Selection of Power Filters for Switched Mode Power Supplies

Konstantin S. Kostov, Jukka-Pekka Sjöroos, Jorma J. Kyyrää, and Teuvo Suntio

Abstract - Power filter manufacturers provide Insertion Loss (IL) measurement data for their products. These are usually 50 Ω / 50 Ω and sometimes the so-called “approximate worst case measurements”. The aim of this work is to find out which of these data should be considered when selecting an input filter for a switched mode power supply. The results show that, the actual common mode attenuation of a filter operating with a buck converter is almost same as the IL data with 0.1 Ω / 100 Ω source and load impedance, whereas the actual differential mode IL is approximately same as the IL data for 100 Ω / 0.1 Ω conditions.

Index Terms—Electromagnetic compatibility, Electromagnetic interference, Insertion Loss, Power filters, Switched mode power supplies.

I. INTRODUCTION

POWER line filter manufacturers provide Insertion Loss (IL) measurements for their products. Most often these are measured with 50 Ω source as well as load impedance. In practice, however, it is very unlikely that a power filter will operate under such conditions. Source and load impedance mismatch is typical in the field of power electronics [1] and that is why 50 Ω / 50 Ω IL measurements are often criticized [2], [3].

In addition to the standard IL measurements, some filter manufacturers also provide measurements with 0.1 Ω / 100 Ω and 100 Ω / 0.1 Ω source and load impedances. These so-called “approximate worst case measurements” are based on CISPR 17 and their aim is to provide IL data, which are closer to the real world operation [3].

This work is concerned with dc-dc switched mode power supplies (SMPS), which are unavoidably sources of electromagnetic interference (EMI). Due to the switching, a SMPS draws pulsating current from the dc power line, which causes differential mode (DM) conducted emissions. The switching actions over the parasitic capacitance to ground, on the other hand, cause common mode (CM) conducted EMI from the SMPS.

The source and load impedance mismatch is the major problem when evaluating the effectiveness of an input filter. The DM noise source impedance depends on the type of the converter and its components, whereas the CM noise source impedance depends on parasitic elements. That is why the CM EMI levels may differ depending on the particular PCB technology, components and layout.

The load impedance for the conducted EMI in operating conditions depends on the power line impedance, which can vary widely. Fortunately, it can be measured, if necessary. As far as the EMC compliance tests are concerned, the line impedance stabilization network (LISN) and the EMI test receiver provide a well defined 50 Ω load for the conducted emissions.

II. INSERTION LOSS

A. Conducted Emissions Measurements

Conducted emissions measurements for single phase, including dc applications, are carried out using two LISN circuits as shown in Fig. 1. Noise levels are measured separately for line and neutral. If any of them fails to comply with the standard, the equipment is not EMC compatible.

It is important to note that the DM noise current flows through two 50 Ω resistors in series, resulting in 100 Ω total load. On the other hand, for the CM EMI current, the two 50 Ω resistors are in parallel, resulting in 25 Ω total load for

Fig. 1. Measuring conducted EMI from a dc-dc SMPS using two LISNs.
the CM noise.

The required IL from an EMI filter is sometimes described as the difference between the measured EMI from the SMPS and the conducted EMI limits specified in the standards. Indeed, that difference is the required attenuation, but that is the attenuation of both DM and CM. It is important to know in what proportion these EMI components are, in order to choose an EMI filter, which will perform adequately. For example, if the EMI is mostly CM and filter’s CM IL too small, the filter will fail to attenuate the noise under the specified limits. Therefore, information about the level of each noise component is crucial for EMI filter selection.

B. EMI Filter Topology and Equivalent Circuits

EMI filter manufacturers usually use π-configuration, as e.g. that in Fig. 2a). They often omit the DM inductor and use only a CM choke. One reason for this is the limited size of Y-capacitors due to safety restrictions on the allowed leakage current. Thus, the burden of CM attenuation is placed mostly on the CM inductor, which can have quite large value. Another reason is that X-capacitors can be as large as possible and instead of using another bulky DM choke, one can rely on the leakage inductance of the CM choke, which is always present and in some cases can be intentionally increased [2].

