Estimation of EMI Filter Performance for the "Worst-Case" System

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Abstract. *This paper deals with the performance problem of the EMC filters. The core of this problem in EMC filter is the uncertainty of impedances that are connected to the input and output of a filter. In addition, an estimation technique is presented that gives approximate insertion loss of the filter. The performance of this technique was tested on several filters and the data obtained were checked by insertion loss measurement. The heart of the matter is based on the L-C equivalent circuits, which are described by Y parameters. The estimation gives pretty good results for the 0.1 Ω/100 Ω and vice-versa systems and also for other systems.*

Also discussed are system configurations with the Δ (delta) and (Y) star topologies of terminating impedances which better approximate the real situation on the input and output terminals of filter.

Keywords

EMI mains filter, insertion loss, impedance termination, supply network impedance, the worst-case EMC filter insertion loss.

1.Introduction

The EMC or power line EMI filters are one of the most often used tools for the suppression of electromagnetic interference (EMI) which can be found in the power supply network. The aim of EMI filters is to increase the immunity of electronic equipment operated on power line inputs and simultaneously decrease the level of HF emission supplied by the equipment into outer power network.

RF attenuation is a basic and important parameter of EMI filters. Its value depends on the source- and load-side terminating impedances of the filter, characteristics of noise sources, etc. In contrast to communication networks, in power circuits (i.e. mains network) these two quantities are not normally known or entirely specified. This can lead to problems with the prediction of the insertion loss, specifying EMI filters and also with the comparison of several EMI filters from different producers.

The performance of EMI filters depends on the type of the noise which is undesirable. In the EMI filter area, two main types of modes are used, in which the insertion loss of filters is measured. The fist one is known as the common mode (asymmetrical) [1] and the second one is the differential mode (symmetrical) [1]. These two modes could be defined between two wires/terminals. The specification of these modes is shown in Fig. 1. For the purpose of this article the term the "non-symmetrical" is defined. The authors know this is nonsense and that this term has the same meaning as the term asymmetrical, but it is necessary to mark two modes off [2]. The problem is that common EMI filters have three clamps (Live, Neutral and Earth) (Fig.1). The difference in the insertion loss between them is clear from Fig. 2. Each line represents a measurement of the insertion loss in agreement with the Czech technical standard [2]. This standard is in agreement with CISPR 17 international standard.

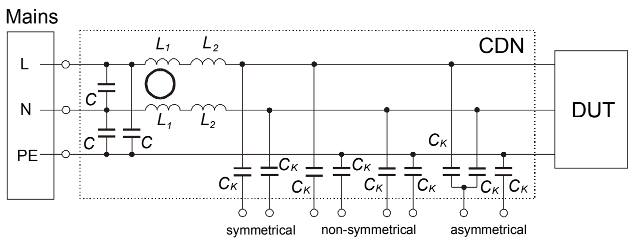

Fig. 1. Coupling-Decoupling Network with the inputs for the asymmetrical, the symmetrical and the "non-symmetrical" configuration of clamps (DUT - device under test; CDN – coupling-decoupling network).

For measuring, the input and output terminals of filters are terminated by 50 Ω. The last two lines in Fig. 2 were taken from data sheets of filter producers and they were added here for comparison.

Basically there are several separate problems, the first with terminating impedances, the second with the configuration of terminating impedances at the input and output side of a filter, etc. The probability of their combination is very high and it can lead to a rapid degradation of the insertion loss of EMI filters.

2.Impedance and Termination Problems

The choice of an accurate EMC filter is complicated by the uncertainty of input and output terminating impedances which are connected to the filter, by the characteristics of noise (common mode, differential mode, etc.) and by the configuration of filters terminals. At the input side of the filter the supply network is usually connected. This impedance is really variable through the frequency range. In addition, the supply network impedance depends on the current loading, on the place of connection (a city, a countryside, etc.) and on the type of the supply network (industrial distribution network, cable earth distribution network, outdoor distribution network, etc.). The differences in the impedance of several types of network are depicted in Fig. 3 [1] and [3]. The impedance characteristics are depicted in Fig. 4 [4]. The data in Fig. 4 were obtained as lots of averaged measurement data.

