Verification of Alternative Measurement System for EMI Filters Worst-case Evaluation

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Abstract — **This paper deals with the approximate worst-case test method for testing the insertion loss of the EMI filters. The systems with 0.1 Ω and 100 Ω impedances are usually used for this testing. These measuring systems are required by the international CISPR 17 standard. The main disadvantage of this system is the 0.1 Ω impedance transformer. The dynamic range for the transformation from the 50 Ω, which is most common matched impedance for the measurement setups, to 0.1 Ω is very large. It is not easy to produce such transformers with this high impedance transformation ratio. These transformers have usually very narrow bandwidth. This paper discusses the alternative system with 1 Ω and 100 Ω impedances. The mathematical model for the first estimation is also discussed there and the optimal configuration with 1 Ω and 100 Ω impedances is chosen according the calculated results. The performance of these systems was tested on several filters and the obtained data are depicted, too. The performance comparison of several filters in several systems is also included. The performance of alternate worst-case system is discussed in the conclusion.**

Keywords — **EMI filters, Worst-case, CISPR 17, MNVM, Insertion loss.**

I. INTRODUCTION

THE "worst-case" identification is specified for the Electromagnetic compatibility. This identification is necessary for the estimation of filter behaviour in the place of the final installation. Generally, the EMC measurement techniques are specified by authorized international standards. Same principle is also applied on the EMI filters insertion loss measurements. Generally, the insertion loss of the EMI filter depends on the impedance terminations of the input and output terminals of the EMI filter. The insertion loss of the filter, which typical measurement setup is depicted in Fig. 1, could be calculated by using the cascade parameters [1] and [2]

$$\begin{aligned} L &= 20 \cdot \log \left| \frac{U_{20}}{U_2} \right| \\ &= 20 \cdot \log \left| \frac{Z_L}{Z_S + Z_L} \cdot \mathbf{A}_{11} + \frac{1}{Z_S + Z_L} \cdot \mathbf{A}_{12} + \right. \\ &\left. + \frac{Z_S \cdot Z_L}{Z_S + Z_L} \cdot \mathbf{A}_{21} + \frac{Z_S}{Z_S + Z_L} \cdot \mathbf{A}_{22} \right| . \end{aligned} \qquad (1)$$

The U_2 is the voltage at the output of the EMI filter on the loading impedance Z_L, the U_{20} is the same voltage, but the filter has been unplugged. The A_{11}, A_{12}, A_{21} and A_{22} are cascade parameters of the EMI filter. These parameters are complex. The Z_S is the impedance of the source of interfering signal or signals.

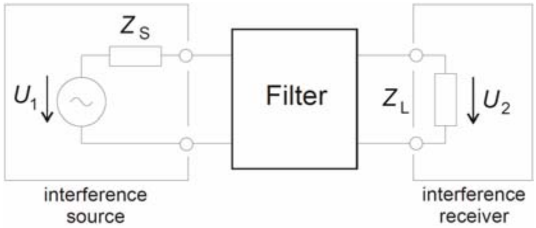

Fig. 1. It is good practice to explain the significance of the figure in the caption.

The insertion loss of the filter depends on the input and output terminating impedances, and on the frequency of the interfering signal. The true values of worst-case could be obtained, but there would be necessary to tune the values of input and output impedances for each tested frequency. The test setup reflects the results which are defined in the equation (1). The identification of the worst-case by the above mentioned test setup will produce the precise data, but the realization would be very complicated and also very frequency limited. The international standards e.g. CISPR 17 [3] define for worst-case identification the approximate test setup The MIL-STD-220B is similar US army standard which is focused on the same topic of measurement. The above described measurement method with the variable input and output impedances is discussed in mentioned standards. The final test setup is not carried out by any standard in addition. These standards also define the approximate method for the EMI filters. The EMI filters have to be tested in impedance systems with the terminating impedances with 0.1 Ω/100 Ω and vice versa. The measurement setup of this method is depicted in Fig. 2. The approximate test setup, according to the CISPR standard, requires usage of two impedance transformers. These transformers transform the characteristic impedance of the measuring system, which is typically 50 Ω, to the impedances of 0.1 Ω and 100 Ω respectively.

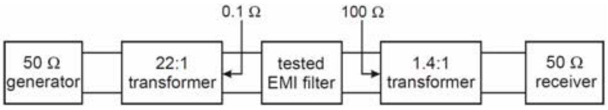

Fig. 2. The approximate method measurement setup.

II. SIMPLE MODEL OF EMI FILTERS

The identification of the "worst-cases" of several different filters from several companies could not be easy.

