The Choice of Suitable Fitness Function for Optimization Spurious Elements of EMI Filters

Zdenek Kejik, Jiri Drinovsky, Vaclav Ruzek, and Jiri Zachar

***Abstract*—In Introduction are introduced main problems of measurement of EMI filter and is suggested that creation of model of EMI filter is useful. In this paper is shown model of EMI filter which is based on basic circuitry of the EMI filter. Reduced equivalent circuitries for EMI filter and his creation are also shown, because these circuitries are more suitable for usage in iteration optimization loop.**

The spurious elements of filter are searched with optimization. Participial swarm optimization is used. Two possibilities of fitness function calculations are shown, too. Results of both approaches are compared in this paper. Using fitness function with weight coefficients gives better results and this fitness function is used for optimization of the measured characteristics.

***Index Terms*—Insertion loss, EMI filter, current compensated inductor, spurious component, participial swarm optimization.**

I. INTRODUCTION

THE main attributes of EMI filters are insertion loss characteristics. These characteristics are typically frequency dependant and they describe the attenuation of the EMI filter. The measurement of insertion loss characteristics is complicated due to several aspects. The first main problem of measurement insertion loss characteristics is the configuration of the input and output terminals of the EMI filter. The technical standards distinguish several types of measurement setups according to the interfering signals, which penetrate through the power supply network. The symmetric insertion loss characteristic defines the attenuation of the symmetrical interfering signals which are directly superposed on the useful signal. The generator of the harmonic signal and measuring receiver with the 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 insertion loss characteristic defines the attenuation of the spurious signals which could be produced by the spurious ground capacitors of the whole system. Measurement setup for asymmetric insertion loss is depicted in Fig. 1a.

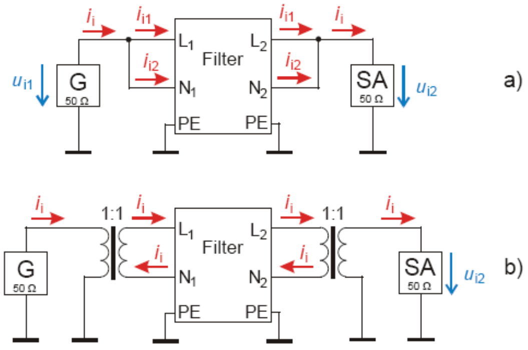

Fig. 1. Possible insertion loss measuring systems: a) asymmetrical; b) symmetrical.

The second main problem is represented by the non-defined impedance termination 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 the 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 standard one with 50 Ω impedances at the input and output terminals of the filter; the approximate method for the EMI filters with 0.1 Ω and 100 Ω at the input and output and vice versa combination, too. But any one of the mentioned method does not correspond to the reality.

It is not possible to perform a lot of measurement of insertion loss characteristics with different impedance termination in several measurement setups due to the technical limits. This is the motivation for the creation of the 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. It will be possible to use of the proposed model for the identifying the "worst case" of the filter which means the identification of the lowest insertion loss of the filter. It is possible to prefabricate the "worst case" test setup and confirm the results of the simulations by the measurements.

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II. MODEL OF FILTER

The main aim for the model creation is its usability in different measurement setups and different impedance conditions. For that reason the models are based on the real circuitry of the EMI filter, which is shown for specific filter in Fig. 2. This basic circuitry has to be enlarged by the spurious components of the filter, which degrade insertion loss in high frequency range. Insertion loss characteristics are changed above 100 kHz with spurious components.

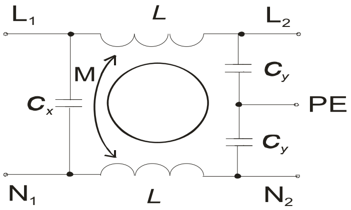


Fig. 2. Basic circuitry of the EMI filter Schurter 5110.1033.1.

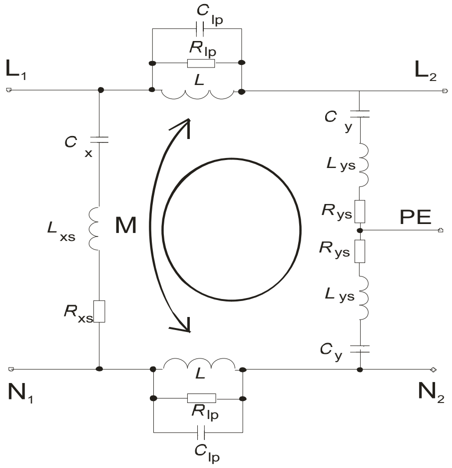


Fig. 3. Enlarged circuitry of EMI filter Schurter 5110.1033.1.

