Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum value</td>
</tr>
<tr>
<td>25</td>
<td>$6.656 \Omega$</td>
</tr>
</tbody>
</table>
5.3.3 Selection of DM Filter Components

The minimum DM noise source impedance is used for the filter design because an X capacitor is used at the input of the SPC. The attenuation of this DM filter topology is expressed using Equation (5.8), where $Z_{C1}$ and $Z_{Cs}$ are given by Equations (5.9) and (5.10), respectively. In Equations (5.9) and (5.10), $Z_{CX}$ is the X capacitor impedance and in Equation (5.8), $Z_{LDM}$ is the DM inductance impedance. In Equations (5.8) and (5.9), $R_{loadDM}$ is the equivalent load resistance of LISN which is 100Ω.

$$|A_{TDM}| = \frac{R_{loadDM} Z_{sDM} (Z_{C1} + Z_{LDM} + Z_{Cs})}{(R_{loadCM} + Z_{sDM}) Z_{Cs} Z_{C1}}$$  \hspace{1cm} (5.8)

$$Z_{C1} = \frac{R_{loadCM} Z_{CX}}{R_{loadCM} + Z_{CX}}$$  \hspace{1cm} (5.9)

$$Z_{Cs} = \frac{Z_{CX} Z_{sDM}}{Z_{CX} + Z_{sDM}}$$  \hspace{1cm} (5.10)

With the results obtained, the lowest spot frequency needed is $F_0 = 500$ KHz. The attenuation needed at this frequency is 7.9. The DM inductance is used as leakage inductance of the CM inductor; hence single inductor is needed to meet the required attenuation for the CM and the DM noise. Equation (5.8) together with $L_{DM} = 33\mu$H, $Z_{sDM_{min}} = 0.128\Omega$, and $C_X = 22nF$, the estimated attenuation $A_{TDM}$ is 9.8 at $F_0 = 500$ KHz, bigger than the required attenuation which is 7.5. The test result of the noise spectrum after the designed DM filter is shown in Figure 5.12. Noise spectrum obviously exposes the reduction in noise level after placing the filter. The DM noise voltage at 0.5 MHz are observed and tabulated in Table 5.4.
Figure 5.12 Noise Spectrum with DM Filter

Table 5.4 DM Noise Voltages

<table>
<thead>
<tr>
<th>Topology</th>
<th>Noise Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DM filter</td>
<td>65 dBµV</td>
</tr>
<tr>
<td>With test DM filter</td>
<td>37 dBµV</td>
</tr>
<tr>
<td>With DM filter</td>
<td>26 dBµV</td>
</tr>
</tbody>
</table>

5.4 DESIGN OF EMI FILTER

CM and DM filters are designed separately in the previous procedures. Now, both the filters are assembled together to get a complete EMI filter. The procedure to design EMI filter is summarized as follows.

**STEP 1:** Separate the CM and DM noise spectrum of the SPC.

**STEP 2:** Determine the noise voltage, $V_{\text{noise}}$, without and with a single filter (example, a capacitor).
STEP 3: Calculate the maximum CM and DM noise source impedances for the frequency range of interest (0.15–30 MHz for the FCC class B).

STEP 4: Design the EMI filter with maximum or minimum value of the noise source impedance which contains the least attenuation.

STEP 5: The completed EMI filter is analyzed.

This procedure agrees that the CM and DM noises that arise from different sources are effectively suppressed. The final EMI filter is illustrated in Figure 5.13.

![Figure 5.13 Complete EMI Filter](image)

A 220-µF electrolytic capacitor is connected at the output of the filter. This makes that the EMI filter strengthens the feedback loop of the SPC. It does not concern the filter design because the resonant frequency of this electrolytic capacitor is comparatively small. This filter is arranged by ceramic capacitors and CM inductors. The relevant value of capacitors $C_Y$ is 47nF and $C_X$ is 22µF.

The inductor used in EMI filter has a value of 33µH and current rating of 3A. The number of windings is 79. Similarly capacitance has a voltage rating of 400V and the ESR requirements are 1.2Ω. Noise spectrum obtained without EMI filter is given in Figure 5.14.
Noise spectrum obtained after placing the complete EMI filter is given in Figure 5.15. Table 5.5 gives the values of noise voltages before and after placing the EMI filter at 0.5 MHz frequency.
### Table 5.5 EMI Noise Voltages

<table>
<thead>
<tr>
<th>Topology</th>
<th>Noise Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EMI filter</td>
<td>72 dBµV</td>
</tr>
<tr>
<td>With EMI filter</td>
<td>28 dBµV</td>
</tr>
</tbody>
</table>

FCC class B standards recommend the Conducted noise emission limit as 48 dBµV. Conducted noise emission without EMI filter is 72 dBµV and with EMI filter is 28 dBµV which is very much below the limit of the FCC class A and class B standards. So the standard regulation is well satisfied. Thus by matching the filter parameters with noise source impedance an efficient EMI filter is designed.

#### 5.5 X2Y FILTER

The complete EMI filter using X2Y is illustrated in Figure 5.16. X2Y replaces five to seven standard passive elements used for the purpose of noise cancellation. Standard two termination capacitors are made of two opposing electrodes that are screened onto layers of dielectric material in an alternating fashion during the fabrication process. X2Y capacitor circuit configurations and physical structure are shown in Figure 5.17. The X2Y filter used is the Johnson Dielectrics catalogue no. 501H47W102KF4T-AC.