Considering only DM noise, the π-filter in Fig. 2a) is equivalent to the π-filter in Fig. 2b). On the other hand, for the CM currents, the equivalent is the L-filter in Fig. 2c), unless the Y-capacitors are connected at both ports of the filter.

The EMI filter built for this study has π-configuration with CM choke only, i.e. the \( L_{DM} = 0 \, \text{H} \) in Fig. 2 and in the following calculations.

C. DM Noise Attenuation

A chain parameter [4] based method for calculation of the IL provided by a passive filter was presented in [5]. According to [5] and Fig. 2b) the DM noise attenuation of a π-filter is:

\[
I_{L,DM} = 20 \cdot \lg \frac{c_{11} \cdot Z_{CM,load} + c_{12}}{1 + Z_{CM,source}} + c_{21} \cdot Z_{CM,load} + c_{22}
\]

Where \( c_{11}, c_{12}, c_{21}, \) and \( c_{22} \) are the chain parameters of the DM filter, which is the π-filter in Fig. 2b). In the DM IL data, provided by filter manufacturers, the DM load and source impedances are equal to 50 \( \Omega \), i.e. \( Z_{DM,load} = Z_{DM,source} = 50 \, \Omega \). In LISN measurements \( Z_{DM,load} = 100 \, \Omega \) and \( Z_{DM,source} \) is unknown. It depends on SMPS’s topology and components.

As shown in [5], the chain parameters of a π-filter are:

\[
C = C_{X} C_{Y} C_{Z} = \begin{bmatrix} 1 & 0 & 1 & Z_2 & 1 & 0 \\ 1 & 0 & 1 & Y_3 & 1 \\ \end{bmatrix}
\]

\[
C = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \\ \end{bmatrix} = \begin{bmatrix} 1 + Z_2 Y_3 & Z_2 \\ Y_1 + Z_3 Y_2 & Y_3 & 1 + Y_3 Z_2 \\ \end{bmatrix}
\]

Where \( Y_1, Z_2 \) and \( Y_3 \) are:

\[
Y_1 = \frac{1}{Z_{CY}} + \frac{1}{2 \cdot Z_{CD}} \quad Z_2 = 2 \cdot Z_{DM} + Z_{CM,load} \quad Y_3 = \frac{1}{Z_{CX}}
\]

All impedances in (3), whether they are X-, or Y-capacitors, or any of the inductors, can be obtained by measurements or from component manufacturer’s data sheets, except the leakage inductance of the CM choke, which can only be measured.

D. CM Noise Attenuation

Similarly to the DM, the IL for CM EMI [5] is:

\[
I_{L,CM} = 20 \cdot \lg \frac{c_{11} \cdot Z_{CM,load} + c_{12}}{1 + Z_{CM,source}} + c_{21} \cdot Z_{CM,load} + c_{22}
\]

In CM IL measurements again \( Z_{CM,load} = Z_{CM,source} = 50 \, \Omega \), whereas in LISN measurements \( Z_{CM,load} = 25 \, \Omega \) as explained earlier and shown in Fig. 2c) and \( Z_{CM,source} \) is unknown.

The CM noise source is different from the DM. It depends on the parasitic impedance to ground. The model of the CM EMI source impedance is further complicated by the fact that the CM current does not flow through ground only in the direction of the power line (or LISN). Part of it flows through the ground to the SMPS’s load. How much CM current will
flow in each direction depends on the ground resistances. Therefore, creating a precise model for the CM noise source is a difficult, if not an impossible task.

The chain parameters for the CM equivalent circuit are:

\[ C = \frac{1}{\omega^2 LC} \]

All impedances in (5) can be measured or calculated from components’ datasheets. Then the chain parameters can be inserted in (4) to obtain the CM attenuation for different noise and load impedances.

III. FILTER COMPONENTS

A. Capacitors

If capacitor’s nonlinearities are ignored, it can be modeled by an equivalent circuit [1] as the one shown in Fig. 3a). Then the impedance of a capacitor is:

\[ Z_C = r_C + j\omega L + \frac{1}{1 + j\omega \rho} \]  

(6)

Both X-capacitors in the EMI filter built for this work are 100 nF. The Y-capacitors are 4.7 nF. All information for these capacitors, as used in the theoretical calculations, is in Table I. It was obtained from manufacturer’s datasheets [6] and [7]. There are also the data for the electrolytic capacitor [8] connected across the input of the buck converter. This capacitor could be considered to be a part of the input filter. However, we view it as a part of the converter, because it was kept in the EMC measurements without EMI filter. The reason was that without a large enough electrolytic capacitor buck converter’s stable operation could not be guaranteed.

