Estimation of the EMI Filter Circuitry from the Insertion Loss Characteristics

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Abstract. *The paper deals with the EMI filter models for the calculation of the insertion loss characteristics. The insertion loss is in fact the basic EMI filter property. Unfortunately it is not easy to precisely define and measure this parameter in a wide frequency range due to variability of terminating impedances. The uncertainty of the potential impedance termination really complicates the measurements and also comparison of the performance of filters. A model with spurious components is introduced in this paper. The procedure model design is also added up. The spurious components make together with the real ones form resonant circuits. The resonance frequencies make breakages in the insertion loss characteristic. Their resonance frequencies were identified by the analysis of equivalent circuits of the filter for different measuring systems. The calculation of the values of spurious components, based on knowledge of resonance frequencies, is mentioned at the end of the paper.*

Keywords

Insertion loss, EMI filter, current compensated inductor, spurious component, MNVM, Modified Nodal Voltage Method.

1. Introduction

The basic property of an EMI filter is usually described by the insertion loss characteristic. That characteristic is typically frequency dependent and it refers to the attenuation of the EMI filter. The measurement of insertion loss is complicated by several aspects. The configuration of the input and output terminals of an EMI filter is changed through several types of measurement setups and this fact complicates the measurement itself. Technical standards distinguish several types of measurement setups according to interfering signals, which penetrate through the power supply network. The symmetric part of the insertion loss defines attenuation of the symmetrical interfering signals which are directly superposed on the useful signal. A generator of harmonic signal and a measuring receiver with symmetrical output and input, respectively, are necessary for the symmetrical measurements. It is also possible to use transformers for signal transformation. Measurement setup with these transformers is depicted in Fig. 1b). The asymmetric part of the insertion loss defines the attenuation of the spurious signals which could be produced by spurious ground capacitors of the whole system. During the measurement of the asymmetrical insertion loss, the input terminals L_1 and N_1 are connected to each other same as the output terminals L_2 and N_2. This situation is shown in Fig. 1a).

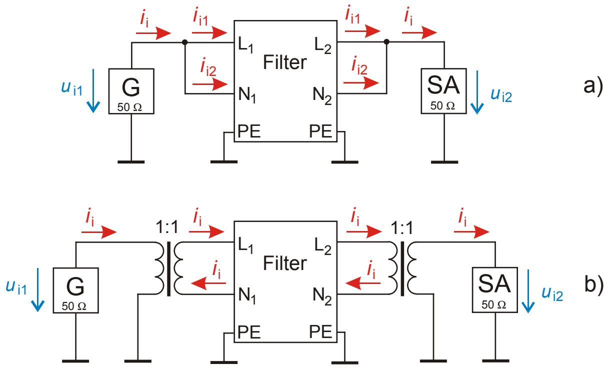

Fig. 1. Possible insertion loss measuring systems: a) asymmetrical; b) symmetrical.

Another problem is represented by non-defined impedance terminations at the input and output sides of the filter. The impedance of the power supply network is connected to the input terminals of the EMI filter. The current impedance value of the power supply network depends on the type of the power network, current load and also on the operating frequency of the test signal. The output of the filter is generally loaded with impedance which is usually unknown and not steady in the time domain. Different terminating impedances could be used for the measurement of the insertion loss of the filter according to the harmonized technical standard ČSN CISPR 17 [1]. This standard distinguishes several methods: the first approach with 50 Ω impedances at the input and output terminals of the filter; the approximate method for the EMI filters with 0.1 Ω at the input and 100 Ω at the output and vice versa. Anyway, none of the mentioned methods corresponds to the reality. It is possible to assert, based on the existing research, that the standard method gives optimistic results compared to the reality and the approximate method produces pessimistic results [2].

It is not possible to produce a lot of physical measurement systems with a huge number of terminating impedances and several test setups for precise testing, due to technical limits. This is the motivation for creation of precise models of EMI filters. These models will be able to compute insertion loss characteristics for a lot of different terminating impedances and different measurement setups. The proposed model will be usable for identifying the "worst case" performance of the filter. The "worst-case" represents identification of the lowest insertion loss of the filter. It is possible to prefabricate the "worst case" test setup and confirm the results by measurements.