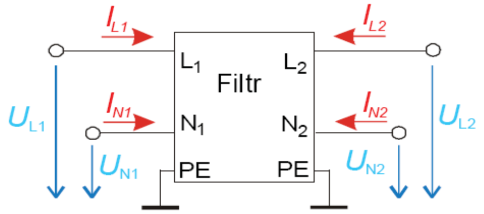


Fig. 4. The EMI filter as a six-pole.

The model of EMI filter that is created by the enlarged circuitry is shown in Fig. 3. The mathematical description is possible due to the six-pole parameters (Fig. 4), e.g. admittance parameters. This way of description is very difficult and the formulas for computing the insertion loss are very large. For that reason is six-pole description unsuitable for using in iteration loop of optimization.

A. Reduced equivalent circuitries for EMI filter

In Fig. 3, the symmetry of model is evident. The basis circuitry elements which are symmetric have the same values according the catalog. It is supposed that the spurious elements that are symmetric will be very similar. Symmetry of the model and connection input and output terminals for specific measurement setup are used for creation the reduced equivalent circuitries [3]. For that reason special equivalent circuitry for each measurement setup is needed.

The real model of the EMI filter with the connection terminals for the asymmetric system is depicted in Fig. 5 a. The Fig. 5 b shows the same circuitry after reduction for the asymmetric measuring system. The capacitor C_x with its spurious components is shorted out with the input termination. This capacitor is not taken into account in the reduced equivalent circuitry, because there is not any influence of this component. The pairing components for the real model with index 1 or 2 are marked in the reduced model without any index number because they are identical, for example $L_{p1} = L_{p2} = L_p$, or $C_{lp1} = C_{lp2} = C_{lp}$, etc. The current compensated inductor is connected in the both longitudinal legs with its spurious component, too. So, 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 by this way [4]:

$$C_{lpn} = 2 \cdot C_{lp}\,, \tag{1}$$

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

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 will flow same currents in same directions. This situation is depicted in Fig. 7a. The voltage over the current compensated inductors is in force with following relation [4]:

$$U_{ab} = U_{cd} = j\omega LI + j\omega MI = j\omega L(1+k)\,. \tag{3}$$

The current compensated inductor is practicable to replace by the equivalent inductor according to next formula [4]:

$$L_{pn} = \frac{L_p \cdot (1+k)}{2}\,. \tag{4}$$

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

$$C_{yn} = 2 \cdot C_y\,, \tag{5}$$

$$L_{ysn} = \frac{L_{ys}}{2}\,, \tag{6}$$

$$R_{ysn} = \frac{R_{ys}}{2}\,. \tag{7}$$

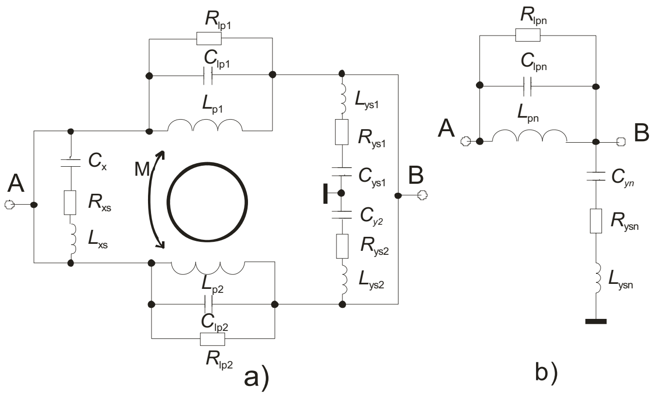


Fig. 5. Real model of Schurter 5110.1033.1 filter in asymmetrical system a); reduced equivalent model in asymmetrical system b).