<table>
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<th>TABLE I</th>
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<tr>
<td>Capacitors [6], [7], [8].</td>
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<tr>
<td>C</td>
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<tr>
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<tr>
<td>X-capacitor</td>
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<tr>
<td>Y-capacitor</td>
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<td>Electr. Cap.</td>
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Tolerance: +20 % -10 % for X- and Y-capacitors; ±20 % for the electrolytic capacitor.

B. Inductors

Fig. 3b) shows the equivalent circuit of an inductor [1]. According to this equivalent circuit the impedance of an inductor is:

\[ Z_L = \frac{r_L + j\omega L}{1 - \omega^2 LC + j\omega L} \]  

(7)

The accuracy of the model in Fig. 3b) with the corresponding impedance (7) is not as certain as the capacitor’s model. Even in a single choke, the parasitic capacitance is distributed between the turns, resulting in a more complex frequency behavior. Moreover, the EMI suppression inductors have two, or more chokes – one for each conductor. The coupling between the chokes determines whether the inductor is DM or CM. The simple equivalent circuit in Fig. 3b) does not take into account the coupling effects between the chokes.

In our EMI filter we used only a CM inductor. The inductance and resistance values used in the theoretical calculation are shown in Table II. They are taken from manufacturer’s data sheets [9]. The parasitic capacitance is not given in those data sheets, but was calculated from the choke’s self-resonant frequency (SRF), which was 1 MHz in manufacturer’s attenuation curves. In accordance with (7), the

<table>
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<th>TABLE II</th>
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<tr>
<td>CM Choke [9].</td>
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<td>RN114-2/02</td>
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Inductance tolerance: +50 %, -30 %
Resistance tolerance: ±15 %, -10 %
the theoretical impedance of the choke is shown in Fig. 4b).

Unfortunately, there is no information about the choke’s leakage inductance. It was measured to be 37 µH. The series resistance used for the model of the leakage inductor is twice the resistance per path, i.e. 204 mΩ. The SRF of the leakage inductor model was assumed to be 2.2 MHz to match a peak in the measured DM IL, which is shown later. Fig. 4b) shows the theoretical impedance of the leakage inductor, assuming it can be modeled with the equivalent circuit in Fig. 3b). The leakage inductor model is the most uncertain one from the theoretical models and probably the main reason for the discrepancy between the measured and calculated DM IL shown later.

IV. CALCULATED AND MEASURED INSERTION LOSS

A. CM Insertion Loss

The 50 Ω / 50 Ω CM IL measurements were carried out according to Fig. 5a) as described in [10], using EMI test receiver ESCS 30 from ROHDE & SCHWARZ [11]. The results for the above-described filter are plotted in Fig. 6a). In the same Figure, there are also the theoretically calculated CM IL curves for the standard conditions, i.e. 50 Ω / 50 Ω. The dotted line is the theoretically calculated IL for 50 Ω / 50 Ω, but with component values reduced by the allowed tolerances in accordance with components’ data sheets. It shows how much the IL may drop in theory, due to component’s variations.

The measured CM IL is lower, but very close to the theoretical curves. There are two resonant peaks, which are a lot smoother in the measured curves. The frequency of the first resonant peak is same as the SRF of the CM choke, i.e. 1 MHz, whereas the second peak is due to the Y-capacitors’ resonance, i.e. about 20 MHz.

The other curves in Fig. 6a) are plots of the theoretically calculated CM IL for 0.1 Ω / 100 Ω and 100 Ω / 0.1 Ω source and load impedances, which correspond to the approximate worst-case measurements. Unfortunately, such measurements could not be performed due to the lack of equipment with such characteristics.

According Fig. 6a), the CM IL of an EMI filter is lowest when the noise source’s impedance is 0.1 Ω and the filter is terminated with 100 Ω impedance.