2. Filter Model Based on Real Circuitry

The main aim of creating the model is its usability in different test systems (asymmetric, symmetric, etc.). For that reason the basics of the model are based on real circuitry of an EMI filter. Other ways for computation of EMI filter models, for example synthesis of insertion loss characteristic, are unusable in different measurement systems and impedance conditions. The basic circuitry of EMI filter is shown in Fig. 2a). This basic circuitry has to be enlarged by spurious components of the filter [3]. The enlarged EMI filter model is depicted in Fig. 2b). This model can be called the realistic model of the filter.

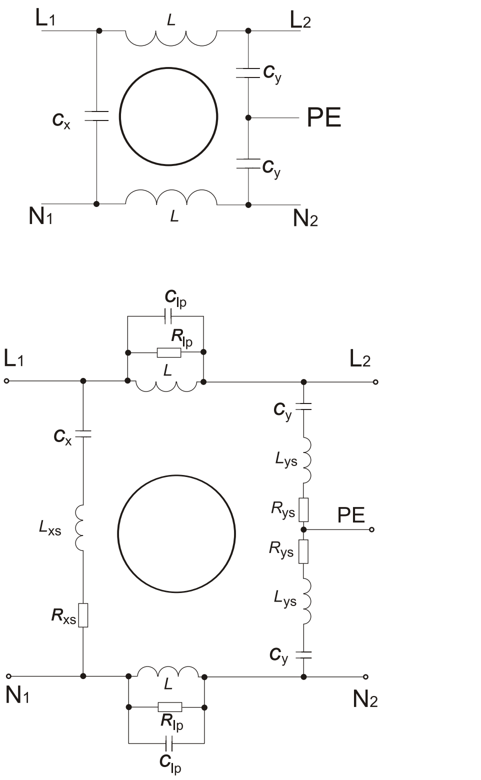

Fig. 2. Basic model of the Schurter 5110.1033.1 filter and its enlarged circuitry.

It is possible to describe the model of an EMI filter mathematically as a six-pole circuit according to the knowledge of the admittance parameters Y. The mathematical description could be made in agreement with Fig. 3 and the following equations [4]:

$$I_{L1} = Y_{11}U_{L1} + Y_{12}U_{N1} + Y_{13}U_{L2} + Y_{14}U_{N2}, \tag{1}$$

$$I_{N1} = Y_{21}U_{L1} + Y_{22}U_{N1} + Y_{23}U_{L2} + Y_{24}U_{N2}, \tag{2}$$

$$I_{L2} = Y_{31}U_{L1} + Y_{32}U_{N1} + Y_{33}U_{L2} + Y_{34}U_{N2}, \tag{3}$$

$$I_{N2} = Y_{41}U_{L1} + Y_{42}U_{N1} + Y_{43}U_{L2} + Y_{44}U_{N2} \tag{4}$$

where Y_{XY} are the components of the admittance matrix $\mathbf{Y}$ of the tested EMI filter; the meaning of the currents and voltages is clear from Fig. 3.

The set of equations (1) to (4) can be easily rewritten into the following matrix form:

$$\mathbf{I} = \mathbf{Y} \cdot \mathbf{U} \tag{5}$$

where $\mathbf{I}$ is the vector of unknown currents; $\mathbf{U}$ is the vector of variable voltages and $\mathbf{Y}$ is the admittance matrix of the EMI filter.

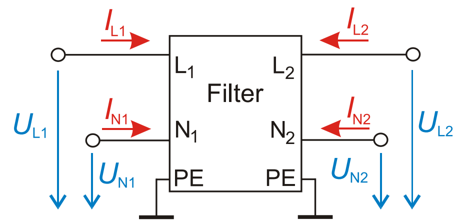

Fig. 3. The EMI filter as a six-pole.

Nearly all EMI filters contain a current compensated inductor, which complicates a model based on the circuitry of the filter. It is necessary to add up the mutual coefficient of induction of the current compensated inductor. The *Modified Nodal Voltage Method* (MNVM) could be used to solve the circuitry [5]. Firstly, the admittance matrix has to be made up from the filter circuitry but without the current compensated inductor. Secondly, the admittance matrix is extended by two lines and columns which refer to the rest of the circuit (about the current compensated inductor) according to the following equations:

$$U_{ab} = j\omega L_1 I_1 + j\omega M I_2, \tag{6}$$

$$U_{cd} = j\omega M I_1 + j\omega L_2 I_2. \tag{7}$$

Each of the quantitie is described by Fig. 3. The mutual coefficient of induction is put together with both inherent coefficients of induction (L_1 and L_2) by:

$$M = k\sqrt{L_1 L_2} \tag{8}$$

where k represents the coupling coefficient. The values of the inherent coefficients of induction L_1 and L_2 are commonly the same for most of EMI filters ($L = L_1 = L_2$). These mathematical operations and formulas can be rewritten into matrixes which are described in details in [4]. Also the pivot condensation of final matrixes are described there and the formulas for calculation of the insertion loss in different measurement setups are determined.