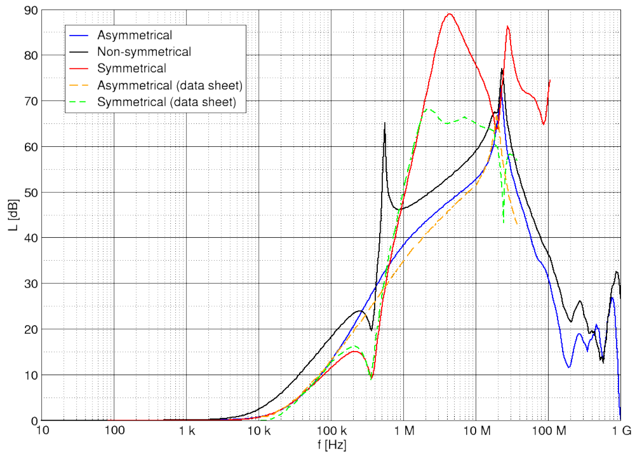

Fig. 2. Schaffner FN 2020-16-06 insertion loss, different modes (asymmetrical, “non-symmetrical”, symmetrical).

At the “load side” of the EMC filter, the RF characteristic impedance of the mains lead to the equipment is around 150 Ω, the impedance of the AC-DC converter circuitry looks like a short-circuit when the rectifiers are turned on and like an open-circuit at all other times. So, the impedance on the output side of the EMI filter is nearly the same (i.e. variable and uncertain), as on its power line input.

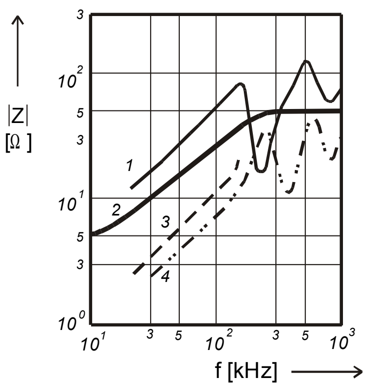

Fig. 3. Impedance of the supply network, [1]and [3]: 1 outdoor distribution network, 2 CISPR standard, 3 industrial distribution network, 4 cable earth distribution network.

The basic configuration of an EMI filter connection is depicted in Fig. 5, where Z_S denotes the source impedance and Z_L denotes the load impedance of the filter [1], [3], [5] and [6].

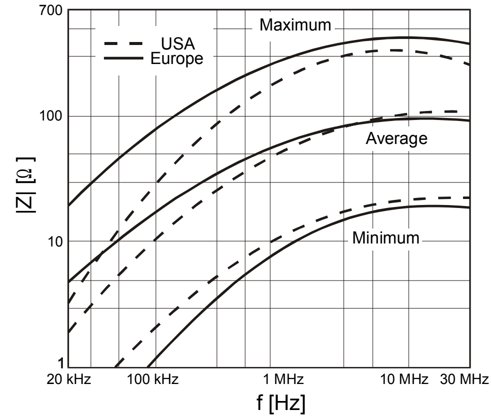

Fig. 4. Impedance of American and European distribution networks [4].

The insertion loss L [dB] is defined as the ratio of the voltage U_{20} across the circuit load without the filter to the voltage U_2 across the filter. The insertion loss could be computed by using the cascade parameters

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

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 cascade matrix **[A]**; Z_S [Ω] and Z_L [Ω] are the source and the load termination impedances.

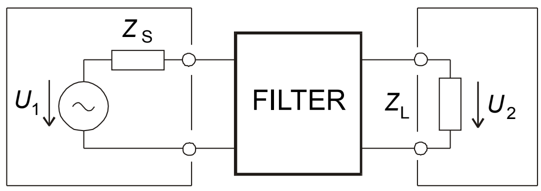

Fig. 5. Basic EMI filter setup.

2.1Configuration of Terminating Impedances

In Fig. 5, the filter is depicted as a four-pole circuit. However, the EMI filter is in fact a six-pole circuit as, mentioned in the Introduction. This feature leads to several different noise signals, whose sources could be connected to the circuit according to Fig. 1. From Fig. 1 and 5 a general scheme shown in Fig. 6 could be made. These two cases represent all the systems mentioned above (asymmetrical, symmetrical and also “non-symmetrical”). The probability that the EMI filter will end in these circuits is in reality very high.