B. DM Insertion Loss

Measuring the DM IL of a power filter requires two transformers as it is shown in Fig. 5b). The attenuation of the transformers without any filter was measured to be only 2-3 dB. Nevertheless, it was subtracted from the DM IL measurements obtained with our filter. The result is plotted in Fig. 6b) as “Measured IL” curve, representing the symmetrical attenuation of the filter under 50 Ω / 50 Ω test conditions.

The theoretically calculated curve for 50 Ω / 50 Ω DM IL is also plotted in Fig. 6b). There are three peaks in the measured and calculated DM IL curves. The first one is at about 2.2 MHz. This was the reason for assuming the unknown SRF of the leakage inductor to be 2.2 MHz. The second peak in the theoretical curve is clearly due to the X-capacitor’s SRF at 3.5 MHz. However, in the measured curve, the second peak appears at 16.7 MHz. The third peak in the theoretical curve is due to the Y-capacitor’s SRF at about 20 MHz. The unknown and inaccurate model of the leakage inductance, which plays role in the DM attenuation, is a major reason for the difference between the theoretical and measured curves.

The other curves in Fig. 6b) are the theoretically calculated DM IL curves corresponding to the approximate worst-case measurements. Up to about 7 MHz these curves overlap each other. Above 18 MHz again the 0.1 Ω / 100 Ω IL is the lowest among all DM IL curves. The peaks encountered in the theoretical curves for the standard DM IL are present in the worst-case curves as well. They appear at the same frequencies, which are the SRFs of filter’s components.
V. EMI MEASUREMENTS FROM A BUCK CONVERTER

A. EMI from the Buck Converter without Input Filter

To obtain the actual attenuation, provided by our filter operating with a SMPS, we used a buck converter with switching frequency 250 kHz and output voltage 12 V. The converter was loaded with 1 A load current and supplied with 35 V input voltage. Under these conditions it drew 0.38 A input current from the dc supply.

The measuring principle was shown Fig. 1. Measurements were conducted in accordance with EN 55022 standard [12]. The same EMI test receiver ESCS 30, as in the IL measurements was used. The 50 µH / 50 Ω LISN ESH3-Z5 is also from ROHDE & SCHWARZ.

The EMI from buck’s line and neutral wires without input filter was measured using quasi-peak (QP) and average (AV) detectors. The results are plotted in Fig. 7a) for the line and b) for the neutral. The standard limits for QP and AV detector are also shown in Fig. 7. Clearly the buck converter does not comply with the limits set in the standard.

B. EMI from the Buck Converter with Input Filter

After inserting the input filter between the buck converter and the LISN, the line and neutral EMI were measured again. Fig. 8 shows the results. Obviously, our EMI filter does not provide enough IL, but that was not the goal. The aim was to find out the actual attenuation of an EMI filter and compare it with the IL data of that filter.

C. Actual Attenuation of the Filter

From the IL measuring principle (Fig. 5) there is a clear distinction between CM and DM IL. To compare them with the actual attenuation, the EMI from the buck converter with and without input filter, need to be divided into its components. This can be done by using DM and CM rejection.
networks [13], [14]. Such devices were not available to us and we tried to measure the CM and DM noise using a current probe. The current probe used was Tektronix A6312 with amplifier AM503B [15].

The measuring principle is shown in Fig. 9. The EMI test receiver measures the CM current, as shown in Fig. 9a), and twice the DM current, as shown in Fig. 9b). The EMI measuring instrument measures the voltage over a 50Ω resistor and scales it according the equation:

\[ \text{EMI} = 20 \cdot \lg U \]  

(8)

It was shown in Fig. 2c), that because of the LISN, the CM current meets 25Ω resistance. Therefore, the CM EMI is:

\[ \text{EMI}_{\text{cm}} = 20 \cdot \lg (I_{\text{cm}} \cdot 25) = 20 \cdot \lg I_{\text{cm}} + 20 \cdot \lg 25 \]  

(9)

Fig. 10a) shows the measured CM current from the buck converter with an added constant according (9), i.e. the CM EMI component. In the same way the CM noise from the buck with input filter is plotted in Fig. 10b). The difference between the measured CM currents without and with input filter is the actual CM IL, plotted in Fig. 11a).