3. Reduced Equivalent Circuitries for EMI filters

The real model of an EMI filter with connection terminals for the asymmetric system is depicted in Fig. 4a). Fig. 4b) shows the same circuitry after reduction for the asymmetric measuring system. The capacitor C_x with its spurious components are shorted out by the input termination. This capacitor is not taken into account in the reduced equivalent circuitry, because there is no influence of this component. The pairing components for the real model with index 1 or 2 are marked in the reduced model with no index number because they are identical, for example $L_{p1} = L_{p2} = L_p$, or $C_{p1} = C_{p2} = C_p$, etc. The current compensated inductor is connected in both longitudinal legs with its spurious component, too. Hence, all of components in the longitudinal legs due to the direct connections L_1/L_2 and N_1/N_2 are connected parallelly. It is possible to write the conversion equations for the equivalent components for reduced model of the asymmetric measuring system as

$$C_{lpn} = 2 \cdot C_{lp}, \tag{9}$$

$$R_{lpn} = \frac{R_{lp}}{2}. \tag{10}$$

The inductors which make the current compensated inductor are also connected parallelly. Generally, it is possible to consider that both inductors have same inherent coefficient of induction. It means that through both inductors flows the same currents in the same direction. This situation is depicted in Fig. 6a). The voltage over the current compensated inductors is given by the following relation:

$$U_{ab} = U_{cd} = j\omega \mathrm{L}I + j\omega \mathrm{M}I = j\omega \mathrm{L}I(1+\mathrm{k}). \tag{11}$$

The current compensated inductor is practicable to replace by the equivalent inductor according to next formula:

$$L_{pn} = \frac{L_p \cdot (1+\mathrm{k})}{2}. \tag{12}$$

The transverse leg contains the capacitor C_y and its own spurious components R_{ys} and L_{ys} which make two serial resonant circuits in the asymmetrical system. These two resonant circuits are in fact connected parallelly. So, the components in the equivalent circuit should have these values:

$$C_{yn} = 2 \cdot C_y, \tag{13}$$

$$L_{ysn} = \frac{L_{ys}}{2}, \tag{14}$$

$$R_{ysn} = \frac{R_{ys}}{2}. \tag{15}$$

Model for the symmetrical measuring system, which is depicted in Fig. 5a), has also similar circuitry. Fig. 5b) shows

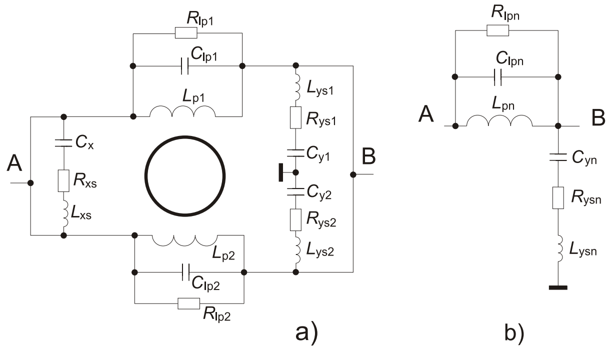

Fig. 4. Real model of Schurter 5110.1033.1 filter in asymmetrical system a); reduced equivalent model in asymmetrical system b).