The two circuits shown in Fig. 6 a) and b) could be transfigured by the following equations: for the direction from Δ→Y

$$R_{11} = \frac{R'_{11} R'_{12}}{R'_{11} + R'_{12} + R'_{13}}$$
$$R_{12} = \frac{R'_{12} R'_{13}}{R'_{11} + R'_{12} + R'_{13}} \qquad (2)$$
$$R_{13} = \frac{R'_{11} R'_{13}}{R'_{11} + R'_{12} + R'_{13}}$$

and for the opposite direction, from Y→Δ

$$R'_{11} = R_{11} + R_{13} + \frac{R_{11} R_{13}}{R_{12}}$$
$$R'_{12} = R_{11} + R_{12} + \frac{R_{11} R_{12}}{R_{13}} \qquad (3)$$
$$R'_{13} = R_{12} + R_{13} + \frac{R_{12} R_{13}}{R_{11}}$$

where the meaning of the variables is obvious from Fig. 6. This process is very often called the Δ–Y ("triangle-star") transfiguration.

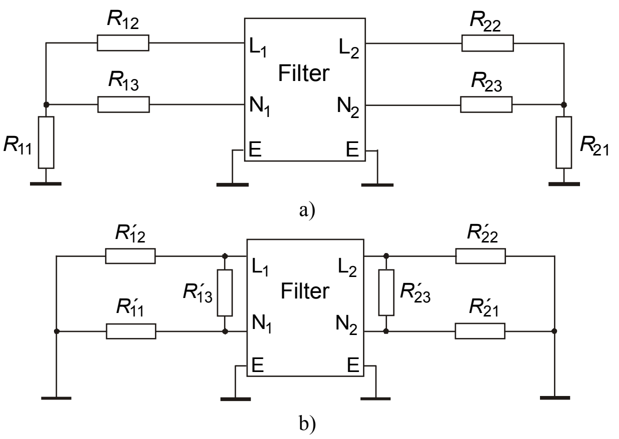

Fig. 6. Measurement and test setup with Y a) and Δ b) termination.

After replacing resistors R_{12}, R_{13}, R_{22} and R_{23} by short circuits, the classical common (asymmetrical) mode setup could be obtained. The insertion loss of EMI filter in this mode could be computed by using small signal admittance parameters Y

$$L\,[dB] = 20 \cdot \log \left| \frac{Y_{12}}{Y_S + Y_L} - \frac{Y_{11} \cdot Y_L}{Y_{21} \cdot (Y_S + Y_L)} - \frac{Y_{22} \cdot Y_S}{Y_{21} \cdot (Y_S + Y_L)} - \frac{Y_{11} \cdot Y_{22}}{Y_{21} \cdot (Y_S + Y_L)} - \frac{Y_S \cdot Y_L}{Y_{21} \cdot (Y_S + Y_L)} \right| \qquad (4)$$

where Y_S [Ω^{-1}] is the admittance connected between the input terminals, Y_L [Ω^{-1}] is the admittance connected between the output clamps and $\mathbf{Y}_{11}$, $\mathbf{Y}_{12}$, $\mathbf{Y}_{21}$, $\mathbf{Y}_{22}$ [Ω^{-1}] are dependent, complex admittance parameters of the particular EMI filter, i.e. elements of the admittance matrix [**Y**]. The EMI filter was regarded as a four-pole. The insertion loss of the same filter, regarded as a six-pole, could be computed as follows:

$$L\,[dB] = 20 \cdot \log \left| \frac{Y_{13} + Y_{14} + Y_{23} + Y_{24}}{Y_S + Y_L} - \frac{(Y_{11} + Y_{12} + Y_{21} + Y_{22})(Y_{33} + Y_{34} + Y_{43} + Y_{44})}{Y_{31} + Y_{32} + Y_{41} + Y_{42}} - \frac{Y_S Y_L (Y_{11} + Y_{12} + Y_{21} + Y_{22})(Y_{33} + Y_{34} + Y_{43} + Y_{44})}{(Y_S + Y_L)(Y_{31} + Y_{32} + Y_{41} + Y_{42})} \right| \qquad (5)$$

where the variables have the same meaning as in the previous case, but in (5) 16 admittance parameters **Y** were used. The solution of insertion loss of the EMI filter with all resistors (Fig. 6) is very demanding.