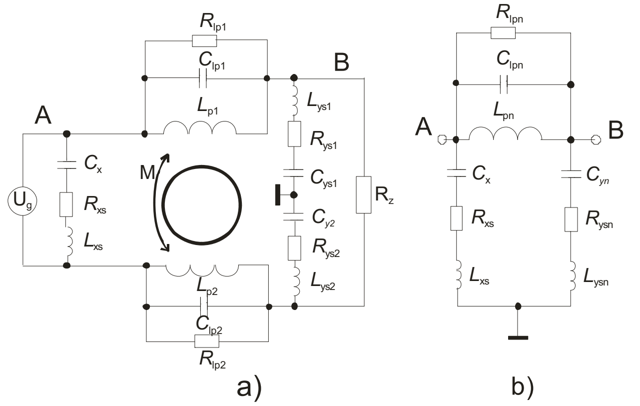


Fig. 6. Real model of Schurter 5110.1033.1 filter in symmetrical system a), reduced equivalent model in symmetrical system b).

Similar circuitry has also model for the symmetrical measuring system which is depicted in Fig. 6a. There is although given reduced equivalent model for the symmetrical test setup (Fig. 6b). This circuitry is extended by the input leg in comparison to the asymmetrical case. This leg consists from the capacitor C_x and spurious components R_{xs} and L_{xs}. There are not any paring components. These spurious components have to be included in the equivalent model without any changes. The current compensated inductor L_p with its spurious components (C_{lp} and R_{lp}) make the longitudinal leg. This leg represents in the symmetrical system two parallel resonance circuits which are connected to each other serially. The values of the equivalent components could be determined by following equations for the symmetric measuring system [4]:

$$C_{lpn} = \frac{C_{lp}}{2}, \tag{8}$$

$$R_{lpn} = 2 \cdot R_{lp}. \tag{9}$$

Single inductors which both create the current compensated inductor are connected according to Fig. 7b. The currents which flow through them have the same values but opposite directions. The voltages over current compensated inductor could be calculated by following formula [4]:

$$U_{ab} = U_{cd} = j\omega L I + j\omega M(-I) = j\omega L(1-k) \tag{10}$$

and current compensated inductor should be replaced by the equivalent inductor with the value [4]:

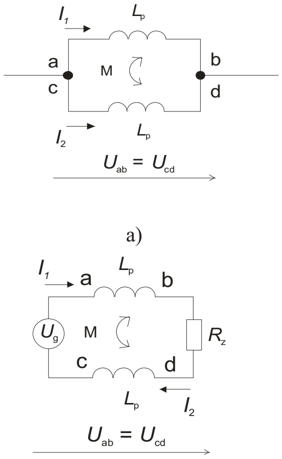
$$L_{pn} = 2 \cdot L_p \cdot (1-k) \tag{11}$$

The output transverse leg in symmetrical system is composed from the serial combination of following components [4]:

$$C_{yn} = \frac{C_y}{2}, \tag{12}$$

$$L_{ysn} = 2 \cdot L_{ys}, \tag{13}$$

$$R_{ysn} = 2 \cdot R_{ys}. \tag{14}$$



a)

b)

Fig. 7. The connection of the current compensated inductor in asymmetrical system (a) and in the symmetrical system b).

Big advantage of reduced equivalent circuitry is four-pole configuration, because input and output connections are connected according specific measurement setup. It is able to compute the insertion loss by following formula due the four-pole admittance parameters [7].

$$L[dB] = 20 \cdot \log \left| \frac{Y_{12} \cdot Y_{21} - (Y_{11} + Y_S) \cdot (Y_L + Y_{22})}{Y_{21} \cdot (Y_S + Y_L)} \right| \tag{15}$$

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 the output clams (load), Y_{11} to Y_{22} are admittance parameters. This way of computing insertion loss is much easier than computing due to the six-pole parameters. Therefore this way is suitable for using in iteration loop of optimization.

B. Breakages in the insertion loss characteristics

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 insertion loss characteristic. The Fig. 8 shows mentioned equivalent circuits for the asymmetric and symmetric measurement systems. It is obvious that both circuits contain several resonance circuits. These resonance circuits are collected by the component of filter and spurious components. The resonance frequencies make the breakages in the insertion loss characteristic [7].

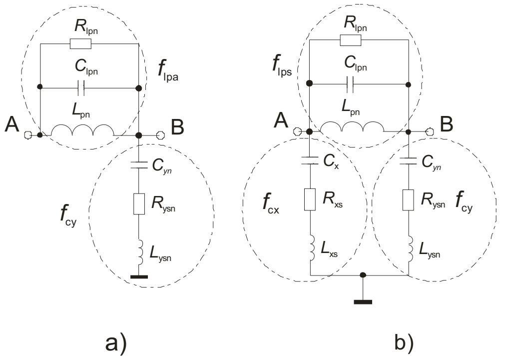


Fig. 8. The reduced equivalent circuits for the asymmetric a) and symmetric b) measuring systems.

