APPROXIMATIVE ESTIMATION OF EMI MAINS FILTERS PROPERTIES IN THE „WORST-CASE“ SYSTEM OPERATION

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SUMMARY

One of the main problems in the design of mains line EMI filters is the uncertainty and ambiguity of their source and load impedances. As these impedances act namely the HF supply network impedance on the one hand, and the HF input impedance on the power input terminal of the protected equipment on the other hand. In the usually operating frequency range from 10 kHz to 30 MHz, both impedances are variable from some tenth Ohms to some hundreds of Ohms, and they are very substantially depended on the type, construction, and instantaneous load of the mains line network, in which the filter should be used. Since the insertion loss of an EMI line filter is dependent on the source and load impedances, most filter manufacturers provide the filter design for the matched 50 Ohms impedance system. From the above reasons of course, this may not give proper and estimated results in real mains line networks installation. The paper presents a new technique for so-called „worst-case“ EMI filter design. It makes possible to predict the real insertion loss limit values of manufactured EMI filters working in arbitrary mains line impedance systems.

Keywords: *EMI mains filter, insertion loss, impedance termination, supply network impedance, worst-case EMI filter design*

1. INTRODUCTION

The mains or power line EMI filters are one of the most efficient and most often used tools for suppression of electromagnetic interference (EMI) which occurs in the supply power network. The aim of EMI filters is to increase the immunity of mains operated electronic equipments on their power line inputs and simultaneously to decrease the level of HF emission supplied by the equipment into outer power network. 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. The filters work on the principle of providing a large discontinuity in the impedance seen by a radio frequency (RF) signal travelling along a line, with the intention of reflecting most of the RF energy back to where it came from.

One of basic parameters of an EMI filter is the RF attenuation introduced by them. Its value depends – beside other factors – on source- and load-side 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 normally know or entirely specified. This can lead to problems in predicting performance and specifying filters.

2. THE INSERTION LOSS OF A FILTER AND THE IMPEDANCE PROBLEM

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

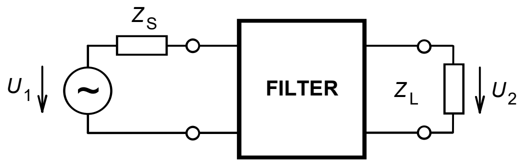

Fig. 1 Basic EMI filter setup

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

$$L = 20 \cdot \log \left| \frac{U_{20}}{U_2} \right| \quad [\text{dB}] \quad . \tag{1}$$

As a linear circuit, the passive filter may be described through the set of arbitrary two-port small signal parameters. So that by using the cascade parameters of the filter we can derive [2]

$$L = 20 \cdot \log \left| \frac{Z_L}{Z_S + Z_L} \cdot \mathbf{A}_{11} + \frac{1}{Z_S + Z_L} \cdot \mathbf{A}_{12} + \frac{Z_S \cdot Z_L}{Z_S + Z_L} \cdot \mathbf{A}_{21} + \frac{Z_S}{Z_S + Z_L} \cdot \mathbf{A}_{22} \right| , \tag{2}$$

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

2.1. The impedance problem

The equation (2) illustrates an important point: the insertion loss of a particular filter depends not only on the filter circuitry, but also on the source and load impedances, and therefore cannot be stated independently of the termination impedances. Since in many cases – typically just by the mains EMI filters – these impedances are not know, design is a compromise and it is possible that the chosen filter may not in practice offer significant improvement.

Consider a typical mains filter according Fig. 1. It fits between the AC mains supply and the AC-DC converter, which is the DC power supply for the mains line powered electronic equipment. The impedance of AC supply network varies from some tenth to some hundreds of Ω during the day, depending on the loads that are connected to it, and the measured frequency. Its value is also very substantially depended on the type and construction of the particular power mains network. These facts are documented in Fig. 2 and in Fig. 3, which are results of many extensive investigations and practical measurement across the world [2], [3].

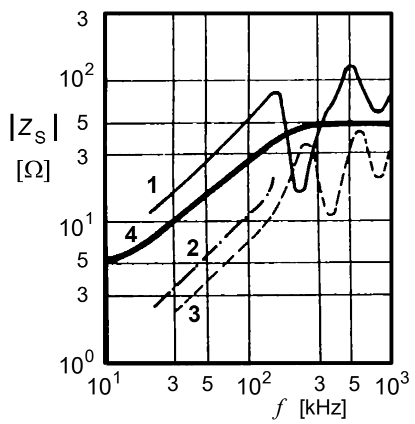

Fig. 2 HF impedance of various types of power line networks (1 – outdoor distribution network; 2 – industrial distribution network; 3 – cable earth distribution network; 4 – CISPR specification [2]

