Insertion Loss and Network Parameters in the Analysis of Power Filters

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***Abstract* - The *insertion loss* (*IL*) is regarded as the best interference suppression characteristic of power filters or suppression components. The *IL* definitions are considered and as an alternative the paper suggests the use of network parameters. It is a known fact that the standard *IL* measurements do not provide reliable information about the operational performance of a suppressor. This is largely due to the source and load mismatch, which is typical in power lines. Arguments are presented, showing that network parameters allow for more complete and reliable characterization of power filters and components. The *IL* would not be abandoned, because the network parameters provide enough information to obtain not only the standard *IL*, but also the *IL* in a non 50 Ω system. A new treatment of "worst case" or minimum *IL* is proposed, which is also based on network parameters. Furthermore, input, output, or transfer impedances, simulation models, and other characteristics, can be obtained from the network parameters, but not from the currently published standard *IL* data.**

***Index Terms* - Electromagnetic interference, interference suppression, power filters, scattering parameters.**

I. Introduction

THE *insertion loss* (*IL*) is used as a measure of the interference suppression capability of passive power filters and components. Sometimes the *IL* is confused with voltage attenuation, which could be in part due to the different definitions in the technical literature. To avoid ambiguity the following Section II considers those definitions. In Section III the equations for *IL* in terms of two-port network parameters are listed. These include chain, impedance, and scattering parameters, which we find most useful. If needed, similar *IL* equations in terms of admittance, or hybrid h- and g-parameters, can be derived easily.

There are also different ideas of "worst case" *IL*. Some think of it as the *IL* measurements in 0.1 Ω/100 Ω and the reverse system. Others understand it as the theoretical minimum *IL* provided by the filter or component. In Section IV we suggest the minimum *IL* to be the lower of the two chain parameters: c_{11} and c_{22}. In theory, the *IL* can be even less than that, but that can happen in very rare cases, which require special attention and more careful analysis.

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Section V discusses the arguments in favor of publishing the filters network parameters, instead of standard *IL* only. There are also the measurements supporting those arguments.

The conclusions are summarized in Section VI.

II. Insertion Loss Definitions

A. Classical Definition

The *IL* is defined in [1] as the ratio, in dB, of two powers in accordance with the following equation:

$$IL = 10 \cdot \lg \frac{P_{20}}{P_2}\text{, dB} \tag{1}$$

where P_{20} is the power delivered to the load impedance Z_L, which is the input impedance of the measurement instrument's receiver, connected to the signal generator as in Fig. 1*a* and P_2 is the power delivered to the same impedance by the same generator, but with a filter inserted between them, as shown in Fig. 1*b*. In the figure, V_1 and V_2 are respectively the input and output voltages of the filter. Similarly, I_1 and I_2 denote the input and output current. For the definition of *IL* the direction of the output current I_2 is irrelevant, but it matters in the definitions of network parameters. Sometimes in the literature the direction of I_2 is reversed, but in the more general case of n-port networks, it is more sensible to uniformly define a port current as flowing into the port. In the reference measurement, Fig. 1*a*, ideally $V_{10} = V_{20}$ and $I_{10} = -I_{20}$.

In the oldest source [2] known to us, the *IL* is defined as the *insertion ratio* (*IR*) in dB:

$$IR = \left|\frac{V_{20}}{V_2}\right| = \left|\frac{I_{20}}{I_2}\right| \quad \Rightarrow \quad IL = 20 \cdot \lg \left|\frac{V_{20}}{V_2}\right| = 20 \cdot \lg \left|\frac{I_{20}}{I_2}\right| \tag{2}$$