the reduced equivalent model for the symmetrical measuring system. This circuitry is extended by the input leg compared to the asymmetrical case. This leg consists of the capacitor C_x and spurious components R_{xs} and L_{xs}. There are no paring components. These spurious components have to be included in the equivalent model with no changes and their values as well. The current compensated inductor L_p with its spurious components (C_{lp} and R_{lp}) make the longitudinal leg. This leg represents two parallel resonance circuits which are connected to each other serially in the symmetrical system. The values of the equivalent components could be determined by the following equations for the symmetric measuring system:

$$C_{lpn} = \frac{C_{pn}}{2} \tag{16}$$

$$R_{lpn} = 2 \cdot R_{lp}. \tag{17}$$

The single inductors which both create the current compensated inductor are connected according to Fig. 5b). The currents which flow through them have the same values but opposite directions. The voltages over current compensated inductor could be calculated by the following formula:

$$U_{ab} = U_{cd} = j\omega \mathrm{L}I + j\omega \mathrm{M}(-I) = j\omega \mathrm{L}I(1-\mathrm{k}) \tag{18}$$

and the current compensated inductor should be replaced by an equivalent inductor with the value:

$$L_{pn} = 2 \cdot L_p \cdot (1-\mathrm{k}). \tag{19}$$

The output transverse leg in the symmetrical system is composed of the serial combination of the following components:

$$C_{yn} = \frac{C_y}{2}, \tag{20}$$

$$L_{ysn} = 2 \cdot L_{ys}, \tag{21}$$

$$R_{ysn} = 2 \cdot R_{ys}. \tag{22}$$

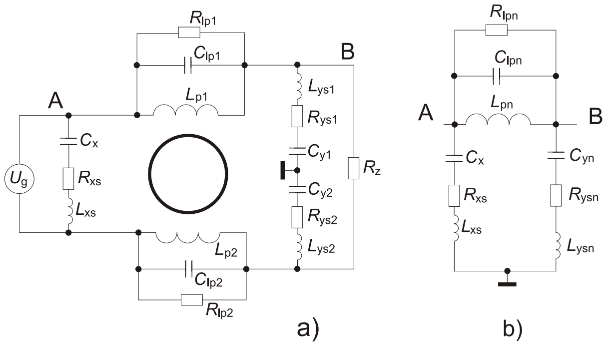

Fig. 5. Real model of Schurter 5110.1033.1 filter in symmetrical system a), reduced equivalent model in symmetrical system b).

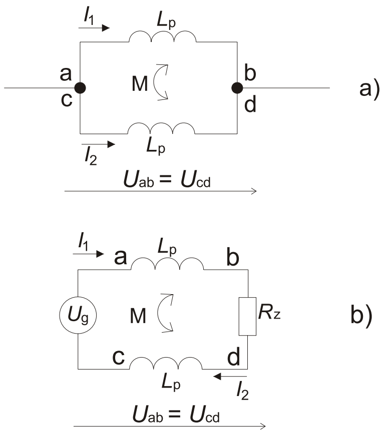

Fig. 6. The connection of the current compensated inductor in asymmetrical system a) and in the symmetrical system b).

Now, the EMI filter could be described as a four-pole circuit. This is the benefit for the generally formulated models and measuring systems. The usual measuring systems define filters as four-pole circuits. Such a filter could be defined by a simple mathematical apparatus based on the admittance parameters. The basic mathematical relationships are:

$$I_1 = \mathrm{Y}_{11}U_1 + \mathrm{Y}_{12}U_2, \tag{23}$$

$$I_2 = \mathrm{Y}_{21}U_1 + \mathrm{Y}_{22}U_2. \tag{24}$$

These equations could also be defined in the matrix form (5).

The exact formulation for the insertion loss could be defined as follows [6]:

$$\begin{aligned} L[\mathrm{dB}] &= 20 \cdot \log \left| \frac{\mathrm{Y}_{12} \cdot \mathrm{Y}_{21}}{\mathrm{Y}_{21} \cdot (\mathrm{Y}_\mathrm{S} + \mathrm{Y}_\mathrm{L})} - \right. \\ &- \left. \frac{(\mathrm{Y}_{11} + \mathrm{Y}_\mathrm{S}) \cdot (\mathrm{Y}_\mathrm{L} + \mathrm{Y}_{22})}{\mathrm{Y}_{21} \cdot (\mathrm{Y}_\mathrm{S} + \mathrm{Y}_\mathrm{L})} \right| \end{aligned} \tag{25}$$

where Y_S is the admittance connected to the input terminal of the EMI filter (source), Y_L is the admittance connected to the output clams (load), Y_{11}, Y_{12}, Y_{21} and Y_{22} are the admittance parameters of the filter. All these parameters make up the admittance 2 by 2 matrix **Y**.