The result of the simulation of Schurter 5110.1033.1 filter as example is depicted in Fig. 9. 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 [6]. Fig. 9 shows the insertion loss characteristics in the asymmetric and also symmetric measurement system. Number of breakages is different for each measurement setup, because number of resonance circuits is different too.

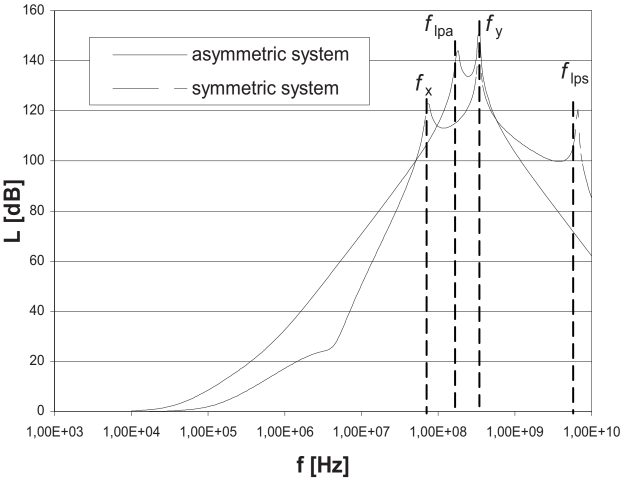


Fig. 9. Simulation of the insertion loss of the Schurter 5110.1033.1 filter in asymmetric and symmetric measuring systems.

III. OPTIMIZATION

Circuitry of model is mentioned in section 2. The next task is found out the values of spurious elements. The values of the basic circuitry elements are assigned via catalog. The values of spurious elements are found out by optimization.

The particle swarm optimization (PSO) has been chosen for its effectiveness in optimizing, but the discontinuous in multidimensional area could cause several problems with the implementation [5]. PSO is a robust stochastic evolutionary computation technique based on the movement and intelligence of swarms.

Agents of the swarm are flying trough the solution space during the optimization. Solution space could be multidimensional and range of dimensions could be limited. In beginning are locations of agents given at random in defined solution space. For each agent is computed result of fitness function, which is single number represents the suitability of position in solution space. Fitness function provides interface between the physical problem and the optimization algorithm.

Each agent knows the position where he found his best value of fitness function. This location is called personal best or *pbest*. Each agent also has some way of knowledge of the best value of fitness function which was discovered by the entire swarm. This location is known as the global best or *gbest*.

Due this knowledge of agents is computed the velocity for each agent v_n with following formula [5]

$$v_n = w \cdot v_n + c_1\, \mathrm{rand}() \cdot (pbest{,}n - x_n) + \\ + c_2\, \mathrm{rand}() \cdot (gbest{,}n - x_n), \qquad (16)$$

where v_n is the velocity of the particle in the n^th^ dimension and x_n is the particle's coordinate in the n^{th} dimension. This calculation is done for each of the dimensions. w is inertial weight provides the inertia of agents move. c_1 is a factor determining how much the particle is influenced by the memory of his best location, and c_2 is a factor determining how much the particle is influenced by the rest of the swarm. The random number function rand () returns a number between 0.0 and 1.0. The velocity is applied for a given time-step Δt, usually chosen to be one and new coordinate is computed for each of the dimensions according the following equation [5]

$$x_n = x_n \cdot \Delta t \cdot v_n \qquad (17)$$

After this process is carried out for each particle in the swarm, the positions of all the particles are evaluated, and corrections are made to the positions of *pbest*, and *gbest* before letting the particles fly around for another run. Repetition of this cycle is continued until the termination criteria are met. There are several methods to determine these termination criteria. The criterion most often used in optimizations is a maximum iteration number. The PSO ends when the process has been repeated a user-defined number of times. Another criterion available is a target fitness termination condition.

Boundary conditions protect agents flying out of determined range of solution space. There are several boundary conditions which are used in optimization [5]

- *Absorbing Walls:* When a particle hits the boundary of the solution space in one of the dimensions, the velocity in that dimension is zeroed, and the particle will eventually be pulled back toward the allowed solution space.

- *Reflecting Walls:* When a particle hits the boundary in one of the dimensions, the sign of the velocity in that dimension is changed and the particle is reflected back toward the solution space.