The insertion loss computed for several EMI filters (Schaffner [7]: FM 2020-16-06, FN 207010-06, FN 321 1/05, Schurter [8] 5110.1033.1, Filtana [9] TS 800 1006, Elfis [10]: 1ELF16V and 1ELF16VY-4) has been done for the three systems presented (asymmetrical, symmetrical and "non-symmetrical") with both termination setups (a simple one and one with all resistors (see Fig. 6)). The values of resistors were set and chosen from three values (0.1 Ω, 50 Ω and 100 Ω). These three values were chosen because they are most frequently used in EMC setups for measuring the insertion loss of filters. The Modified Nodal Voltage Method was used to obtain the final equation for computing the insertion loss. Computed data were checked by measurement on the filters mentioned above. Examples of data obtained are shown in Fig. 7, 8 and 9 for Schaffner FN 2020-16-06. These figures show the "worst-case" insertion loss which represents the lowest possible insertion loss of the EMI filter. The conditions in which the "worst-case" was achieved are mentioned below the figures. The "worst-cases" were achieved for the terminating configuration according to Fig. 6. The abbreviation L1 - L2 in the "non-symmetrical" mode means that the measurement was done between the "Live" terminals. "Neutral" terminals were ended by the 50 Ω.

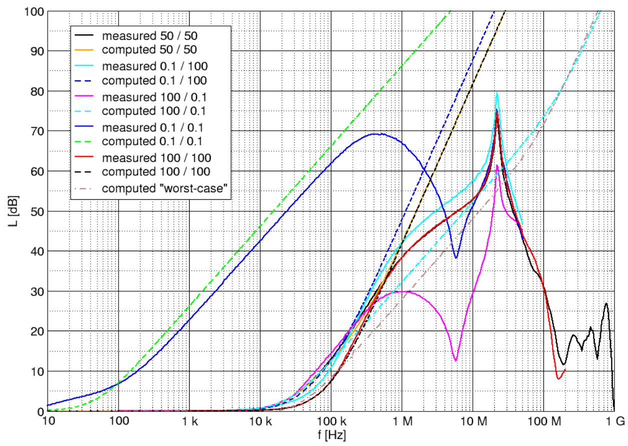

Fig. 7. Schaffner FN 2020-16-06 insertion loss, the asymmetrical mode. The "worst-case" was achieved with the following configuration of resistors in Y topology: R_{21} and R_{23} = 0.1 Ω, R_{11}, R_{12}, R_{13} and R_{22} = 100 Ω, the numbers within the figures mean the values of input and output terminating impedances.

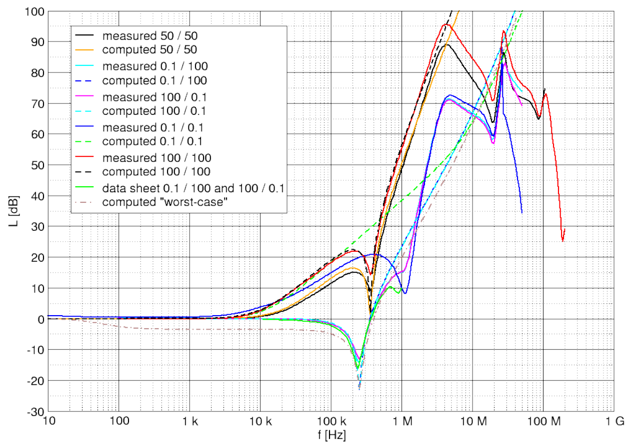

Fig. 8. Schaffner FN 2020-16-06 insertion loss, the symmetrical mode. The “worst-case” was achieved with the following configuration of resistors in Δ topology: R'_{12}, R'_{21} and R'_{23} = 0.1 Ω, R'_{11}, R'_{13} and R'_{22} = 100 Ω.

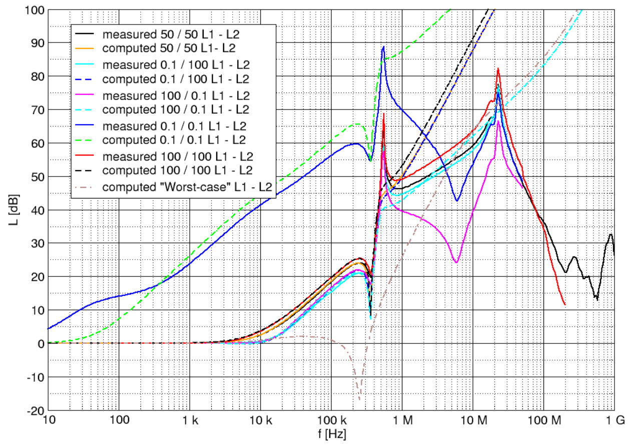

Fig. 9. Schaffner FN 2020-16-06 insertion loss, the “non-symmetrical” mode. The “worst-case” was achieved with the following configuration of resistors in Δ topology: R'_{13} and R'_{21} = 0.1 Ω, R'_{11}, R'_{12}, R'_{22} and R'_{23} = 100 Ω.