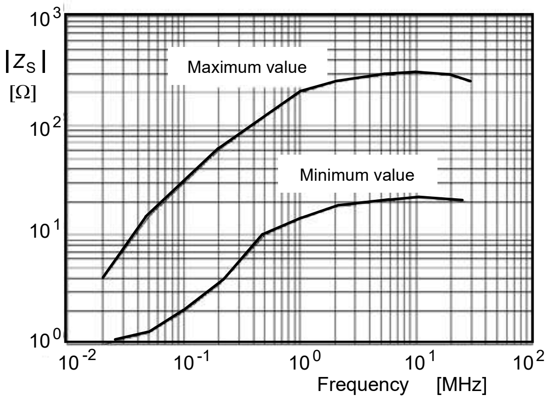

Fig. 3 Powerline HF impedance of commercial European power lines [3]

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 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 (i.e. variable and uncertain), as on its power line input.

2.2. The “worst-case” filter specification

Nearly all of mains filter manufacturers be apt to specify data of their filters in so-called 50 Ω source and load impedances matched system, i.e. it is assumed that $Z_S = Z_L = 50\ \Omega$. This is because most RF test equipment uses 50 Ω signal sources, loads and cables; and never mind the fact that for many practical uses of filters the attenuation measurements obtained by this method (i.e. in matched impedance system) are at best optimistic and at worst misleading. As mentioned in the previous part, in practical circuit applications the source and load impedances may be quite different from 50 Ω. So use of the manufacturer’s insertion loss data to assess the performance of the filter in a product may not give realistic results.

To deal with this “impedance problem”, it is best to only purchase EMI filters for which the manufacturer has specified their performance with both “matched” 50/50 Ω and “mismatched” source and loads. In the ČSN CISPR 17 standard [4], the mismatched measurement is defined as so-called “worst-case” approximation measurement made by using a 0.1 Ω source and 100 Ω load (and vice-versa). Because the technical realisation 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 source and 100 Ω load impedances [5]. From Fig. 2 and Fig. 3 it can be seen, that the prospective error caused by this “nearly worst-case” assumption will be probably very small. Note, that all these measurements should be made both in common-mode (asymmetrical) and differential-mode (symmetrical) filter operation [1].

The trick is then to measure and to draw an insertion loss versus frequency curves which follows the worst-case figures from all of those attenuation curves, and then to assume that this “overall worst-case” curve is the filter’s real specification. When filters are chosen in this way to suit the predicted needs of their application, their performance is usually as good as or better than expected.

Of course, the full realisation of this treatment is very time 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 mode operation [6].

To avoid such difficulties and to provide information on the real expected insertion loss, we present an approximate method, which enables to assess the “worst-case” performance of a filter from its commonly published data stated (i.e. measured or by design exact computed) in the 50/50 Ω impedance matched system.

3. APPROXIMATE PREDICTION OF THE WORST-CASE FILTER ATTENUATION

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

$$L = 20\cdot\log\left|1+\frac{Z_L\cdot(\mathbf{A}_{11}-1)+Z_S\cdot(\mathbf{A}_{22}-1)}{Z_S+Z_L}+\right.$$
$$\left.+\frac{Z_S Z_L\cdot\mathbf{A}_{21}+\mathbf{A}_{12}}{Z_S+Z_L}\right| \quad . \qquad (3)$$

Usually we know neither the filter circuit parameters nor correct values of source and load impedances, and then we cannot state the correct magnitude of insertion loss in 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 any filter.

3.1. High impedance termination system

In this case, the filter works or will be operated in a system, in which both source and load impedances are very high, i.e. $Z_S >> 1$ and $Z_L >> 1$. From the equation (3), we can specify these conditions as

$$|Z_{S,L}| >> \left|\frac{\mathbf{A}_{11}+\mathbf{A}_{22}-2}{\mathbf{A}_{21}}\right| \quad . \qquad (4)$$

By this assumption, the equation (3) can be simplified to the form

$$L_H \approx 20\cdot\log\left|1+\mathbf{A}_{21}\cdot\frac{Z_S Z_L}{Z_S+Z_L}\right| =$$
$$= 20\cdot\log\left|1+\mathbf{K}_H\cdot\frac{Z_S Z_L}{Z_S+Z_L}\right| \quad , \qquad (5)$$

where $\mathbf{K}_H = \mathbf{A}_{21}$ $[\Omega^{-1}]$ means the transfer coefficient of the particular filter in high impedance system.

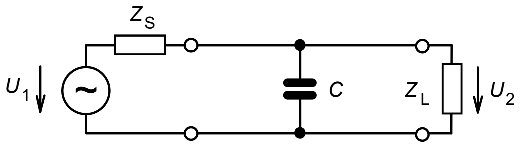

Fig. 4 Basic form of a C-filter

The typical and at the same time the simplest (limiting) type of an EMI filter for effective operation just in high impedance systems is the capacitor filter (C-filter) with parallel connected capacitor element(-s) according Fig. 4. The capacitor element can be made as either a two terminal capacitor or a three terminal (so-called feed-thru) one. The insertion loss of this "elementary" filter is given exact by the equation (5) with the transfer coefficient $\mathbf{K}_H = 1/(\mathrm{j}\omega C)$.