The biggest problem is to obtain data for different filters and in the same time for several combinations of impedance terminations to obtain the general “worst-case” data. One possible way could be through the analysis of filters’ models. This approach has several advantages. The method based on the models is not so time consuming as a lot of measurements with different impedance terminations. For making the models, plenty of commercial software could be used (PSpice, Micro-Cap, Ansoft Designer®, etc). These all software systems are very specialized for specific tasks. The EMI filters performance analysis should be very universal and variable because the configuration of each filter is very variable. The circuitry knowledge of the certain EMI filter is other precondition, which should be fulfilled. For that reasons, the Matlab® was chosen for this analysis. Using of the Matlab® brings universality because the determination of the insertion loss relation uses only general Y parameters. These parameters could be effectively changed in relation with the circuitry of the concrete EMI filter. The basic single-phase EMI filter, which diagram of connections is depicted in Fig. 3, could be described by the following equations

$$\begin{aligned} I_{L1} &= Y_{11}U_{L1} + Y_{12}U_{N1} + Y_{13}U_{L2} + Y_{14}U_{N2}, \\ I_{N1} &= Y_{21}U_{L1} + Y_{22}U_{N1} + Y_{23}U_{L2} + Y_{24}U_{N2}, \\ I_{L2} &= Y_{31}U_{L1} + Y_{32}U_{N1} + Y_{33}U_{L2} + Y_{34}U_{N2}, \\ I_{N2} &= Y_{41}U_{L1} + Y_{42}U_{N1} + Y_{43}U_{L2} + Y_{44}U_{N2}, \end{aligned} \tag{2}$$

where I_{x1} is the input current for clamps L or N, I_{x2} is one of the two output currents. In the same manner the input and output voltages are determined as it is shown in Fig. 3. The Y_{xy} is the admittance parameter of the tested EMI filter. The single admittance parameters in admittance matrix Y could be easily calculated by the modified nodal voltage method. By these admittance parameters it is possible to construct the admittance matrix Y. Equations (2) could be rewrite in to the matrix form

$$\mathbf{I} = \mathbf{Y} \cdot \mathbf{U}, \tag{3}$$

where **I** is the vector of the unknown currents, and **U** is the vector of the variable voltages. The equations (2) exactly describe the properties of an arbitrary EMI filter, but for correct calculations, it is necessary to add more equations which will refer to configurations of the impedance network and to the location of the source of the interference signal. The insertion loss data are obtained after calculations of these several equations. The real frequency on which the insertion loss of the tested filter is calculated is also included in each element of matrix **Y**. By this method it is possible to determine the insertion loss data, e.g. (L in dB).

The usual EMI filters include the current compensated inductors, which are not easy to describe by the modified nodal voltage method. This method fits well for description of simple and linear electronic circuits. The above shown method has to be extended for correct determination of admittance matrix **Y** of the EMI filters. The admittance matrix **Y** has to be enlarged by two columns and two lines. The influence of the current compensated inductors is written into the added cells. By this step the equations (2) will be added up by the following two equations

$$\begin{aligned} U_{ab} &= j\omega L_1 I_1 + j\omega M I_2, \\ U_{cd} &= j\omega M I_1 + j\omega L_2 I_2 \end{aligned} \tag{4}$$

where the meaning of variables U_{ab}, U_{cd}, I_a to I_d is obvious from Fig. 4. The constants L and M represent own and mutual coefficients of induction of the current compensated inductor. The relationship between these two quantities is given by

$$M = k\sqrt{L_1 L_2}, \tag{5}$$

where k is the coupling coefficient. The values of the own coefficients of induction L_1 and L_2 are commonly the same for most of EMI filters ($L = L_1L_2$).

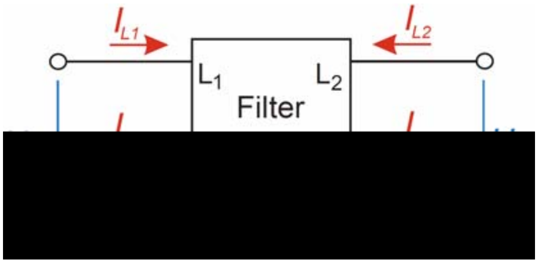

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Fig. 3. Tested filter and distribution of currents and voltages.

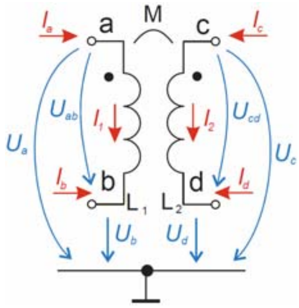

Fig. 4. Current compensated inductor with the mutual coefficients of induction.