The measured and computed data depicted in Fig. 7, 8 and 9 fit very well up to 1 MHz. However, from a frequency of 1 MHz, spurious capacities reduce the insertion loss of the filter. The rate of degradation depends on the values of terminating impedances used as shown in Fig. 7, 8 and 9.

3.Setup of Estimation Method

The following estimation method can be derived from the previous section, where the Modified Nodal Voltage Method was used. This method is based on the simplification of the original circuit of the EMI filter. From the original circuit it is possible to get a very simple circuit which is shown in Fig. 10 together with the scheme of EMI filter. The equivalent circuit is made up only a coil and a capacitor. Fig 10a and 10b represent the setup for the asymmetrical mode.

The computation of the values of the electrical parts of the L-C equivalent circuit could be done using the following equations

$$L_A = \frac{(1+k)\cdot L_F}{2\cdot N_L} \qquad (5)$$

$$C_A = N_Y \cdot C_Y \qquad (6)$$

where N_L is the number of the current-compensated inductors, k is the coupling coefficient, N_Y is the number of Y-type capacitors, and the meaning of other symbols is clear from Fig. 10. The capacities C_X (Fig. 10a) are shorted by the asymmetrical setup. These capacities do not influence the insertion loss. The position of capacity C_A has to correspond with the position of capacity C_Y.

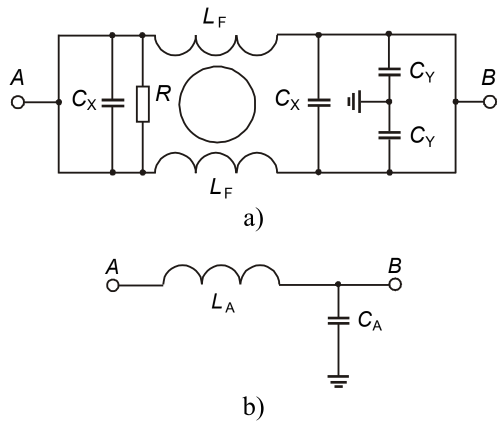

Fig. 10. Schaffner FN 2020-16-06 a) electric circuit scheme for the asymmetrical mode; b) L-C equivalent circuit.

In Fig. 11, the insertion loss characteristics of the L-C equivalent circuit and the EMI filter are shown. High accuracy of estimated insertion loss was achieved. The error is less than 10^{-6} dB.

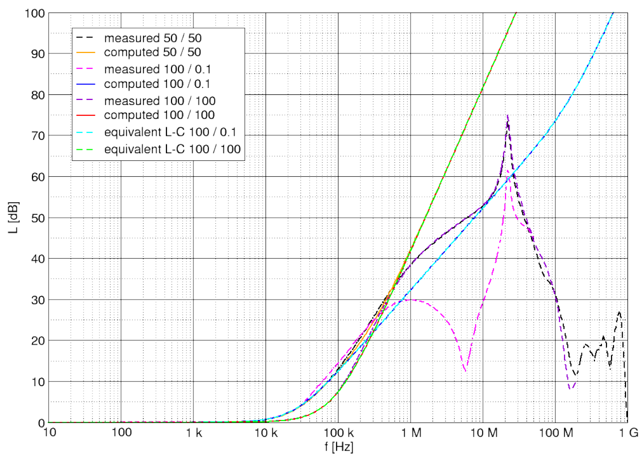

Fig. 11. Schaffner FN 2020-16-06 insertion loss, the asymmetrical mode; estimation of the “worst-case” by L-C equivalent circuit.

For performance estimation in the symmetrical mode it is necessary to make a special equivalent circuit. Its circuit scheme is shown in Fig. 12b. An example of the symmetrical setup with EMI filter Schaffner FN 2020-16-06 is depicted in Fig. 12a. In addition it is necessary to modify the equations for computing the circuit parameters. Equations (5) and (6) could not be used, they have to be modified:

$$L_S = 2 \cdot (1 - k) \cdot L_F \quad (7)$$

$$C_{S1} = N_{\text{Xinput}} \cdot C_X + \frac{N_{\text{Yinput}} \cdot C_Y}{4} \quad (8)$$

$$C_{S2} = N_{\text{Xoutput}} \cdot C_X + \frac{N_{\text{Youtput}} \cdot C_Y}{4} \quad (9)$$

where N_{Xinput} and N_{Xoutput} are the numbers of X-type capacitors at the input and the output of the EMI filter, N_{Yinput} and N_{Youtput} are the numbers of Y-type capacitors at the input and the output, respectively; the meaning of the other symbols are obvious from Fig. 12.