The four-pole description is used in the reduced equivalent models. The models are different for different measuring systems, therefore it is necessary to produce several different models. The connection with real models is not lost because the components of the equivalent circuits were calculated by precise transformation formulas. The formula (25) is more elementary than in the six-pole models, so PC calculations are faster and also the requirements put on the PC performance are lower.

4. Finding Spurious Components from the Insertion Loss Characteristic

The benefit of the reduced equivalent circuits was not only in the reduced relation formula for the calculation of the insertion loss of the filter. Reduced circuitry is now more transparent and it is now possible to see the new relationships between the components and the insertion loss characteristic. Fig. 7 shows the mentioned equivalent circuits for asymmetric and symmetric measuring systems. It is obvious that both circuits contain several resonant circuits. Each resonant circuit is collected by one component of filter and some spurious components. Each resonant circuit resonates on the resonant frequency which could be calculated by the Thompson's formula.

L and *C* in the Thompson's formula represent the concrete components of the resonance circuit. The resonance frequencies make breakages in the insertion loss characteristic.

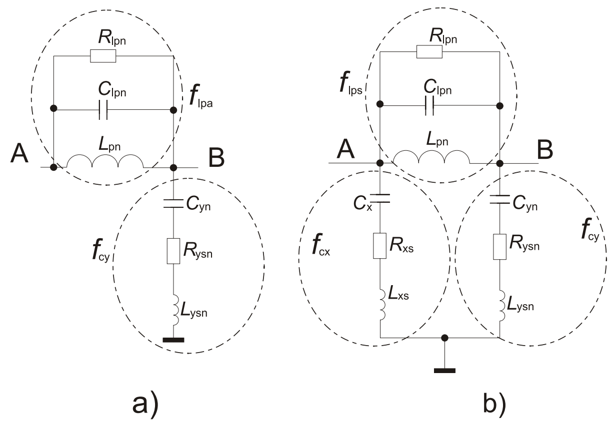

Fig. 7. The reduced equivalent circuits for the asymmetric a) and symmetric b) measuring systems.

The result of simulation of Schurter 5110.1033.1 filter as an example is depicted in Fig. 8. Simulation was executed with the value of spurious components, which was chosen according to the expected range of these spurious components [7]. The chosen values of spurious components are given in Tab. 1. The standard test method with 50 Ω input and output impedances was used in this case. The components of the filter were set according to the data sheet and the spurious components were chosen randomly in the expected range.

Spurious element	Chosen value
C_{lp} [F]	1.00 e^{-15}
R_{lp} [Ω]	1.00 e^{7}
L_{xs} [H]	1.00 e^{-10}
R_{xs} [Ω]	5.00 e^{-3}
L_{ys} [H]	1.00 e^{-10}
R_{ys} [Ω]	1.00 e^{-3}

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

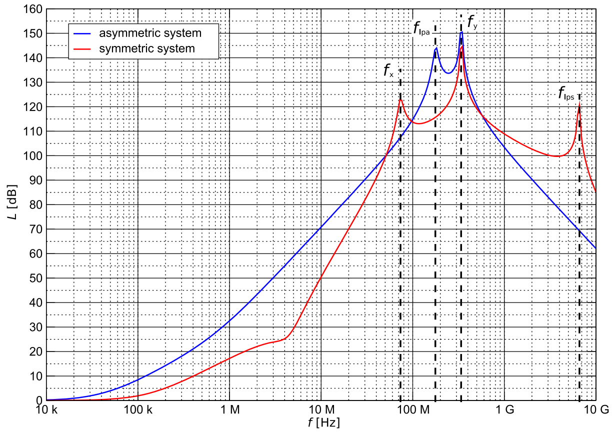

Fig. 8. Simulation of the insertion loss of the Schurter 5110.1033.1 filter in asymmetric and symmetric measuring systems.

Fig. 8 shows the insertion loss characteristics in the asymmetric and also symmetric measuring system. The characteristic for the symmetric system has three resonance frequencies, but the asymmetric one has only two. The different number of the resonance circuits is caused by the different connection of the EMI filter in the measuring setups.

Identification of each resonant circuit and its resonant frequency is necessary for the potential use of the Thompson's formula. The leg with the capacitor C_{y} is in the same position in both systems . The resonant frequency f_{cy} of the resonant circuit C_{y}, L_{ys} and R_{ys} is same for both measuring modes (asymmetrical and symmetrical). By comparison of (13) and (14) for the asymmetrical system with (20) and (21) for symmetrical system, the proof for that assertion is determined.

