Insertion Loss Estimation of EMI Filters in Unmatched Input/Output Impedance System

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Abstract. *One of the problems in the design of power-line EMI filters is the uncertainty and ambiguity of their source/load impedances which results in breach of expected filter parameters in a real installation. The paper presents a simple technique for prediction of insertion loss limit values of EMI filters working in arbitrary unmatched mains line impedance systems.*

Keywords

EMI mains filter, insertion loss, estimation, impedance termination, unmatched impedance system.

1. Introduction

The power line EMI filters are the most efficient tools for suppression of electromagnetic interference (EMI) which occurs in the power supply networks. Passive LC mains filters suppress electromagnetic interference in two basic ways. The capacitor elements shunt the interference to ground, and the series inductor elements raise the impedance of the line making the shunt capacitor elements even more effective. One of the basic parameters of EMI filters is the RF attenuation introduced by them. Its value depends on source and load terminating impedances of the filter. In power circuits (i.e. mains network) these two quantities, in contrast to the case for communication networks, are not usually known or entirely specified. This fact can cause problems in predicting performance and specifying filters.

The basic setup of an EMI filter connection is illustrated in Fig. 1, in which Z_S denotes the source impedance, and Z_L the load impedance of the filter. Although both impedances are generally complex, the standard used values are taken as pure real [1].

The insertion loss L [dB] is the commonly measured suppression effectiveness of the filter. It is defined as the ratio of the voltage U_{20} across the circuit load without filter and the voltage U_2 across the load with the filter

$$L = 20 \cdot \log \left| \frac{U_{20}}{U_2} \right| . \quad (1)$$

As a linear circuit, the passive (such as LC) filter may be described through a set of arbitrary two-port small signal parameters. We can derive it by using the cascade parameters of the filter following formula [2]

$$\begin{aligned} L &= 20 \cdot \log \left| \tfrac{Z_L}{Z_S+Z_L} \cdot \mathbf{A}_{11} + \tfrac{1}{Z_S+Z_L} \cdot \mathbf{A}_{12} + \right. \\ &+ \left. \tfrac{Z_S \cdot Z_L}{Z_S+Z_L} \cdot \mathbf{A}_{21} + \tfrac{Z_S}{Z_S+Z_L} \cdot \mathbf{A}_{22} \right| \end{aligned} \quad (2)$$

where A_{11}, A_{12}, A_{21}, A_{22} are frequency dependent, complex cascade parameters of the particular EMI filter, i.e. elements of its transfer matrix [**A**].

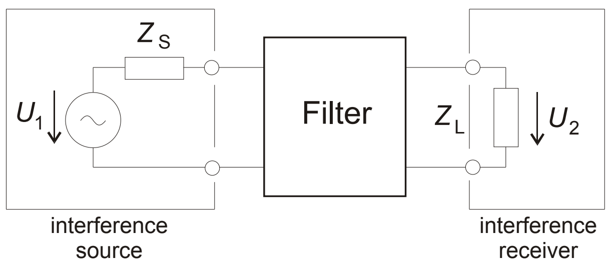

Fig. 1. The EMI filter as an ideal two-gate circuit with shown impedances.

The equation (2) illustrates that the insertion loss of a filter depends not only on the filter circuitry, but also on the source and load impedances, and therefore cannot be stated independently on the termination impedances. In many cases, which are typical for the mains EMI filters, the terminating impedances are not known. The filter design itself is a compromise and causes that the chosen filter does not meet declared characteristics.

Consider a typical mains filter according to Fig. 1. It fits between the AC mains supply and the AC-DC converter on the mains input of the fed equipment. The impedance of AC supply network varies from some tenth to some hundreds of Ω during the day, depending on the connected loads. Its value also very substantially depends on the type and construction of the particular main power supply network. These facts are documented in Fig. 2, which is a result of many extensive investigations and practical measurements across the world [2], [3].