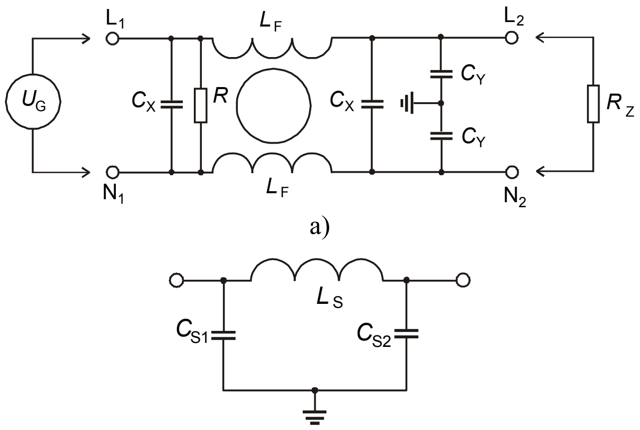

Fig. 12. Schaffner FN 2020-16-06 a) electric circuit scheme for the symmetrical mode; b) L-C equivalent circuit.

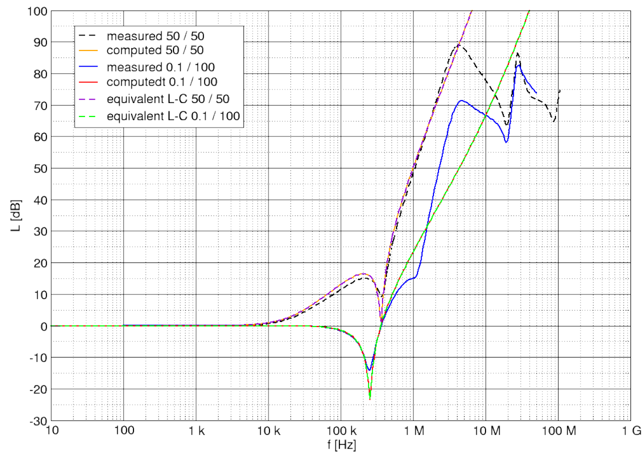

Fig. 13. Schaffner FN 2020-16-06 insertion loss, the symmetrical mode; estimation of the "worst-case" by L-C equivalent circuit.

The accuracy of estimated insertion loss fits very well with the data computed. The error of estimated line is less than 0.1 dB, as is shown in Fig. 13. However, it is difficult to specify the L-C equivalent circuit for the "non-symmetrical" mode. The setup of the "non-symmetrical" mode is shown in Fig. 14a, the L-C equivalent circuit is shown in Fig. 14b and is really very similar to the original one. In this case, computing the L-C circuit parameters does not take place, because the values of circuit parts are the same as in the original EMI filter scheme. Fig. 15 shows a comparison between computed and estimated data of the EMI filter. The accuracy of estimated data is low, but the estimate of the values of terminating impedances in which the lowest insertion loss of filter could be expected.

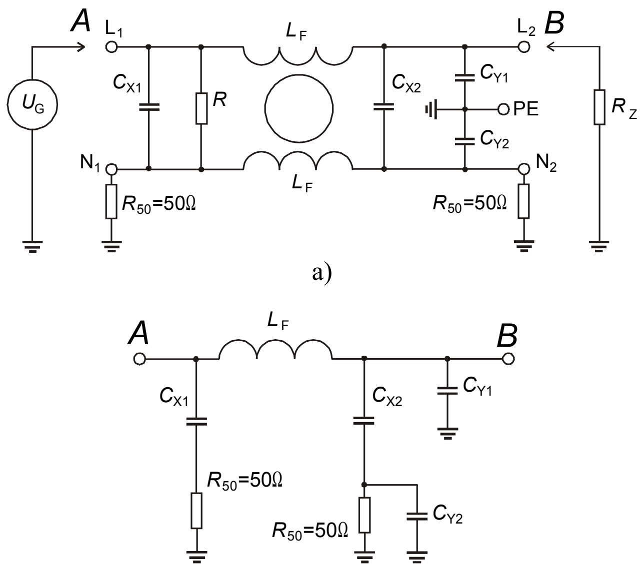

Fig. 14. Schaffner FN 2020-16-06 a) electric circuit scheme for the "non-symmetrical" mode; b) L-C equivalent circuit.