It is easy to show that definitions (1) and (2) are equivalent:

$$IL = 10 \cdot \lg \frac{P_{20}}{P_2} = 10 \cdot \lg \frac{V_{20}^2 \operatorname{Re}\{Y_L\}}{V_2^2 \operatorname{Re}\{Y_L\}} = 20 \cdot \lg \left|\frac{V_{20}}{V_2}\right| \tag{3}$$

and similarly:

$$IL = 10 \cdot \lg \frac{P_{20}}{P_2} = 10 \cdot \lg \frac{I_{20}^2 \operatorname{Re}\{Z_L\}}{I_2^2 \operatorname{Re}\{Z_L\}} = 20 \cdot \lg \left|\frac{I_{20}}{I_2}\right| \tag{4}$$

Notice that the requirement in the classical definition of *IL* is that the source impedance Z_s and load impedance Z_L are same in both measurements - with and without the filter. Z_s and Z_L do not have to be resistive, equal to each other, or constant.

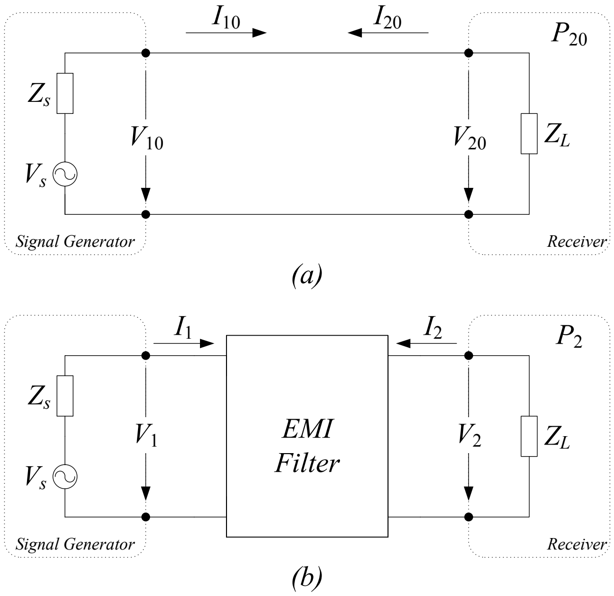

Fig. 1. Insertion loss definition: *a*) reference measurement (filter replaced by short circuit), *b*) measurement with the filter inserted.

B. CISPR 17 Definitions

The international CISPR 17 standard [3] requires that the source and load impedances are equal to the reference impedance $Z_0 = 50\ \Omega$. When $Z_s = Z_L$ the load voltage $V_{20} = V_s/2$ and (3) becomes:

$$IL = 20 \cdot \lg\left|\frac{V_s}{2V_2}\right| \tag{5}$$

which is the IL equation given in the standard [3].

According to CISPR 17, the IL is measured both with and without load current, in three different test circuits: asymmetrical (common-mode), shown in Fig. 2*a*; symmetrical (differential-mode), shown in Fig. 2*b*; and unsymmetrical test circuit, which is shown in Fig. 2*c*. In the last test circuit all lines that are not connected to the ports of the measuring instrument, must be terminated to ground reference through impedances, equal to the reference impedance Z_0, which is specified to be 50 Ω.

Probably the primary concern of CISPR 17 is the reliability and repeatability of the measurements. This could be why the standard emphasizes that the source and load impedances must be equal to the reference impedance and defines the IL by (5), which is a special case of the classical definition (1). Indeed, whenever $Z_s \neq Z_L$, (5) does not yield IL.

CISPR 17 also gives instructions for IL measurements in non 50 Ω systems. These are not mandatory and should be done in the frequency range from 1 kHz to 300 kHz with 0.1 Ω/100 Ω source/load impedances as well as in the reverse system. The impedance transformation can be achieved with two wideband transformers connected as shown in Fig. 3. The standard suggests turns ratio of 1.4:1 to get the 100 Ω, and 22:1 to obtain 0.1 Ω impedance, seen by the filter when both the generator and the receiver have 50 Ω impedance. These turns ratios are obviously calculated from:

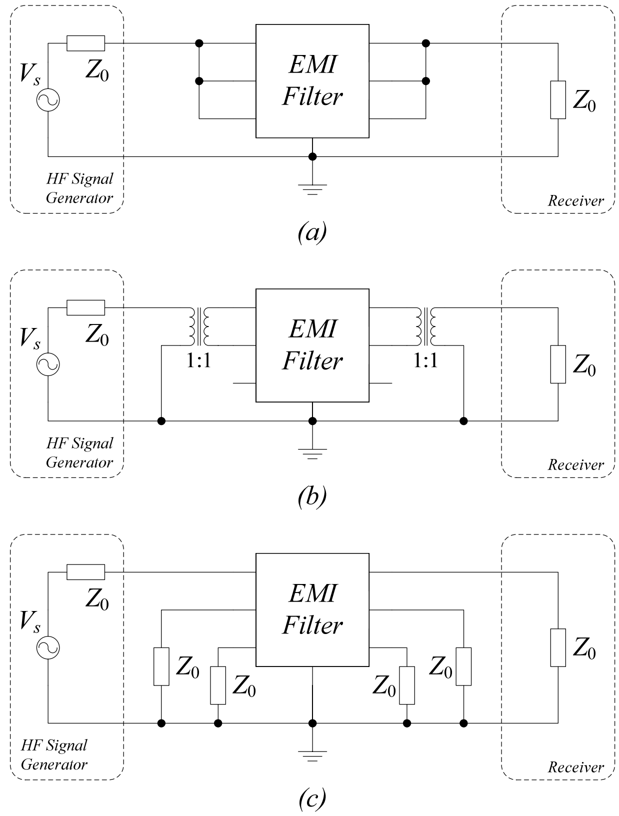

Fig. 2. Matched system insertion loss measurement test circuits: *a*) asymmetrical (common-mode), *b*) symmetrical (differential-mode), *c*) unsymmetrical.

$$n = \sqrt{\frac{Z}{Z_0}} \tag{6}$$

where Z is the desired Z_s or Z_L, seen from the input or output port of the filter, and $Z_0 = 50\ \Omega$ is the measurement system impedance. In theory, (6) is correct, but in practice the resulting impedances are far from the target values, as it will be shown later. Then it is not clear whether engineers should

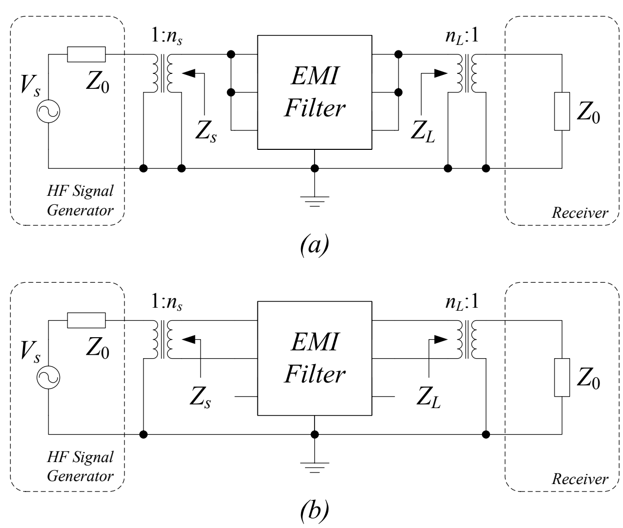

Fig. 3. Test circuits for measuring insertion loss in non 50 Ω systems: *a*) common-mode, *b*) differential-mode.

adjust the turns ratio, to get closer to the 0.1 Ω/100 Ω target, or keep the turns ratio constant. In either case, the mismatched *IL* of a filter, measured with one pair of wideband transformers, would not match that measured with another pair of transformers.

C. Other Definitions

There can be also other definitions of *IL* in different standards and publications, e.g. [4], but it is doubtful that they can reveal some hidden qualities, or improve the characterization of *electromagnetic interference* (EMI) filters or components.

