EMI Filter Design for Reducing Common-Mode and Differential-Mode Noise in Conducted Interference

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Abstract

The demand for high-speed electronics at high frequencies is leading to increasing amounts of Electromagnetic Interference (EMI) which is in two forms - conducted and radiated. The mitigation of conducted interference is a major challenge today and the best solution is the use of EMI filters. This paper focuses on designing an EMI filter to reduce both common-mode and differential-mode noise using AWR microwave office and MATLAB. The comparison between inductor and choke filter for reducing common-mode noise is shown in this paper and a basic \( \pi \) filter has been designed for reducing differential-mode noise. The use of Microwave Office made the design easier and the availability of extensive tools in this software made the design more efficient and practical for use.

Keywords: Electromagnetic interference (EMI), Common-mode noise, Differential-mode noise, EMI filters, Choke, Insertion loss

Introduction

The use of sophisticated electronic equipment has led to rapid increase in Electromagnetic Interference (EMI). EMI is in two forms- conducted and radiated, of which the term conducted emissions refers to the coupling of electromagnetic energy produced by equipment to its power cord [1-3]. The conducted interference can further be classified into two types, namely common-mode and differential-mode.

Common-mode (CM) noise and Differential-mode (DM) noise
CM noise current flows in the same direction on both power conductors and returns via the ground conductor and can be suppressed by the use of inductors within an
EMI filter that are placed in series with each power line and by Y-capacitors that are connected from both power line conductors to ground [4-6]. Differential mode (DM) current flows through one ac conductor and returns along another [7-9] and can be suppressed by the filter which contains an inductor in series and X-capacitors connected in parallel between the two current carrying conductors. The CM and DM noises exist as shown in Figure 1.

**Figure 1:** Common-mode and differential-mode noise.

Common mode noise is given as,

\[ V_{cm} = \frac{V_p + V_N}{2} \]  

and differential noise is given as,

\[ V_{dm} = \frac{V_p - V_N}{2} \]

where, \( V_p \) is phase voltage and \( V_N \) is neutral voltage. The capacitors \( C_p \) are connected in shunt to the power lines to reduce CM noise and in order to reduce DM noise capacitors should be connected across the power line [9].

**EMI Filters**

EMI filtering circuits are employed so that the end product complies with the applicable EMC standards. Among the most frequently cited EMC standards are EN55022 or its equivalent CISPR 22 standard for IT equipment, EN55011 for industrial equipment [7].

**Table 1:** CISPR 22 Conducted Emissions Limits for Class A Devices

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>( \mu V ) QP (AV)</th>
<th>dB(( \mu V )) QP (AV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 - 0.5</td>
<td>8912.5 (1995)</td>
<td>79 (66)</td>
</tr>
<tr>
<td>0.5 - 30</td>
<td>4467 (1000)</td>
<td>73 (60)</td>
</tr>
</tbody>
</table>
Table 2: CISPR 22 Conducted Emission Limits for Class B Devices

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>µV QP (AV)</th>
<th>dB(µV) QP (AV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 - 0.5</td>
<td>1995-631 (631-199.5)</td>
<td>66-56 (56-46) (limit varies linearly)</td>
</tr>
<tr>
<td>0.5 - 5</td>
<td>631 (199.5)</td>
<td>56 (46)</td>
</tr>
<tr>
<td>5 - 30</td>
<td>1000 (316)</td>
<td>60 (50)</td>
</tr>
</tbody>
</table>

The frequency limits for conducted emissions are shown in Table 1 and Table 2 [4-5]. Conducted emissions are regulated by CISPR over the frequency range from 150 KHz-30MHz [10-12]. If the emissions are found to exceed the limits specified by EMC standards, then EMI filter would be designed in order to reduce the noise produced by the equipment under test.

Filter Design
The basic setup shown in Figure 2 consists of Line Impedance Stabilization Network (LISN), Equipment under Test (EUT) which is a 2-transistor SMPS circuit, mains power supply and a noise separator circuit.