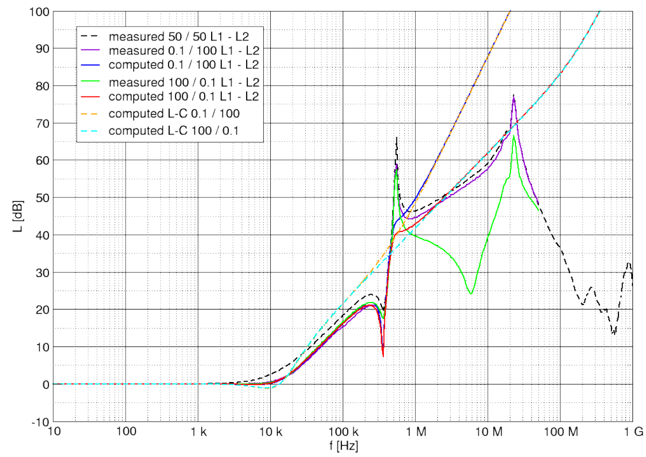

Fig. 15. Schaffner FN 2020-16-06 insertion loss, the "non-symmetrical" mode; estimation of the "worst-case" by L-C equivalent circuit.

4.Conclusion

The techniques presented were tested on several EMI filters. The estimated lines for common (asymmetrical) and different (symmetrical) modes show the high accuracy of this simple method. A similar L-C equivalent circuit could be used for a great number of single-stage EMI filters. The computation of insertion loss of the L-C equivalent circuits is based on Modified Nodal Voltage Method. These single-stage filters have similar Y parameters. Matrix **Y** has a 2×2 dimension. These facts contribute to the simplicity of the method presented. This means in fact that for different single-stage filters it is necessary to use two different L-C equivalent circuits and to derive two equations for direct insertion loss computation. After that it is simple to insert these equations parameters of L-C circuits for the asymmetrical and the symmetrical modes and easy to compare different EMI filters of different terminating impedances.

The estimation performance in the “non-symmetrical” mode does not reach such good results as the previous two techniques. However, this setup could be used for the prediction of the values of terminating impedances. The “non-symmetrical” test setup is not so common either. Filter producers do not give the insertion loss in this mode. The fact that the estimation technique based on L-C equivalent circuits does not work properly does not matter in this case because the aim was to present a simple and fast technique for easy comparison of the EMI filters and to discover the “worst-case termination setup.

Acknowledgements

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References

[1] HABIGER, E. *Elektromagnetische Verträglichkeit.* Hüthig Buch Verlag, Heidelberg 1992. 200 pages. ISBN 3-7785-2092-X

[2] ČSN CISPR 17: *Methods of Measurement of the Suppression Characteristics of Passive Radio Interference Filters and Suppression Components*. Czech Technical Standard. Czech Normalization institute. Prague November 2000 (in Czech)

[3] SVAČINA, J., *Electromagnetic Compatibility, Principles and Methods.* Brno University of Technology 2001. “Join to European Union”.Volume 2, 156 pages. IBSN 80-214-1873-7

[4] MALACK, J. A., ENGSTROM, J., R. RF Impedance of United States and European Power Lines. *IEEE Transactions on Electromagnetic Compatibility.* 1976, vol. EMC-18, no. 1, p 36-38.

[5] SVAČINA, J., DŘÍNOVSKÝ, J. Approximative Estimation of EMI Mains Filters Properties in the "Worst-Case" System Operation. *Acta Electrotechnica et Informatica*, 2005, vol. 5, num. 1, p. 13-17. ISSN 1335-8243

[6] SCHLICKE, H. M. Assuredly Effective Filters. *IEEE Transactions on Electromagnetic Compatibility.* 1976, vol. EMC-18, no. 3, p 106-110. ISSN 0018-9375

[7] Schaffner Holding AG, Switzerland. http://www.schaffner.com/

[8] Schurter AG, Switzerland. http://www.schurter.com/

[9] FILTANA, Ltd., *EMI Filters for AC Voltage 250V/50Hz 811 Series (data sheet)*. Polná, Czech Republic

[10] ELFIS Ltd., Czech Republic. http://www.elfis.cz/

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