The resonant frequencies are not the same in case of the current compensated inductor in different measuring systems. This inductor is composed by the L_{p} and spurious components C_{lp} and R_{lp}. The influence of the coupling coefficient is different in these systems and the values of the equivalent inductors are not the same according to (12) for the asymmetric system and (19) for the symmetric system. The current compensated inductor is composed from two different inductors which are winded up usually on the same toroid core. One can assume that the coefficient of induction reaches the higher values between 0.9 and 1 which refers to the tight coupling. The difference between the equivalent inductions according to (12) and (19) is significant. The resonant frequency which is defined by the Thomson's formula will differ a lot. The difference between these two frequencies for asymmetrical and symmetrical system can be defined exactly. The following formula defines the resonant frequency of the L_{p} and C_{lp} circuit in the symmetrical circuit if the resonance frequency is known in the asymmetrical system:

$$f_{\mathrm{lps}} = f_{\mathrm{lpa}} \cdot \sqrt{\frac{1+\mathrm{k}}{1-\mathrm{k}}}. \tag{26}$$

If the resonant frequency is known in the symmetric system, it is possible to calculate the resonant frequency for the asymmetrical system:

$$f_{\mathrm{lpa}} = f_{\mathrm{lps}} \cdot \sqrt{\frac{1-\mathrm{k}}{1+\mathrm{k}}}. \tag{27}$$

The experience mentioned above can be used in the identification of resonant frequencies of individual resonant circuits with C_{y}, L_{p} and spurious components. The remaining resonance circuit based on the C_{x} capacitor with spurious L_{xs} and R_{xs} components is displayed only in the symmetrical system. Each resonant frequency was matched to the exact resonant circuit. After that, the Thomson's formula can be used for calculating the C_{lp}, L_{ys} and L_{xs} components.

Fig. 9 compares the results of simulation of the Schurter 5110.1033.1 insertion loss characteristics in the symmetric measuring system. The performance in two different impedance systems is compared: 50 Ω standard method and approximation method when the input impedance was set on the 100 Ω and output impedance was 0.1 Ω. The resonant frequencies have the same values in this case. It is obvious from this example that the R_{lp}, R_{ys} and R_{xs} components only inhibited the resonance circuits. The resonant circuits could be strongly inhibited, so the frequency responses are not visible. This fact really complicates the usage of this method. The biggest influence of the inhibited resistors is easily visible around the resonant frequency on a concrete resonance circuit. This experience could be used in optimizing the values of spurious resistors, e.g. by particle swarm optimization (PSO) [8]. The optimization itself could have only one dimension according to the knowledge of resonant frequencies of each circuit, where the optimized component has the main influence. It is possible to define the part of the insertion loss characteristic for that optimization in this case. This experience is the precondition for the successful creation of models of EMI filters.

Figs. 10 and 11 show comparison of the measurement characteristic and the optimized characteristic of the Schurter 5110.1033.1 filter in both measuring systems. A certain correspondence between the characteristics is evident. PSO optimization was used. In the measured data, breakages of the insertion loss characteristic were searched. The points where the breakages appeared were privileged. Optimization was based on the breakages. Direct identification of the reactive spurious component was impossible, because the measured characteristics had difficult shapes.

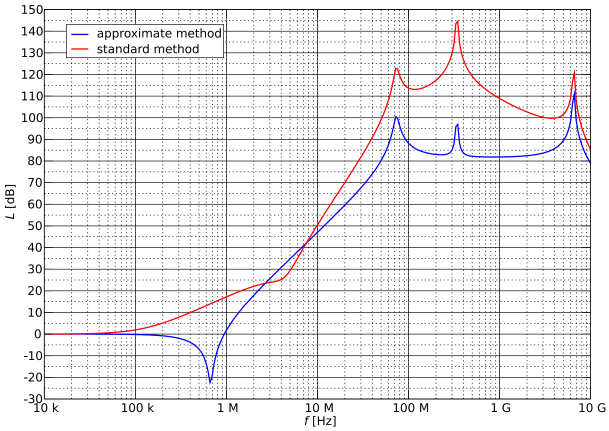

Fig. 9. Simulation of the insertion loss of the Schurter 5110.1033.1 filter in the symmetrical measuring system for different impedance conditions.