![Figure 2: Conducted emissions measurement setup](image)

Line Impedance Stabilization Network (LISN)
The conducted EMI measurement procedure requires a 50 W/ 50 mH Line Impedance Stabilization Network (LISN) to be inserted between the equipment under test (EUT) and the ac utility line to provide specified measuring impedance for noise voltage measurement [5]. The basic schematic of LISN is shown in Figure 3.
Equipment Under Test (EUT)
The EUT used in this setup is a 2-transistor SMPS circuit that consists of two transistors, diodes which act as noise sources from which conducted EMI is generated.

Noise Separators
The common mode and differential mode noises from the measured output are separated using a noise separator. DM noise rejection is done using a passive circuit while an active circuit is used for CM noise rejection.

Basic EMI filters
There are numerous EMI filters that could be considered for noise reduction, but the most popularly used are the LC inductor filter and the π filter for CM and DM noises respectively [13]. The aim is to obtain the maximum impedance mismatch between the filter and the outside system.
A better solution over the inductor filter is the choke filter. Chokes withstand high DC currents without degradation of filtering performance. Chokes reduce noise considerably over the entire desired frequency range. The components of inductor filter are designed such that

\[
1 \frac{1}{w(2C_{CM})} \ll Z_P, \text{ then } \quad w(L_{CM}) \gg 25\Omega \quad (3)
\]

Where \( L_{CM} \) and \( C_{CM} \) are inductor and capacitor used in the design of inductor filter and \( Z_P \) is the impedance of the equipment used [3].

The components of \( \pi \) filter are designed such that

\[
1 \frac{1}{w(C_{DM})} \gg 100 \quad \text{and} \quad \frac{1}{w(C_{DM})} \ll Z_P, \text{ then } \quad w(L_{DM}) \gg 100\Omega \quad (4)
\]

Where \( L_{DM} \) and \( C_{DM} \) are inductor and capacitors used in the design of \( \pi \) filter and \( Z_P \) is the impedance of the equipment used [3].

**Conducted Emissions Measurements**

The experiment was initially conducted with the measurement setup shown in Figure 2, but without filter across 150KHz-1.5MHz frequency range. The actual connected schematic has been shown in Figure 6. The measured common-mode noise voltage, \( V_{cm} \) (dB) and DM noise \( V_{dm} \) (dB) across the noise separator, are shown in Figure 7 and Figure 8. Using these magnitudes, the insertion loss graphs were obtained in MATLAB. The simulation plots obtained in MATLAB showed that the \( V_{cmdB\mu V} \) and \( V_{dmdB\mu V} \) without filter have exceeded the \( V_{limdB\mu V} \) set by the EMC standard for Class B equipment. Hence, the basic EMI filters were designed to be placed between the LISN and EUT and the noise outputs were once again measured and graphs were simulated.
Figure 6: Conducted emissions measurement setup using AWR-Microwave Office.

Figure 7: $V_{cm}(dB)$ measured without filter across output of noise separator.

Figure 8: $V_{dm}(dB)$ measured without filter across output of noise separator.
The Insertion loss without filter was calculated by,

\[ IL_{cm\ dB\ uV} = V_{cm\ dB\ uV} - V_{lim\ dB\ uV} \]  

(5)

\[ IL_{dm\ dB\ uV} = V_{dm\ dB\ uV} - V_{lim\ dB\ uV} \]  

(6)

where, \( V_{cm} \) is the common mode noise obtained in Microwave office whose magnitude is shown in Figure7, \( V_{dm} \) is the value differential mode noise obtained whose magnitude is shown in Figure8. \( V_{lim} \) is the EMC limit for conducted emissions which is in dB \( \mu \)V and hence the output noise obtained is converted into dB \( \mu \)V by adding 120 to output noise magnitude[5]. The aim was to design the filter to reduce the CM and DM noises and hence the design needs an insertion loss greater than that given equations 5 and 6.