On the “load site” of the mains filter, the RF characteristic impedance of the mains lead to the equipment is around 150 Ω, and the impedance of the AC-DC converter circuitry

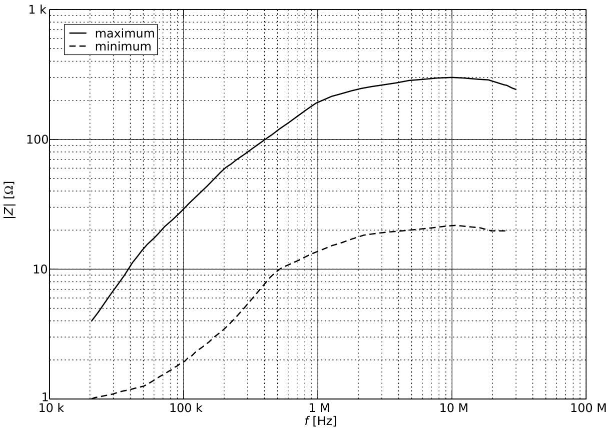

Fig. 2. Variability of power supply network impedance.

looks like a short-circuit when the rectifiers are turned on and an open-circuit at all others times. Thus, the impedance situation on the output site of the mains EMI filter is nearly the same, it means variable and uncertain as on its input site.

It is necessary to take into account both "matched" 50 Ω/50 Ω and "unmatched" data of EMI filters sometimes given by the manufacturer to avoid the potential "impedance problems". The CISPR 17 international standard specified the unmatched measurement so-called "worst-case" approximation measurement using a 0.1 Ω and 100 Ω source and load impedances and vice-versa. Because the technical realization of a 0.1 Ω frequency independent real impedance is very difficult, some authors recommend a "nearly worst-case" measurement, which is made with 1 Ω and 100 Ω impedances. Fig. 2 shows, that the potential error caused by using the "nearly worst-case" replacement would be probably very small.

The full realization of the measurement in an unmatched impedance system is very time consuming and technical expensive, so that only very few of filter manufacturers use it. For instance, Schaffner Ltd. gives the "worst-case" data for most of EMI filters, but only in their symmetrical operation mode [4]. To avoid such difficulties, there is presented an approximate method, which enables to estimate the "unmatched" performance of a filter from its data measured in the conventional 50 Ω/50 Ω impedance matched system.

2. Approximate Limit Values of the Unmatched Filter Attenuation

The equation (2) for insertion loss of a filter can be rewritten to the following form

$$\begin{aligned} L &= 20\cdot\log\left|1+\tfrac{Z_L\cdot(A_{11}-1)+Z_S\cdot(A_{22}-1)}{Z_S+Z_L}+\right.\\ &+\left.\tfrac{Z_SZ_L\cdot A_{21}+A_{12}}{Z_S+Z_L}\right|. \end{aligned} \tag{3}$$

Usually we know neither the filter circuit parameters nor the correct values of source and load impedances, and so we cannot state the correct magnitude of insertion loss in the given impedance system. Nevertheless, even by this uncertainty we can give an approximate guideline to estimate the potentially prospective value of an EMI filter insertion loss. In the general equation (3) we can distinguish between two approximate cases, which can be understand as limiting states of all EMI filters.

If the filter works in an impedance system with very high source and load impedances, then $Z_S \gg 1$ and $Z_L \gg 1$ or more precisely

$$|Z_{S,L}| = \left|\frac{A_{11}+A_{22}-2}{A_{21}}\right|. \tag{4}$$

By this simplification (3) can be simplified to the form

$$\begin{aligned} L &\approx 20\cdot\log\left|1+A_{21}\cdot\tfrac{Z_SZ_L}{Z_S+Z_L}\right| = \\ &= 20\cdot\log\left|1+\tfrac{1}{Z_F}\cdot\tfrac{Z_SZ_L}{Z_S+Z_L}\right| \end{aligned} \tag{5}$$

where $Z_F = 1/A_{21}$ [Ω] denotes the so-called filter impedance of the particular filter in a high impedance system.