III. Insertion Loss in Terms of Two-Port Network Parameters

By definition the concept of *IL* is applicable to two-port networks, and therefore, it can be expressed in terms of two-port network parameters. A derivation of the following expression for *IL* in terms of chain c-parameters (often called ABCD-parameters) can be seen in [5]:

$$IL = 20\cdot\lg\left|\frac{c_{11}Z_L + c_{22}Z_s + c_{12} + c_{21}Z_sZ_L}{Z_s + Z_L}\right| \tag{7}$$

where c_{11}, c_{12}, c_{21}, and c_{22} are the c-parameters of a linear two-port network, defined as:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}\begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \tag{8}$$

with port voltages and currents as defined in Fig. 1*b*.

In a similar manner, equations for the *IL* in terms of other port parameters can be derived. The *IR* in terms of z- and c-parameters have been published in [1], but referred to as *IL*, which apparently confuses the *IR* and *IL* in (2). The *IL* in terms of z-parameters is:

$$IL = 20\cdot\lg\left|\frac{(Z_s + z_{11})(Z_L + z_{22}) - z_{12}z_{21}}{(Z_s + Z_L)z_{21}}\right| \tag{9}$$

where z_{11}, z_{12}, z_{21}, and z_{22} are the impedance z-parameters of a linear two-port network, defined as:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{10}$$

If needed the *IL* can be expressed in terms of other network parameters by using the conversion tables found in the related literature, e.g. in [6].

The easiest and most accurate way to measure two port parameters nowadays is via the scattering s-parameters, which are measured with *vector network analyzer* (VNA) and are defined as:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{11}$$

where s_{11}, s_{12}, s_{21}, and s_{22} are the scattering s-parameters of a linear two-port network; the a_1 and a_2 are incident, and b_1, b_2 reflected power waves. The equation for *IL* in terms of s-parameters has also been published [7]:

$$IL = 20\cdot\lg\left|\frac{(1-\rho_s s_{11})(1-\rho_L s_{22}) - \rho_s\rho_L s_{12}s_{21}}{(1-\rho_s\rho_L)s_{21}}\right| \tag{12}$$

where ρ_s and ρ_L are the source and load reflection coefficients, defined as:

$$\rho_s = \frac{Z_s - Z_0}{Z_s + Z_0} \quad \text{and} \quad \rho_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{13}$$

Equation (12) can be derived by using signal flow graphs [6], or the power gain equations [6] and [7].

Equations (7), (9), and (12) relate the *IL* in the sense of the classical definition, to the two-port network parameters, which characterize the filter for a given conduction mode – common-mode or differential mode. In the special case of matched source and load impedances, i.e. when $\rho_s = \rho_L = 0$, (12) simplifies to:

$$IL = -20\cdot\lg|s_{21}| \tag{14}$$

which is the *IL* equation in terms of s-parameters, given in CISPR 17 standard [3].

IV. Minimum Insertion Loss

In [8] the *IL* measurements in 0.1 Ω/100 Ω and the reverse system are called the “approximate worst case”. According to [1] there are different “worst case” insertion losses, which are achieved, at different source and load mismatch cases. In the next Section, it is shown that the “approximate worst case” *IL*, measured according to CISPR 17 guidelines for non 50 Ω systems, is a lot higher than the minimum *IL*. The theoretical minimum *IL* can be found via the chain parameters. Equation (7) can be rewritten in the following form:

$$IL = 20\cdot\lg\left|\frac{c_{11}\dfrac{Z_L}{Z_s} + c_{22} + \dfrac{c_{12}}{Z_s} + c_{21}Z_L}{1 + \dfrac{Z_L}{Z_s}}\right| \tag{15}$$

When $Z_s \to \infty$, i.e. in the case of an ideal current source, it follows from (15) that the *IL* becomes:

$$IL_{cs} = 20\cdot\lg|c_{22} + c_{21}Z_L| = 20\cdot\lg|c_{22}| + 20\cdot\lg\left|1 + \frac{c_{21}Z_L}{c_{22}}\right| \tag{16}$$