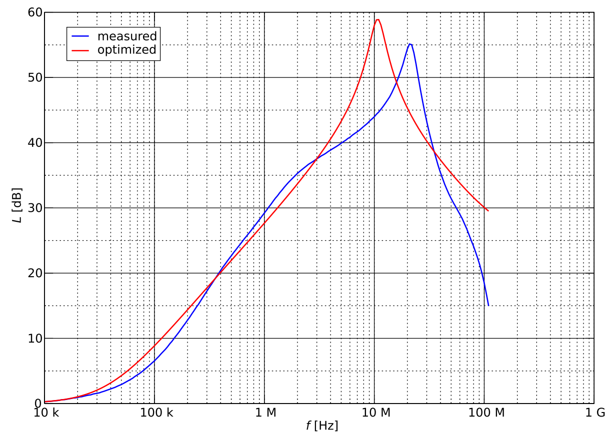

Fig. 10. Comparison of measurement characteristic and optimized characteristic of the Schurter 5110.1033.1 filter in asymmetrical measuring system.

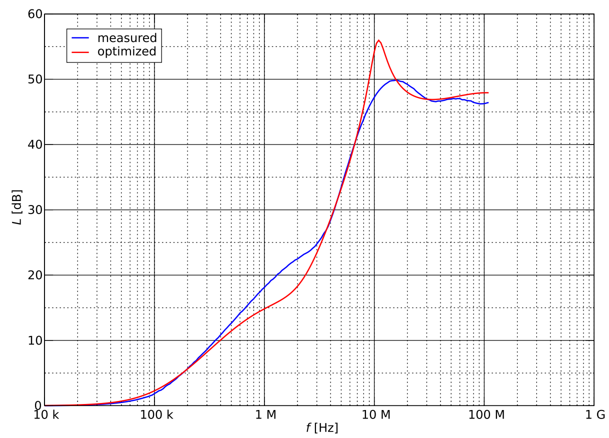

Fig. 11. Comparison of measurement characteristic and optimized characteristic of the Schurter 5110.1033.1 filter in symmetrical measuring system.

Some of the breakages were suppressed or not contained because of the frequency range of measurement. Optimized values of spurious components acquired by PSO are written in Tab. 2.

Spurious element	Optimized value
C_{lp} [F]	1.00 e^{-17}
R_{lp} [Ω]	3.19 e^{3}
L_{xs} [H]	8.32 e^{-9}
R_{xs} [Ω]	4.01
L_{ys} [H]	1.00 e^{-7}
R_{ys} [Ω]	1.87

Tab. 2. Optimized values of spurious components acquired by PSO.

5. Conclusions

The description of the model creation was mentioned in the beginning of the paper. The models were based on real circuitry of EMI filters and also included the current compensated inductor. The spurious components of EMI filter, which degrade the insertion loss in the high frequency range, were also added up. The six-pole mathematic description was used for the model concretization and the modified nodal voltage method was used, too. The basic equations were extended for the current compensated inductor description. This led to requirement of a bigger matrix. Pivot condensation was used for matrix reduction to the 4×4 dimension.

The equivalent circuits for the asymmetrical and symmetrical measuring systems were used for better orientation in the insertion loss characteristics. The equivalent circuits were based on real circuitry of the tested EMI filter. The influence of the input and termination was also taken into account for both systems under test. Same values of the pair components were considered. The advantage of the equivalent circuits is in the four-pole configuration, which corresponds to the basic measuring setups. The final calculation of the insertion loss characteristics is easier and faster.

The relationship between the equivalent circuits and the insertion loss characteristics were introduced at the end of the article. Th the similarities of both measuring systems were discussed. The matching between the resonant circuits and the exact resonant frequenies were shown in addition. After this identification, it is possible to calculate the values of the reactive spurious components according to the knowledge of the resonance frequency by the Thompson's formula.

The confrontation with the measured characteristics was shown at the end of the paper. Spurious components of EMI filter were acquired by PSO, which was based on breakages found in measured data. The measured and the optimized characteristics are not completely similar. This may be caused by spurious elements of the whole measurement system, especially in higher frequency range. These components were not involved in the used model. The future work will be focused on creation of more accurate models of the whole measurement system based on physical measurement.

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