The final admittance parameters have to be added into the equations (2). The influence of current compensated inductors is not taken into account. The final obtained matrix of the filter could be written as following

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & 1 & 0 \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & 0 & 1 \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & -1 & 0 \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} & 0 & -1 \\ -1 & 0 & 1 & 0 & j\omega L & j\omega M \\ 0 & -1 & 0 & 1 & j\omega M & j\omega L \end{bmatrix} \cdot \tag{6}$$

This presented matrix is deduced for single-phase EMI filter which contains only one current compensated inductor. For the description of filters with more inductors it is necessary to create a bigger matrix. This fact rapidly reduces an efficiency and degrades universality of this analysis. More universal method could be made by using a firmly set of the matrix dimension. The smallest dimension of the matrix could be 4 × 4 because single-phase filters have usually 2 input and 2 output clamps. Thus, it is possible to produce a universal relation for insertion loss calculation, which depends only on the admittance parameters of the filters (Y_{11} to Y_{44}). These parameters are defined for input and output nodes (clamps) of the EMI filter. The rest of the nodes has to be reduced into the dimension 4 × 4. For this reduction it is possible to use the pivot condensation. The principle of the reduction is possible to write down in this mathematical form

$$\mathbf{M}_{\mathrm{R}} = \mathbf{M}_{\mathrm{E}} - \mathbf{M}_{\mathrm{EI}} \cdot \left(\mathbf{M}_{\mathrm{I}}\right)^{-1} \cdot \mathbf{M}_{\mathrm{IE}} . \tag{7}$$

Matrices $\mathbf{M}_{\mathrm{E}}$, $\mathbf{M}_{\mathrm{EI}}$, $\mathbf{M}_{\mathrm{I}}$ and $\mathbf{M}_{\mathrm{IE}}$ were created from the admittance matrix $\mathbf{Y}$ of the EMI filter by the following way in this mathematical form

$$\begin{bmatrix} \mathbf{M}_{\mathrm{E}} & \mathbf{M}_{\mathrm{IE}} \\ \mathbf{M}_{\mathrm{EI}} & \mathbf{M}_{\mathrm{I}} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{X}_{\mathrm{I}} \\ \mathbf{X}_{\mathrm{E}} \end{bmatrix} = \begin{bmatrix} \mathbf{L}_{\mathrm{I}} \\ \mathbf{L}_{\mathrm{E}} \end{bmatrix}, \tag{8}$$

where $\mathbf{X}_{\mathrm{I}}$ and $\mathbf{X}_{\mathrm{E}}$ represent the internal and external unknowns. The $\mathbf{L}_{\mathrm{I}}$ and $\mathbf{L}_{\mathrm{E}}$ represent external sources. The matrix $\mathbf{M}_{\mathrm{R}}$ is the final reduced matrix after pivot condensation. This matrix has the desired dimension of 4 × 4. Each matrix element is afterwards established into the relation for calculating the insertion loss data. This element depends on the frequency.

By the described method it is possible to calculate insertion loss of single-phase EMI filters. The method could be modified for multi-phase filters. This setup calculates only with the data which are written in the data sheet. From this condition it follows that calculations of insertion loss are not possible on higher frequencies, because in this setup, spurious properties of real electronic parts and devices are not covered. The value of coupling coefficient k should be set by measuring or by optimization. The measured insertion loss data, e.g. in 50 Ω/50 Ω, which should be given in data sheets, could be used for this optimization. The equation for the calculation of the insertion loss can be determined for each system asymmetrical, symmetrical or non-symmetrical. The similar setup can be used for the estimating of the insertion loss with different impedance terminations [3] which could lead to the "worst-case" system.

III. MODIFICATION OF APPROXIMATE TEST SETUP

The modified approximate test setup should replace the 0.1 Ω be another transformer with different impedance ratio. This new setup should produce similar results like the approximate one, but the realization would be easier and also the operational frequency range of low impedance transformer should be wider. Firstly was carried out the simulation of such measuring system based on the introduced simple models. The good choice is the system with the 1 Ω/100 Ω and vice versa impedances. The models and new measuring system were tested on several models of EMI filters: Schurter 5110.1033.1, Schaffner FN 321 1/05, FN 2020-16-06, FN 2070-10-06, Elfis 1ELF16V, 1ELF16VY-4 and Filtana TS 800 1006. Fig. 5 and 6 shows the result obtained by the simulations on simple models of the EMI filters.