From (16), the larger Z_L, the larger the IL_{cs} would be, unless

$$\left(\mathrm{Re}\{Z_L/Z_{2,\infty}\} + 1\right)^2 + \left(\mathrm{Im}\{Z_L/Z_{2,\infty}\}\right)^2 < 1 \tag{17}$$

where $Z_{2,\infty} = c_{22}/c_{21}$ is the open-circuit output impedance. Therefore, the minimum of IL_{cs} is when $Z_L = 0$, i.e. when short-circuiting the output, except in the rare cases when (17) is fulfilled. In most practical cases the minimum of IL_{cs} is:

$$IL_{cs,\min} = 20\cdot\lg|c_{22}| \tag{18}$$

When $Z_s = 0$, i.e. in the case of an ideal voltage source, from (7) it follows that:

$$IL_{vs} = 20\cdot\lg\left|c_{11} + \frac{c_{12}}{Z_L}\right| = 20\cdot\lg|c_{11}| + 20\cdot\lg\left|1 + \frac{c_{12}}{c_{11}Z_L}\right| \tag{19}$$

As long as the following condition is not fulfilled:

$$\left(\mathrm{Re}\{Z_{2,0}/Z_L\} + 1\right)^2 + \left(\mathrm{Im}\{Z_{2,0}/Z_L\}\right)^2 < 1 \tag{20}$$

where $Z_{2,0} = c_{12}/c_{11}$ is the output impedance with shorted input, the minimum IL_{vs} is when $Z_L \rightarrow \infty$, and it is:

$$IL_{vs,\min} = 20 \cdot \lg\left|c_{11}\right| \qquad (21)$$

It can be concluded that in most practical cases, the lover limit for the *IL* curves can be constructed by plotting the smaller of the c_{11} and c_{22} coefficients over the frequency range of interest. However, if conditions (17) and (20) are fulfilled, then even lower *IL* is possible.

V. Measurements and Discussion

Publishing the full set of s-parameters, i.e. both common- and differential-mode, would give customers the most complete, accurate and reliable information about filters and components. The s-parameters can be converted to any other set of network parameters, depending on the need. Using (7), (9), or (12), designers could predict the insertion loss of a filter in any line where it would be inserted, provided they have estimation of the line's impedances. The full set of network parameters can also be utilized to build circuit simulation models of suppression components or filters – another advantage of network parameters over *IL* data.

The standard *IL* data, which are currently published by manufacturers, would not be lost, because according to (14), s_{21}coefficient is the standard *IL* curve with an opposite sign. As an example, the common-mode s-parameters of the filter in Fig. 4 are shown in Fig. 5, where the s_{21} subplot is a mirror image of Fig. 6a, which is the measured standard common-mode *IL* of the same filter.

The standard *IL* measurements do not provide sufficient information to determine the *IL* at mismatched source and load impedances. The latter can be easily calculated, if the four network parameters for a given conduction mode are known. For example, Fig. 6*b* shows the mismatched common-mode *IL* of the same filter (Fig. 4) with s-parameters in Fig. 5, but with Z_s and Z_L as shown in Fig. 7. Equations (7), (9), and (12) are equivalent and any of them would yield the same mismatched *IL* (Fig. 6*b*), for a given set of network parameters, source, and load impedance.

A wideband transformer WBT1.5-1SLB [9] was used to increase the source impedance. With a 1:1.5 turns ratio, one would expect $Z_s \approx 112.5\ \Omega$ according to (6), but the result is very far from that (Fig. 7) although WBT1.5-1SLB has a very wide bandwidth – from 40 kHz to 350 MHz.

WBT16-1SLB, which has a bandwidth from 100 kHz to 100 MHz [9], was used to lower the load impedance. Again

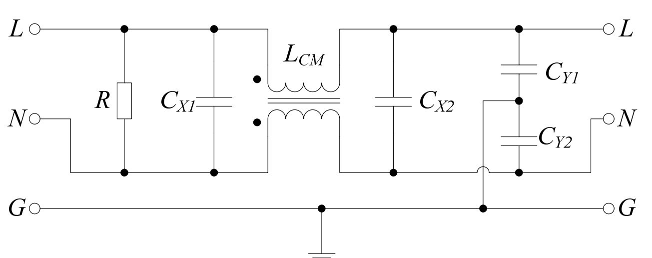

Fig. 4. An example of a single-phase power filter: $R = 1\ \text{M}\Omega$, $C_{X1} = C_{X2} = 100$ nF, $L_{CM} = 1.8$ mH, $C_{Y1} = C_{Y2} = 3.3$ nF.