Hence, the filter components were tuned in Microwave Office referring to the equations 3 and 4 such that they produce noise voltages that would give an Insertion loss greater than that in equations 5 and 6. Once these components were tuned to give the required insertion loss, the same was simulated in MATLAB using the equations 7 and 8 for inductor and \( \pi \) filter for CM and DM noises respectively. The obtained insertion losses using the filters is simulated using,

\[ IL_{cm\ dB\ uVf} = V_{cm\ dB\ uVf} - V_{cm\ dB\ uVf} \]  

(7)

\[ IL_{dm\ dB\ uVf} = V_{dm\ dB\ uVf} - V_{dm\ dB\ uVf} \]  

(8)

where, \( V_{cm\ dB\ uVf} \) and \( V_{dm\ dB\ uVf} \) are values obtained without using filter and \( V_{cm\ dB\ uVf} \) and \( V_{dm\ dB\ uVf} \) are the noise voltages obtained after tuning filter components for inductor and \( \pi \) filter respectively.

**Inductor filter**

The inductor filter was placed between the LISN and EUT and the filter circuit was tuned to obtain insertion loss greater than the loss obtained before embedding filter across the desired frequency range. The obtained CM noise voltage, \( V_{cm\ dB\ uV} \) was measured across the output of noise separator in AWR-Microwave Office. It could be observed that noise output reduced considerably by using the inductor filter. Figure9(a) shows that for frequencies from 300KHz-1.5MHz, the noise is within the limits specified by EMC standards. To obtain desired insertion loss below 300KHz, the choke filter was used instead of inductor filter and the results were obtained as in Figure9(b).

**Choke filter**

It shows that by using choke filter there is a tremendous reduction in noise for frequencies less than 300KHz and over the entire range till 1.5MHz. The loss simulations are shown in Figure10.
Figure 9(a): Comparision of CM Voltage with and without filter with $V_{\text{lim}}$ set by EMI standards

Figure 9(b): Comparision of CM voltage without filter and with choke with $V_{\text{lim}}$ set by EMI standards

Figure 10: Insertion loss(dBuV) vs Frequency for inductor and choke filter in comparison to insertion loss without filter.
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Figure 11: Comparison of DM output with and without filter with $V_{\text{lim}}$ set by EMC standards.

Figure 12: Insertion loss(dBµV) vs Frequency for filter in comparison to insertion loss without filter.

**pi filter**

To reduce the differential-mode noise, the filter was placed between the LISN and EUT and the filter was tuned to obtain DM noise voltage, whose insertion loss obtained is greater than the loss before embedding filter across the desired frequency range. The result obtained is shown in Figure11. Figure12 plots the insertion loss measurement with and without π filter.

**Results**

The conducted emissions measurement setup without the filter produced an insertion loss of around 40-90dBµV for 150-300KHz frequency range and 30dBµV over the
frequency range from 300KHz-1.5MHz for common mode noise. Insertion loss of 50-100dBµV was obtained over 150KHz-300KHz and 50dBµV over 300KHz-750KHz for differential mode. The designed filters pi, inductor and choke produced an insertion loss greater than the measurement setup without a filter. The inductor filter produced insertion loss of around 40-80dBµV from 300KHz-1.5MHz range and the choke filter produced loss of around 320-550dBµV over the frequencies from 150KHz-1.5MHz. The π filter produced an insertion loss of 80-560dBµV for 150KHz-300KHz and 550-750dBµV over 300KHz-750KHz. The use of AWR-Microwave Office made it much easier to tune the EMI filter to get the required Insertion loss.

**Conclusion**
The inductor filter produced desired insertion loss for frequencies from 300KHz-1.5MHz, but the choke filter produced better results than the inductor filter and also the obtained noise reduced considerably over the entire considered frequency range from 150KHz-1.5MHz. The π filter is a good option for reducing the DM noise over the frequencies from 150KHz-750KHz. Hence, choke and pi filter are good EMI solutions over the conducted emissions range of 150KHz-1.5MHz.

**References**


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