After the analysis of the simulated and optimized data, the suggest measuring system with the 1 Ω/100 Ω was designed and produced. There were produced two impedance pairs for different frequency bands. The first transformer pair was produced as a toroidal one on the iron-powdery core RIK 20. The frequency range of that pair was from 250 kHz up to 380 kHz. The second transformer pair was based on the Mini-Circuits wide band frequency transformer T16-1 with the accurate impedance ration. The operational frequency range of that pair was from 1 kHz up to 40 MHz. The deviation of module of the transformed impedance was in the 10 % toleration limits. The output transformed impedance fluctuated from the 0.9 to 1.1 Ω. If the only pure real output impedance (not imaginary) has been taken in account, the operational frequency range would be narrower. But the information about the output impedance character is not in fact recommended by any standard. But great matched between the insertion loss data which is produced by the EMI filters' manufactures in comparison to own taken data in the 50 Ω system is great. It is possible to think that the producers of EMI filters use same criteria for their measuring system. More detail about the impedance transformers, their construction and features measurements could be found in [5].

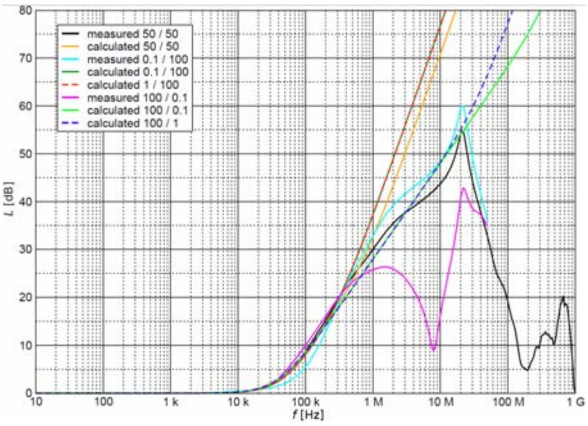

Fig. 5. Insertion loss of the Schurter 5110.1033.1 in asymmetrical systems.

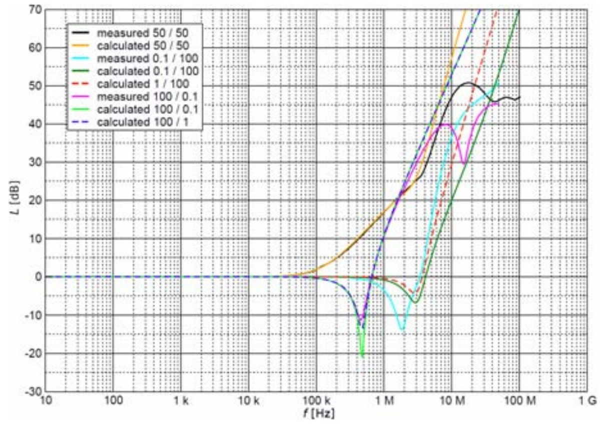

Fig. 6. Insertion loss of the Schurter 5110.1033.1 in symmetrical systems.

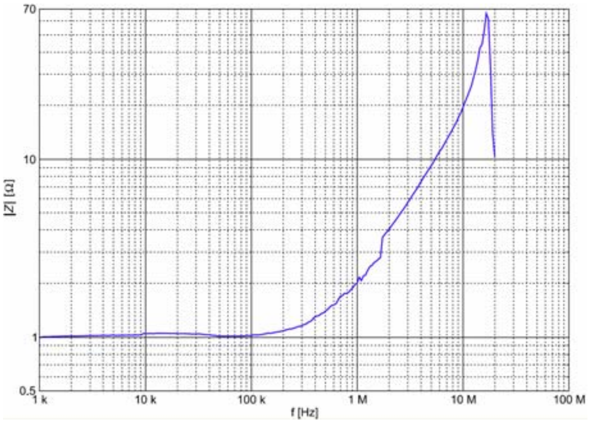

Fig. 7. Performance of the impedance transformer with the impedance ratio 1 Ω/50 Ω

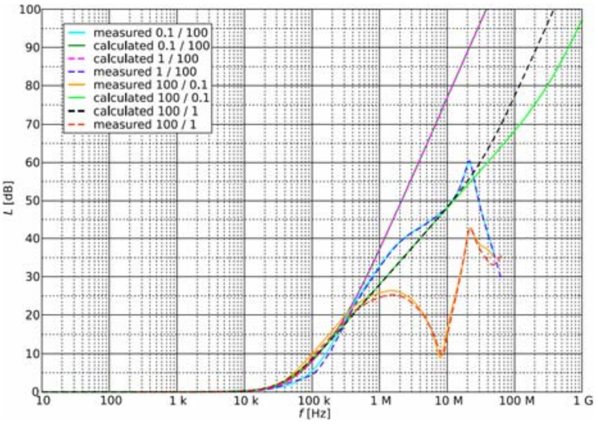

Fig. 8. Comparison of insertion loss performance of the Schurter 5110.1033.1 in asymmetrical systems.