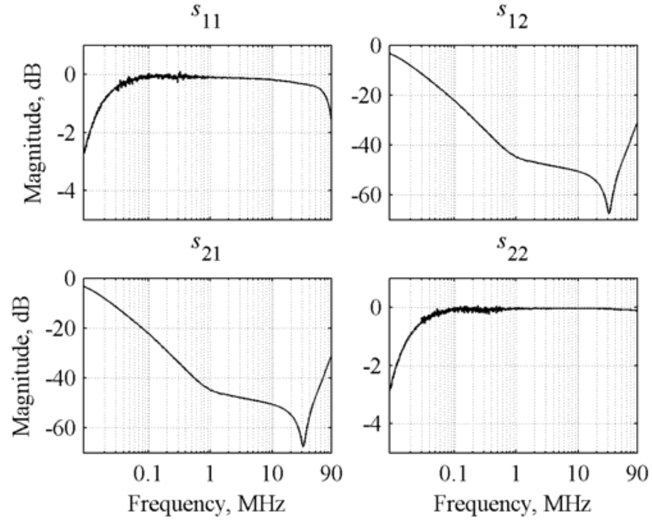

Fig. 5. Common-mode s-parameters of the filter in Fig. 4, measured with VNA. Reference impedance $Z_0 = 50\ \Omega$.

there is a large discrepancy between theoretical and measured impedance. From (6), with turns ratio of 1:16, the load impedance seen from the output of the filter should be $Z_L \approx 0.2\ \Omega$, but it is more than 3 Ω for all frequencies above 50 kHz.

Fig. 6*c* represents the mismatched common-mode *IL* measured as in Fig. 3*a*, with the above mentioned impedance changing transformers. It differs significantly from Fig. 6*b*, which was calculated from the measured standard common-mode s-parameters according to (12).

Obviously, the impedance transformation depends on the characteristics of the transformers. This makes it impossible to have reliable and repeatable mismatched *IL* measurements, which is probably the reason, why these are not mandatory. In contrast, if the network parameter measurements of a filter are reliable and repeatable, one would expect reliable and repeatable mismatched *IL* from (7), (9), or (12). Therefore, the value of *IL* measurements in non 50 Ω systems is

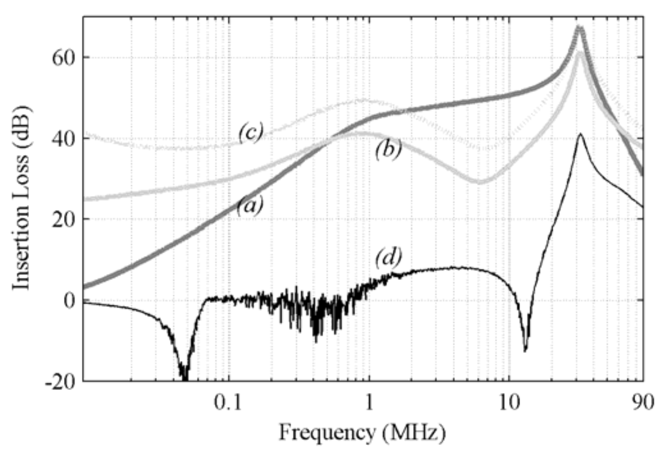

Fig. 6. Common-mode insertion loss of the filter in Fig. 4: *a*) Standard measurement in 50 Ω system. *b*) Calculated from network parameters with Z_s and Z_L as in Fig. 7. *c*) Measured in test circuit Fig. 3*a*, with Z_s and Z_L as shown in Fig. 7. *d*) Minimum *IL*, which is constructed from (21) up to 700 kHz, and (18) for the remaining frequencies up to 90 MHz.