Under assumption, that Z_S and Z_L are real, and $\mathbf{K}_H$ is pure imaginary, the equation (5) changes to

$$L_H = 20\cdot\log\sqrt{1+\left(\mathrm{K}_H\cdot\frac{Z_S Z_L}{Z_S+Z_L}\right)^2} \quad , \qquad (6)$$

where K_H denotes the magnitude of the transfer coefficient.

3.2. Low impedance termination system

If both source and load impedances of a filter are very low (i.e. $Z_S << 1$ and $Z_L << 1$), we have the opposite case as described in part 3.1. By this, the equation (3) simplifies to the approximate form

$$L_L \approx 20\cdot\log\left|1+\frac{\mathbf{A}_{12}}{Z_S+Z_L}\right| =$$
$$= 20\cdot\log\left|1+\frac{\mathbf{K}_L}{Z_S+Z_L}\right| \quad , \qquad (7)$$

in which $\mathbf{K}_L = \mathbf{A}_{12}$ $[\Omega]$ is the transfer coefficient of the particular filter.

The limiting simplest and typical EMI filter, which needs for effective HF suppression just low source and load impedances, presents the inductor filter (L-filter). An L-filter consists of one (or several) inductive element L (reactance coil, choke) connected in series with the source and load impedances (Fig. 5). To determine its insertion loss we can use exact the equation (7), in which now the transfer coefficient $\mathbf{K}_L = \mathrm{j}\omega L$.

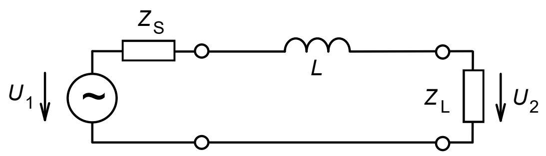

Fig. 5 Basic form of an L-filter.

If the impedances Z_S and Z_L are real, and $\mathbf{K}_L$ is pure imaginary, the equation (7) takes a form

$$L_L = 20\cdot\log\sqrt{1+\left(\frac{\mathrm{K}_L}{Z_S+Z_L}\right)^2} \quad , \qquad (8)$$

where K_L states for magnitude of the transfer coefficient.

3.3. The transfer coefficient graphs

For easier treatment of equations (6), and (8), they are both displayed in Fig. 6 as so-called transfer coefficient graphs, i.e. the insertion loss vs. the particular value of transfer coefficient magnitude. At that both graphs in Fig. 6 are created for a matched impedance termination system (i.e. $Z_S = Z_L = 50\,\Omega$), too.

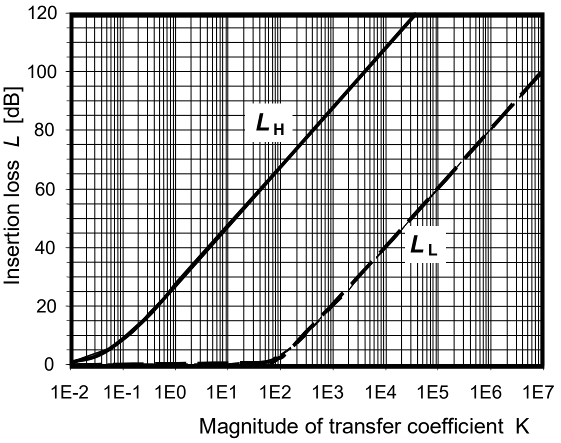

Fig. 6 Transfer coefficient graphs

4. PRACTICAL USING AND CHECK ON THE INSERTION LOSS ESTIMATION

To explain the using of the previous analysis, we consider the following example.

System, in which the EMI filter should be used, shows the source and load impedances 100 Ω and 600 Ω, respectively. Selected EMI filter has (according manufacturer data) the insertion loss of 50 dB at 100 MHz in a 50 Ω source/load system. From the transfer coefficient graphs in Fig. 6 or by direct computing from equations (6) and (8), the magnitude of transfer coefficients are K_H = 12.65 and K_L = 31622.62, respectively. Now, using these values and the required source and load impedances (100 Ω and 600 Ω, respectively) we have from equations (6) and (8)

$$L_H = 20 \cdot \log \sqrt{1 + \left(12.65 \cdot \frac{100 \cdot 600}{100 + 600}\right)^2} = 60.7\text{ dB} \quad ,$$

$$L_L = 20 \cdot \log \sqrt{1 + \left(\frac{31622.62}{100 + 600}\right)^2} = 33.1\text{ dB} \quad .$$