![Figure 5.16 X2Y Circuit](image-url)
Figure 5.17 X2Y capacitor circuit configurations and physical structure

Image Plane Shield

Figure 5.18 X2Y Architecture

Figure 5.19 Simultaneous CM and DM

The layers are repeated to increase capacitance value, \( C = \varepsilon \cdot \text{Area/Distance between plates} \). 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.

The X2Y architecture as shown in Figure 5.18 uses image planes (shields), which create rectangular current loops that share a common image plane. The X2Y plates A and B charge the image plane with opposing skin currents. When the currents are common on the image plane or 180° out of phase, they are oppositely charged and get cancelled.

A structure with X2Y circuitry contains 1 “X” capacitor and two “Y” capacitors in a single component as shown in Figure 5.19. This structure replaces three regular capacitors with one component that can simultaneously filter CM and DM noise. The test result for the X2Y filter is shown in Figure 5.20. CM noise is filtered to ground by the two Y capacitors. As X2Y is a balanced circuit that is tightly matched in both phase and magnitude with respect to ground, CM to DM noise conversion is minimized and any DM noise is cancelled within the device.

![Figure 5.20 Noise Spectrum after the X2Y Filter is added](image)
5.5.1 High Frequency Decoupling Capacitor Requirements

The power distribution system on a PC board must provide a low impedance source over a very wide frequency range. Various size decoupling capacitors are typically mounted on the PC board for frequencies up to a few hundred MHz. At frequencies above a few hundred MHz, the parallel plate capacitance of the PC board power planes take over and provide the low impedance source.

Small capacitors are used to cover the high frequency range just below the point that requires internal PCB plane capacitance. The most important characteristic of a high frequency decoupling capacitor is the ESL (Equivalent Series Inductance). The ESL of interest is the effective inductance of the capacitor including the surface footprint and via necessary to connect to the internal power planes of the PCB. With lower ESL, fewer decoupling capacitors (in parallel) are required to provide the low impedance at high frequencies.

Depending on currents and voltages there are many different forms of decoupling. The major application driving the need for improved decoupling in the past decade has been the decoupling of the power supply for high-speed microprocessors in electronic data processing applications. Power Systems for modern CMOS technology are becoming harder to design.

The design methodology is to identify a target impedance to be met across a broad frequency range and specify components to meet that impedance. Given the voltage and power consumed, the current is calculated from Ohm’s Law. Assuming that only a small percentage of the power supply voltage (e.g. 5%) is allowed as ripple voltage (noise), target impedance for the PDS is calculated. The target impedance is falling at an alarming rate, 5X per computer generation and has now reached mOhm and sub mOhm levels.
Figure 5.21 Low impedance in a broad frequency ranges requires different solutions in each frequency segment.

Good decoupling requires low impedance over a broad frequency range. For the low end, the voltage regulator supplies the low impedance, for higher frequencies successively higher valued caps are used and low value caps and power planes provide the low impedance at higher frequencies.

To achieve extremely low target impedance, circuit designers have to continuously improve circuit layout and refine component selection. Capacitor manufacturers join the battle to lower system inductance by developing components with lower inductance.

5.5.2 X2Y for Decoupling

- Ultra-low equivalent series inductance (ESL)
- Reduces component count and associated placement costs.
- Dramatic reduction in via used, which improves routing.
- Using fewer components increases product reliability
- Systems savings through circuit design simplification.
- Cost effective on the IC package and the printed circuit board.
Table 5.6 shows the comparison of hardware results for various frequency ranges with filters and without filters. Figure 5.22 shows the Photograph of the measurement arrangement. Fig 5.23 shows the flowchart of the proposed filter design method.

### Table 5.6 Comparison of Filter Waveform Results

<table>
<thead>
<tr>
<th>Frequency in MHz</th>
<th>Without Filter (dBµV)</th>
<th>With Filter (dBµV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>CM</td>
</tr>
<tr>
<td>10</td>
<td>79</td>
<td>65</td>
</tr>
<tr>
<td>20</td>
<td>78</td>
<td>62</td>
</tr>
<tr>
<td>30</td>
<td>76</td>
<td>58</td>
</tr>
</tbody>
</table>

Figure 5.22  Photograph of the Converter with LISN, Noise Separator and Control Circuit
Figure 5.23 Flowchart of the Proposed Filter Design Method
Design methods ensure complete decoupling of the characteristics of the CM and DM filters that are combined to produce the X2Y design. The transfer functions of the combined filter ensure that the frequency responses expected of the individual sub filters are retained.

The parametric study on the combined X2Y filter discovers capacitor variations have biggest effects to degrade the performance of the filter. The X2Y filter affects the steady-state waveforms, Input-output characteristics and the dynamic response of the Switching Power Converters.

5.6 CONCLUSION

The procedure of designing an enhanced and simple method of EMI filter depends on the noise spectrum and with the measured data to determine the maximum and minimum magnitude of the noise source impedance used in the EMI filter design. The CM and DM filters are designed individually. For the CM part of the EMI filter, two types of filters are considered. In the first type, the CM inductor appears at the input side of SPC. In the second type, the X capacitor appears at the input side of SPC. A π type filter is used to restrain the DM noise, since this type presents improved performance than other types for example, LC type. At last, the CM and DM filters are collected together to get the total EMI filter. The X2Y filter provides considerable perfection in reducing the Conducted emissions while compared to four mica filter arrangements. From these results X2Y filter is found to be better than other filters taken for analysis in this thesis.