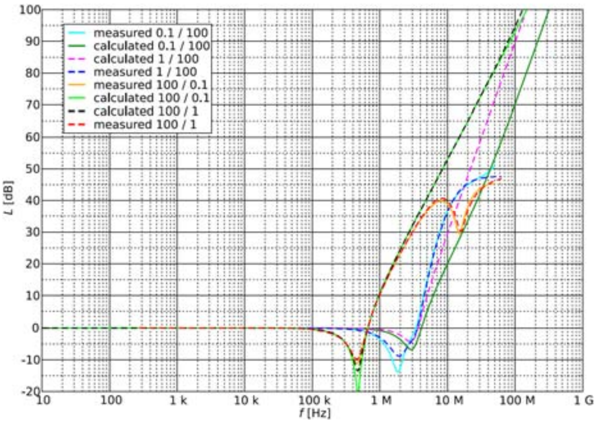

Fig. 9. Comparison of insertion loss performance of the Schurter 5110.1033.1 in symmetrical systems

The performance of the impedance transformer form 50 Ω to 1 Ω is depicted in the Fig. 7. It was necessary to use two different types of impedance transformers for the covering the frequency range from 1 kHz up to 60 MHz. The magnitude of the transformed impedance was taken for the determining of the frequency range of each transformer.

The performance of the alternative measuring system was also checked by measurements of real EMI filters. The measuring system consisted from the newly provided 1 Ω/50 Ω transformers. The seven above mentioned filters were taken under the testing in this new measuring system. The comparison of performance of the Schurter 5110.1033.1 and Elfis 1ELF16V in the asymmetrical and symmetrical system is depicted in the Fig. 8 nad Fig. 9 respectively.

Fig. 8 and 9 show really great correspondence between the 0.1 Ω/100 Ω (100 Ω/0.1 Ω) and 1 Ω/100 Ω (100 Ω/1 Ω) measured data. The maximal differences are more or less in the range 2 dB. This error values could be covered in the total error of whole measurement setup, which is typically around 4 dB for most of EMC measurements and test. The fabrication of the 50 Ω to 1 Ω transformer is easier and also the frequency range of these transformers is wider, in addition. Only to different types of transformers were necessary for covering the frequency range from 250 Hz to 40 MHz. But for the same frequency measuring range was necessary to use 3 different types of impedance transformers. The advantage of the proposed setup is in the significant reduction of the number of used transformers. This reduction will also shorten the measuring time. The final data has to be linked from two resp. three different measurement setups. The measurement itself has to also for each transformers couple reconnected which significantly increase essential measuring time.

IV. CONCLUSION

The error of the alternative worst-case test method for EMI filters was firstly confronted with the approximate test method by the performance of the simple EMI filter models. After that the impedance transformers with the different impedance ratio 1 Ω/50 Ω were prefabricated. There were carried out two types of them for two different frequency ranges. Both types were also produced in two samples for better measuring of their own insertion loss characteristics and also for the transformational impedance ratio measurements. For the EMI filters measurements were chosen the transformer with the better features and with the more stable output transformed impedance. More details and also more measurements are possible to find out in [5]. The performance of proposed measuring system with 1 Ω/100 Ω or vice versa system is very good in comparison with the standardized approximate system performance. The absolute inaccuracy of the alternative test method is under 2 dB in measured frequency range up to 40 MHz. This error is not higher than the typical error or uncertainty of the electromagnetic compatibility measurements. According to the data measured on the 7th different EMI filters is possible to recommended the alternative test setup for the testing the worst-case performance of the EMI filters. This proposed setup also securely identified the negative behaviour of the EMI filter also identify the potential insertion loss oscillations. It is also possible to advice this method for the "worst-case" EMI filter testing. Their advantage is in the simpler construction and design of the impedance transformers, which operate in the wider frequency range. The measurement itself are faster, because there is not necessary to change several pairs of the impedance transformer for the cover of the frequency range from the

10 kHz up to 30 MHz as is usually recommended by international standards.

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