The simplest type of an EMI filter for effective operation just in high impedance systems is the capacitor filter (C-filter) with parallel connected capacitor element depicted in Fig. 3. Its insertion loss is given exactly by the equation (5) with the filter-impedance $Z_F = 1/j\omega C$. By supposing that Z_S and Z_L are real, and Z_F is purely imaginary, (5) changes to

$$L_H = 20\cdot\log\sqrt{1+\left(\frac{1}{Z_F}\cdot\frac{Z_SZ_L}{Z_S+Z_L}\right)^2} \tag{6}$$

where Z_F denotes the magnitude of the filter impedance.

Secondly, source and load impedances of a filter are very low (i.e. $Z_S \ll 1$ and $Z_L \ll 1$), this is the opposite case of the previously described situation. By the following (3) simplifies so we can obtain

$$\begin{aligned} L &\approx 20\cdot\log\left|1+\tfrac{A_{12}}{Z_S+Z_L}\right| = \\ &= 20\cdot\log\left|1+\tfrac{Z_F}{Z_S+Z_L}\right| \end{aligned} \tag{7}$$

where $Z_F = A_{12}$ [Ω] is the filter impedance of the particular filter this time for low impedance network.

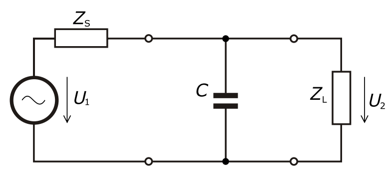

Fig. 3. Simple capacitor filter.

In this case, EMI filter is terminated by low input and output impedances. The HF suppression of this filter in the mentioned conditions is represented by the inductor filter (L-filter) depicted in Fig. 4. To determine its insertion loss we can use (7), in which the filter impedance Z_F is equal to $j\omega L$. If the impedances Z_S and Z_L are real, and Z_F is pure imaginary, the (7) takes a form

$$L_L = 20\cdot\log\sqrt{1+\left(\frac{Z_F}{Z_S+Z_L}\right)^2} \tag{8}$$

where Z_F states for the filter-impedance magnitude only.

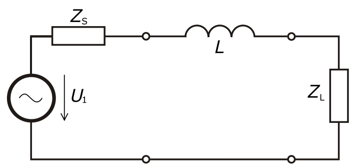

Fig. 4. Simple inductor filter.

For easier processing with equations (6), and (8), they are both displayed in Fig. 55 as the so called filter impedance graphs, i.e. the insertion loss vs. the value of filter impedance magnitude in a given impedance system. In Fig. 5 both graphs are created for a matched impedance system (i.e. $Z_S = Z_L = 50\ \Omega$).

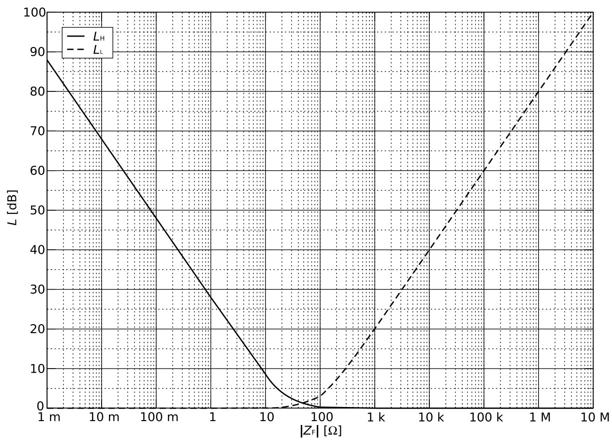

Fig. 5. Filter impedance chart.

3. Practical Use and Verification of the Insertion Loss Estimation

To explain the use of the previous analysis, we came up with the following example. System, in which the EMI filter should be used, shows the real source and load impedances 100 Ω and 600 Ω, respectively. The selected filter has (according to the data sheet) the insertion loss of 50 dB at 100 MHz in a 50 Ω/50 Ω system. From the filter impedance graphs in Fig.5 or by direct calculations from equations (6) and (8), the magnitudes of the filter-impedance are $Z_F = 0.079\ \Omega$, and $Z_F = 31622.62\ \Omega$, in high and low impedance systems, respectively. Now, using these values and the required source and load impedances (100 Ω and 600 Ω, respectively) we have, from (6) and (8), $L_H = 60.7$ dB and $L_L = 33.1$ dB, respectively.