- *Invisible Walls:* The particles are allowed to fly without any physical restriction. However, particles that roam outside the allowed solution space are not evaluated for fitness.

A. Choice of fitness function

Solution space, which is searched by swarm, is composed from values of spurious elements (L_{xs}, R_{xs}, C_{lp}, R_{lp}, L_{ys}, R_{ys}). Obviously, it is six-dimensional space. One of the sources for optimization is the model of EMI filter, which is described by admittance parameters. For reason of lower computing demand are used reduced equivalent circuitries. The insertion loss characteristic taken in asymmetrical and symmetrical measurement setups are data sources for optimization.

The core of optimization is computing of the fitness function, which is based on evaluation of differences between given insertion loss characteristics and insertion loss characteristics that are made by current iteration of optimization from current values of spurious elements. The computation of fitness function is possible write by following formulas

$$\Delta_A = \sum_f (\mathrm{L}_{\mathrm{Avyp}} - \mathrm{L}_{\mathrm{Aměm}})^2 \tag{18}$$

$$\Delta_S = \sum_f (\mathrm{L}_{\mathrm{Svyp}} - \mathrm{L}_{\mathrm{Směm}})^2 \tag{19}$$

where Δ_A is computation of deviation in asymmetrical measurement setup and Δ_S is computation of deviation in symmetrical measurement setup. Total deviation consequently result of both fitness functions is

$$\Delta = \Delta_A + \Delta_S \tag{20}$$

In following examples are used insertion loss characteristics that are simulated instead insertion loss characteristics taken by measurement. Spurious elements in simulations are chosen according to expected values [6]. By this way it is possible to find out possibilities of optimization only.

Set of optimization was following. The inertial weight was decreased linearly from 0.9 to 0.4 over 100 iterations. For each run, the PSO had a population size set at 20 - 30 particles. Usage of more particles was ineffective. Coefficients c_1 and c_2 was set both to 1.49 according to the recommendation in [5]. All the introduced boundary conditions were used whose influences were the same in the optimization. Optimization process was run many times.

In Fig. 5 and 6 are given results of optimization in both measurement setups. It is evident that the result of optimization is not successful. One successful optimized breakage in characteristic for symmetrical measurement setup is shown. This breakage is not created by the right resonance circuit, which cause the wrong breakage in characteristic for asymmetrical measurement setup. In this situation the value of fitness function will be risen although the value of spurious elements will be better. Therefore the optimization fixes in this result.

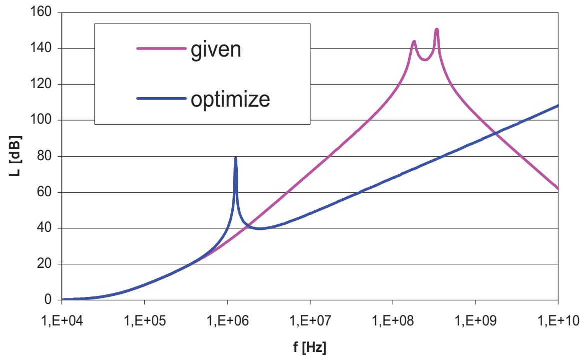


Fig. 10. The result of optimization for filter Schurter 5110.1033.1 in asymmetrical measurement setup.

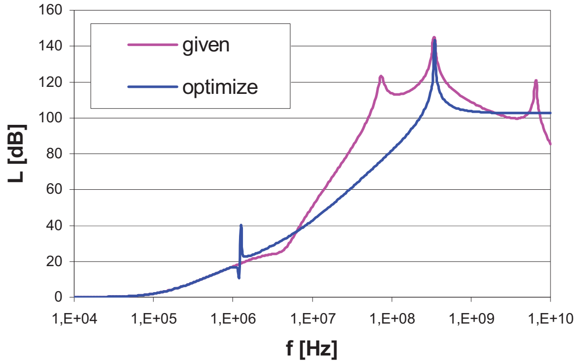


Fig. 11. The result of optimization for filter Schurter 5110.1033.1 in symmetrical measurement setup.

B. Chosen the input dates for optimization

Characteristics are taken with 50 points per decade. In previous case each characteristic had 350 points, in total for both measurement setup 700 points. In each point was computed an error. However this was non effective.