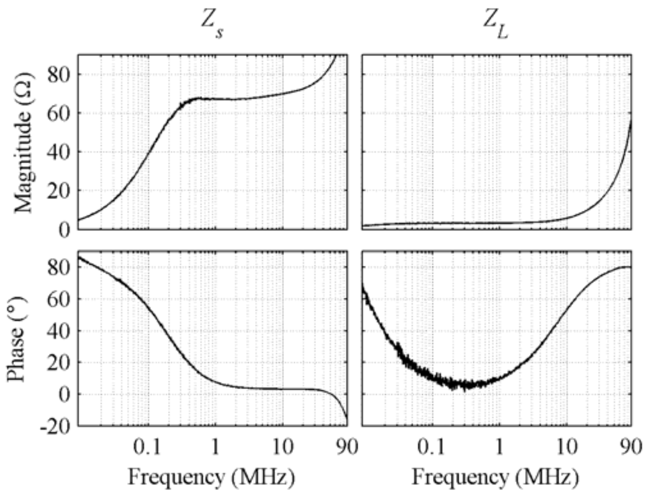

Fig. 7. The source and load impedances seen from the input and output ports of the filter.

questionable. Instead, what is needed is the complete set of network parameters for common- and differential-mode.

It was mentioned earlier that the definition of *IL* is applicable only to two port networks. However, even the simplest single-phase filters are in fact 4-port networks (Fig. 4), a 3-phase filter would be a 6-port network, etc. This necessitates the use of the test circuits, shown in Fig. 2, the realization of which requires some auxiliary networks - connecting wires, balanced-unbalanced transformers (baluns) [7]. These auxiliary networks are not part of the filter itself and affect the measurement results. In other words, they add measurement errors. In this respect network parameters obtained with VNA can have an advantage over *IL* data measured with EMI test receivers due to the following reasons:

1) A VNA uses more sophisticated calibration, which can take into account the connecting wires.

2) If the s-parameters of the auxiliary networks are measured, deembedding [10] can be used to remove the errors due to these networks.

3) The standard n-port s-parameters can be measured in the unsymmetrical test circuit Fig. 2*c* and converted to mixed-mode network parameters [11], which contain the common- and differential-mode s-parameters. Unsymmetrical test circuit measurements do not require auxiliary networks, thus, eliminate the associated measurement errors.

To summarize, the standard *IL* data alone are incomplete and it is impossible to analyze the filter or suppressing component in greater detail. They do not provide enough information to predict the *IL* under mismatched source and load conditions. Furthermore, it is impossible to construct the minimum *IL* curve, to find the input, output, or transfer impedances, or simulate the performance of a component or a filter, if only its *IL* is known.

VI. Conclusion

The classical *IL* definition was compared with the definitions, given in the CISPR 17 standard. The equations for *IL* in terms of network parameters were given as well. Many of the advantages of network parameters were pointed out. Nowadays, any set of network parameters is usually calculated from the measured scattering s-parameters, which are accurate, reliable and repeatable. Therefore, publishing the s-parameters, instead of *IL* data, would provide the necessary information to obtain any set of network parameters that a customer might need. Those used to the standard *IL* would not lose anything, because it is visible from the s-parameters. However, those who need the *IL* in mismatched conditions are currently unable to get it.

It was shown that the CISPR 17 recommended procedures for mismatched *IL* measurements do not produce reliable and repeatable results. With the network parameters, it is possible to obtain the *IL* for arbitrary source and load terminations. Furthermore, the standard *IL* does not give any idea of how the performance of an EMI filter could deteriorate in extreme cases of mismatch, but with network parameters the minimum *IL* can be obtained.

Finally, the input, output, or transfer impedances, simulation models, and other characteristics of the suppressor, can be obtained from the network parameters, but not from the currently published standard *IL* data.

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