The interpretation of these results is as follow: in the required (no matched) impedance system, the real insertion loss of selected EMI filter may vary potentially from approx. 33 dB to 60 dB depending on the circuitry of the filter. By considering the thinkable worst-case performance, we should expect the lowest value of insertion loss, i.e. approx. 33 dB. Thus the selected filter fails to satisfy the insertion loss of 50 dB reported by its manufacturer while using 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, respectively), 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 fair difficult, which be due to the fact, that attenuation data of EMI filters measured in other than matched 50/50 Ω impedance system are published (and may be also realised) only very exceptionally. Thus, we have used the available data from Schaffner EMI filters [6]. Unfortunately, the data measured in “worst-case” impedance systems 0.1 Ω/100 Ω and 100 Ω/0.1 Ω are presented only for symmetrical mode of filter operation and only in the frequency range under 1 MHz. From [6] we have selected some mains filters with a single stage, that are generally very sensitive to source and load impedances up to the gain providing when operated with source and load impedances other than their specification.

The FN 2020 is a general purpose single stage filter utilizing one common-mode choke for the current rating of 20 A. Its insertion loss is 50 dB at 1 MHz measured in a 50 Ω source/load 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 (common-mode). This corresponds quite well with our procedure, which offers the result of 4.2 dB (L_H value).

An other examples may provide the single stage three-phase RFI power filter of type FN 3100 for the current rating of 50 A. The manufacturer’s declared insertion loss is 50 dB at 100 kHz and 80 dB (maximal measured value) at 170 kHz, both in a matched 50 Ω source/load system. Manufacturer’s measured “worst-case” values are about 7 dB and 36 dB, respectively. At the same time, our analysis gives the L_H values of 4.2 dB and 32 dB. Thus, the estimation is fair good again.

The last selected example presents the general-purpose power entry filter module FN 290, which is constituted as a single stage EMI filter for the current rating of 6 A. Its insertion loss makes 30 dB at 1 MHz (common mode) in a 50 Ω source/load system. 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 gives similar values: the L_H value of approx. 0.1 dB and L_L value of approx. 30 dB.

It can be pointed, that also all other EMI filters from [6] conform to our estimations by their understanding as potentially limiting values. That means that the real measured “worst-case” insertion loss data are always in the limit range determined by the relevant values of L_H (6) and L_L (8).

To compare our results also with the “real” practice, we have realised some measurements of insertion loss on two types of EMI filters: the first of them was a SIEMENS MATSUSHITA Components filter of the type B84263-A21-B13, the second one was the RAY PROOF EMI filter of the type L 2980. Both measurement were made in the realtionship to research project solution for the Czech National Security Authority in Prage [7]. Since the practical realisation of true "worst-case" impedance systems 0.1 Ω/100 Ω and/or 100 Ω/0.1 Ω is very difficult, we have accomplished our experiments "only" in so-called "nearly worst-case" system 1 Ω/100 Ω and 100 Ω / 1 Ω. The appropriate impedance trasformers are described in [7]. Selected results of our measurements together with computed limit range insertion loss values are show in Tab. 1. We can see, that the measured data of both filters are really in the limit range computed from eqns. (6) and (8).

f **[kHz]**	**Measured data *L* [dB]**		**Calculated for 1 Ω/100 Ω system**	
	50 / 50 Ω	1 / 100 Ω	L_H [dB]	L_L [dB]
2	**SIEMENS B84263-A21-B13**			
	40	2	0,6	19,9
20	**RAY PROOF L 2980**			
	100	80	71,9	99,9

Tab. 1 Measured and calculated insertion loss data for two EMI filters

5. CONCLUSION

We have shown, 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 value 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 data measured in the particular un-matched impedance system occur always in the limit range determined by the relevant values of L_H and L_L given by equations (6) and (8), respectively. The comparison of our procedure with some published "worst-case" insertion loss data of EMI filters, and also with some measured data provided sufficiently good agreement.

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BIOGRAPHY

Jiří Svačina received the M.Sc., and Ph.D. degrees from Brno University of Technology, Czech Republic, in 1971, and 1978, respectively. Since 1995 he is a professor in Electronics and Communication at the Institute of Radio Electronics, Brno University of Technology. His research interests include problems of planar structures for microwave integrated circuits. He is also interested in specialized problems of EMC, EMI, and EMS. Prof. Svačina is the Head of the Institute of Radio Electronics at the Brno University of Technology, member of its Scientific and Pedagogical Boards, and also member of the scientific boards of Faculties of Electrical Engineering CTU in Prague, and West Bohemian University in Pilsen, and of the Institute of Radio Engineering Czech Academy of Sciences in Prague. He is the Senior Member of IEEE, U.S.A., and the Fellow of IEE, U.K.

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