It is important to choose accurate frequency range for characteristics. The searched spurious elements caused changes in insertion loss characteristics from middle frequencies (about from 100 kHz), which determines minimum frequency. Maximum frequency is determined by frequency range of measurement system. (In symmetrical measurement setup transformers that reduction the frequency range of measurement system are involved). Also model of EMI filter does not involve spurious behavior of whole measurement system.

In reduced frequency range is still a lot of samples which are not necessary. So this data set could be reduced up to five points per decade. If points are close to breakage, they are not reduced so much. The amount of rest points is now lower, but the shape of the insertion loss characteristic has not been changed.

In part 2 of this paper it is mentioned that the breakages in insertion loss characteristics are caused by spurious components. For that reason several points are privileged in area of breakages. Privileging is made by setting higher importance of these points. Therefore fitness function expression is remade as [8]

$$\Delta_A = \sum_f (\mathrm{L}_{\mathrm{Avyp}} - \mathrm{L}_{\mathrm{Aměm}})^2 \cdot \mathrm{v}_\mathrm{A} \qquad (21)$$

$$\Delta_S = \sum_f (\mathrm{L}_{\mathrm{Svyp}} - \mathrm{L}_{\mathrm{Směm}})^2 \cdot \mathrm{v}_\mathrm{S} \qquad (22)$$

Weight coefficient for asymmetrical measurement setup is marked v_a, for symmetrical measurement setup is v_s. Weight coefficient is given for each point of both insertion loss characteristic and set to one for all points in the beginning. If the point is marked as point of breakage, then its value of weight coefficient is set higher than one. Therefore the result of fitness function is more depend on the points of breakages. Experimentally was found out that the best value for weight coefficient in area of breakages is forty. The results of optimization are shown in Fig. 12 and 13. Approximation of given and optimized characteristics is evident. The values of given and optimized spurious elements are written in table 1. Set of optimization process was the same as in the previous case.

TABLE I. COMPARISON OF GIVEN AND OPTIMIZED VALUE OF SPURIOUS ELEMENTS OF EMI FILTER FOR FILTER SCHURTER 5110.1033.1.

Spurious element	Given value	Optimize value
C_{lp} [F]	1.00 e-15	1.02 e-15
R_{lp} [Ω]	1.00 e7	57.80 e7
L_{xs} [H]	1.00 e-10	0.95 e-10
R_{xs} [Ω]	5.00 e-3	2.79 e-3
L_{ys} [H]	1.00 e-10	0.93 e-10
R_{ys} [Ω]	1.00 e-3	8.85 e-3

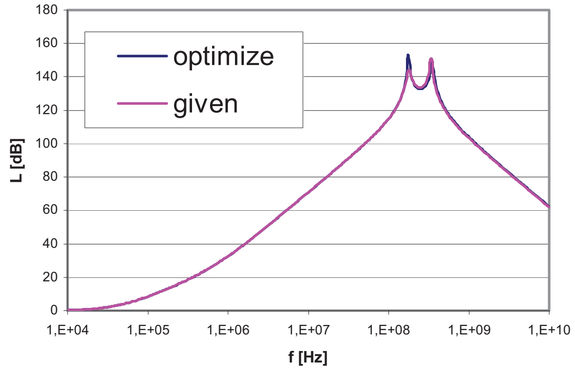


Fig. 12. The result of optimization using weight coefficient for filter Schurter 5110.1033.1 in asymmetrical measurement setup.

C. *Optimization executed on measured characteristics*

Both Fig. 14 and 15 show comparison of measurement characteristic and optimized characteristic of the Schurter 5110.1033.1 filter, in both measuring systems. It is evident certain correspondence between characteristics. Optimization method PSO was used. In measured data were searched breakages of the insertion loss characteristic. Breakages in insertion loss characteristic were searched and weighted coefficient was used. Optimized characteristics are not fitted as well as in case with simulated characteristics. There are some reasons. Some of breakages was suppressed or was not contained because frequencies range of measurement. The next problems are spurious elements caused by whole measurement system especially in higher frequencies, which are not involved in used model. Optimized values of spurious components acquired by PSO are written in table 2.