The interpretation of these results is as follow: in the required (not matched) impedance system, the real insertion loss of selected EMI filter may potentially vary from approximately 33 dB to 60 dB depending on the circuitry of the filter. By considering the thinkable or potential worst-case performance, we should expect the lowest value of insertion loss, i.e. approximately 33 dB. Thus the selected filter fails to satisfy the insertion loss of 50 dB reported by its manufacturer while being used in other than matched 50 Ω impedance system. By this, if the circuit parameters of the selected filter fulfil the condition (4) for required source and load impedances (100 Ω and 600 Ω), the insertion loss get near the "highest limit" value of 60.7 dB, in the opposite case, the insertion loss falls to the "lower limit" value of 33.1 dB.

The detailed verification of our treatment is fairly difficult, because the data of EMI filters measured in other than matched 50 Ω/50 Ω impedance system are published only very rarely. So, we have used some available data from Schaffner EMI filters data sheets [4] from which we have selected single stage filters only, that are generally more sensitive to source and load impedances up to the gain providing when they operate with different terminating impedances than their are mentioned in specification.

The FN 2020 is a general purpose single stage filter with the insertion loss of 50 dB at 1 MHz measured in a 50 Ω/50 Ω impedance system. The manufacturer's declared insertion loss in the "worst-case" impedance systems 0.1 Ω/100 Ω and 100 Ω/0.1 Ω makes about 5.5 dB in common mode. This corresponds quite well with introduced procedure, which gives the lowest limit value of 4.2 dB (L_H value).

The next examples provide the single stage three-phase RFI power filter FN 3100. Specified insertion losses are 50 dB at 100 kHz and 80 dB (maximal measured value) at 170 kHz, both in a matched 50 Ω system. "Worst-case" values provided by manufacturer are about 7 dB and 36 dB, respectively, while our analysis gives the limit L_H values of 4.2 dB and 32 dB. The precision of the estimation is fairly good again.

The last selected example presents the general purpose power entry filter FN 290, which is constituted as a single stage EMI filter with the insertion loss of 30 dB at 1 MHz in common mode also terminated by the 50 Ω impedances. The declared "worst-case" attenuation values are about 0.9 dB in 0.1 Ω/100 Ω system and about 30 dB in 100 Ω/0.1 Ω impedance system. Also our procedure above gives similar values: the limit L_H value of approximately 0.1 dB and L_L value of approximately 30 dB. Also by other EMI filters from [4] we have state that measured "worst-case" insertion loss data are always in the limit range determined by the relevant limit values of L_H (6) and L_L (8).

To compare our results also with the practice, we have realized some measurements of insertion loss on two types of EMI filters: the first of them was a SIEMENS MAT-

f [kHz]	measured data L [dB]		calculated data 1 Ω/100 Ω	
	50 Ω/50 Ω	1 Ω/100 Ω	L_H [dB]	L_L [dB]
	Siemens B84263-A21-B13			
2	40	2	0.6	19.9
	Ray Proof L2980			
20	100	80	71.9	99.9

Tab. 1. Chosen value of spurious components used for simulation.

SUSHITA Components filter of the type B84263-A21-B13, the second one was the RAY PROOF EMI filter of the type L 2980. We have accomplished our experiments in accordance with CISPR 17 standard [5] in so called "nearly worst-case" system 1 Ω/100 Ω and 100 Ω/1 Ω. Selected results of our measurements together with computed limit range insertion loss values are shown in Tab. 1. We can see, that the measured data of both filters are really in the limit range computed from (6) and/or (8).

4. Conclusions

The paper shows, that even in the case, when the real measured attenuation data in other than matched impedance systems of an EMI filter are missing, it is possible to determine the potentially prospective values of the filter insertion loss. Simultaneously, this determination must be considered as an estimation of potentially limiting values of insertion loss. Then, the real insertion loss measured in the particular unmatched impedance system occurs always in the limit ranges determined by the relevant values of L_H and/or L_L given by equations (6) and (8), respectively.

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