\[ IL_{\text{cm}} = \text{EMI}^{\text{uf}}_{\text{cm}} - \text{EMI}^{\text{f}}_{\text{cm}} = 20 \cdot \lg I^{\text{uf}}_{\text{cm}} - 20 \cdot \lg I^{\text{f}}_{\text{cm}} \]  

(10)

It was mentioned earlier that the current probe captures twice the DM noise current. It was also shown that the DM current flows through a 100Ω resistance. That is why, the DM EMI from the buck converter without and with input filter plotted in Fig. 10a) and b), can be obtained from:

\[ \text{EMI}_{\text{dm}} = 20 \cdot \lg \left( \frac{2 \cdot I_{\text{dm}}}{2} \cdot 100 \right) \]  

\[ \text{EMI}_{\text{dm}} = 20 \cdot \lg (2 \cdot I_{\text{dm}}) + 20 \cdot \lg 50 \]  

(11)

The actual DM attenuation is again the difference between the measurements of the DM currents without and with input filter:

\[ H_{\text{dm}} = \text{EMI}^{\text{uf}}_{\text{dm}} - \text{EMI}^{\text{f}}_{\text{dm}} = 20 \cdot \lg I^{\text{uf}}_{\text{dm}} - 20 \cdot \lg I^{\text{f}}_{\text{dm}} \]  

(12)

The actual DM attenuation, obtained according (12), is plotted in Fig. 11b).

This method for measuring CM and DM noise by using current probe would be perfect, provided the current probe is sensitive enough and there is no environmental noise entering the current probe. Unfortunately, the noise measured from the current probe without any conductor and with the buck turned off, was quite substantial. This noise measured with QP detector is plotted in Fig. 10a), and with AV detector in Fig. 10b). For the lower frequencies under 2 MHz it can be as high as 30 dB. This explains why the first half of the CM and DM measurements does not look very trustworthy – they are quite flat and the spikes, very large in the LISN measurements, are almost absent in the current probe measurement. The reason is that the environmental noise currents are almost as large as the CM and DM currents from the buck converter. It would be wrong to subtract the current probe noise from the measured CM and DM currents, as it was done with the transformers’ attenuation in the DM IL measurements, because the sources of the CM and DM currents and the environmental noise are different.

Above 2 MHz the error is relatively small – the noise from the current probe, measured with AV detector is less than 10 dB. Therefore, the actual attenuation results are more reliable above 2 MHz. Within that range, from 2 to 30 MHz, the actual CM IL is approximately same as the theoretical CM IL curve for 0.1Ω / 100Ω source and load impedance, as seen in Fig. 11a). The actual DM IL is closest to the theoretical DM IL curve for 100Ω / 0.1Ω above 10 MHz. Under that the actual DM IL is lower than any of the IL curves. The current probe measurement error is one reason for that. Another one is that the filter cannot attenuate more EMI than there is available. For example, if there is a filter with 80 dB attenuation and the noise is 40 dB, the actual attenuation cannot exceed 40 dB. The DM EMI from the buck converter is already reduced by the electrolytic input capacitor and it is unfortunate that at lower frequencies the error in current probe measurements is too large, preventing us from knowing the real level of DM noise at lower frequencies.

VI. CONCLUSION

Based on the results and calculations, it can be concluded that the “approximate worst case” IL data, are the right source of information for the designer, when selecting power line filters for SMPS.

The CM attenuation of a passive EMI filter, operating with a SMPS is most likely to be about the magnitude of the IL
data of that filter for 0.1 Ω / 100 Ω conditions.

The DM attenuation of a passive EMI filter, operating with a SMPS can be expected to be about the level of the filter’s IL data for 100 Ω / 0.1 Ω source and load impedance conditions.

If the approximate worst-case IL measurements data are not available, the designer has no other choice, but to use the usual 50 Ω / 50 Ω IL data. However, the actual IL can be 2-3 times lower.

During the selection process the designer should not forget the interactions between the EMI filter and the SMPS. To avoid them, the power filter’s output impedance must be a lot smaller than the SMPS’s input impedance, and the resonant frequencies of the input filter and output filter of the SMPS should be as far apart as possible.

REFERENCES