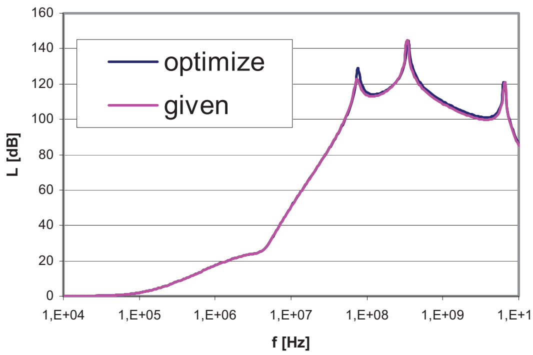


Fig. 13. The result of optimization using weight coefficient for filter Schurter 5110.1033.1 in symmetrical measurement setup.

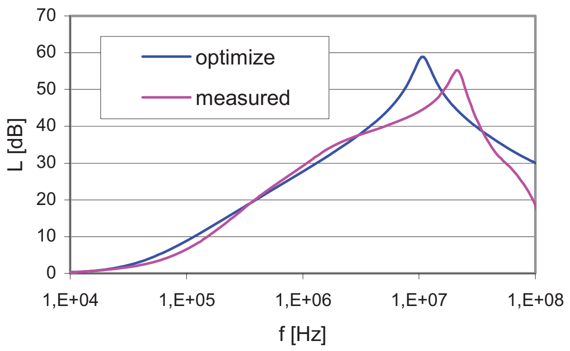


Fig. 14. Comparison of measurement characteristic and optimized characteristic of the Schurter 5110.1033.1 filter in asymmetric measuring system.

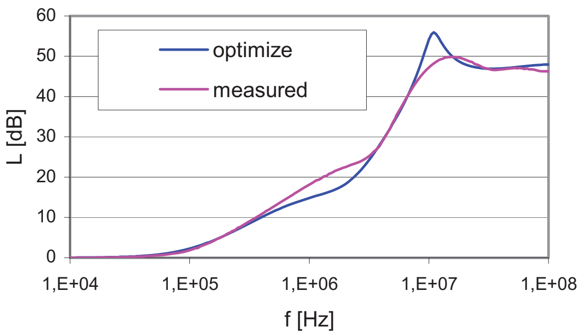


Fig. 15. Comparison of measurement characteristic and optimized characteristic of the Schurter 5110.1033.1 filter in symmetric measuring system.

IV. CONCLUSIONS

In introduction the main problems about EMI filter measurement were depicted. Motivation of creation model of EMI filter was mentioned.

TABLE II. OPTIMIZED VALUES OF SPURIOUS ELEMENTS OF EMI FILTER FOR FILTER SCHURTER 5110.1033.1. OBTAINED FROM THE MEASURED CHARACTERISTICS

Spurious element	Optimized value
C_{lp} [F]	1.00 e-17
R_{lp} [Ω]	3.19e3
L_{xs} [H]	8.32 e-9
R_{xs} [Ω]	4.01
L_{ys} [H]	1.00 e-7
R_{ys} [Ω]	1.87

The model is based on the real circuitry of the EMI filter. There were also added up the spurious components of EMI filter, which degrade the insertion loss in the high frequency range. The six-pole mathematic description was needed for this model.

The equivalent circuits for the asymmetrical and symmetrical measuring systems were introduced. The advantage of the equivalent circuits is in the four-pole configuration, which corresponds with the basic measuring setups. The final calculation of the insertion loss characteristics is easier and faster. The relationship between the equivalent circuits and relevant insertion loss characteristics were introduced and breakages in insertion loss characteristics were depicted.

Particle swarm optimization is used for searching values of spurious elements of model of EMI filter. The solution space is six dimensional. Simulated insertion loss characteristic was used because the possibilities of optimization were founded. Shape of the insertion loss characteristic is not smooth. There are local maxima and local minima. Therefore demand for fitness function was higher.

In part 3 A was fitness function based on evaluation of differences between given insertion loss characteristics and insertion loss characteristics that are made by current iteration of optimization. Insertion loss characteristics are computed in iteration loop of optimization by reduced equivalent circuitry, which have four-pole configuration. This is convenient because the demanding of computing is lower than usage six-pole circuitry. In this case optimization does not reach the expected reasons. Problem was that optimization was usually fixed in wrong results.

This problem is solved in part 3 B Fitness function is remade and weight coefficients are used. Result of the fitness function is influenced more by point of breakages. In this case the result of optimization was successful.

Fitness function described in 3B was used for optimization measured characteristic too. Measured and optimized characteristics are not completely similar. There are some problems by using measurement characteristics. The breakages can be suppressed. The next problems are spurious elements caused by whole measurement system especially in higher frequencies, which are not involved in used model.

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