Proceedings of the 9th International Zürich Symposium on EMC, 12-14 March 1991, pp. 583-588

DESIGNING POWER-LINE FILTER FOR THEIR WORST-CASE BEHAVIOUR

Frédéric BROYDE, Evelyne CLAVELIER

EXCEM
29, avenue Mary
92500 Rueil Malmaison - France

ABSTRACT

Various additions to the theory of the design and optimization of power-line filters (PLF) are presented. The paper starts with a presentation and discussion of existing worst-case quantities. The concept of impedance domain is then defined and several examples are given, both theoretical and experimental. The paper then defines a new kind of worst-case quantities, called "in a specified impedance domain", which gives a realistic picture of the worst behaviour of a PLF. The paper ends with a presentation of existing methods and new proposals for the measurement of worst-case quantities.

1. INTRODUCTION

In its most general form, the problem of the determination of the worst-case behaviour of a passive linear filters can be stated as: what is the worst performance which can be expected from the filter, when its terminations are not well defined?

As we will restrict ourselves to Power Line Filters (PLF), the worst performance is implicitely in this paper the smaller reduction of amplitude in the stop-band.

The importance of this question when dealing with power-line filters was recognized by Hinton et al [1] in 1966, and these authors also proposed the determination of the minimum voltage attenuation of the filter as a solution. Almost simultaneously, H.M. Schlicke et al [2] proposed an other approach based on the determination of the worst-case insertion loss of the filter. Most subsequent works on the subject were thereafter restricted to these two parameters.

An important step in the history of the treatment of the worst-case behaviour of power-line filter was the introduction of the C.I.S.P.R. 17 standard [3] in 1981, which in addition to the "standard method" according to which filter performances are measured between well defined resistive terminations, offered three different worst-case measurement methods:

- the impedance variation method (to be developped);
- the quasi-analytic method, which required only two separate measurements at each frequency, in order to obtain the minimum voltage attenuation α_{Vmin};
- the approximate methods according to which the filter was to be inserted in a 0.1 Ω/ 100 Ω measurement system and a 100 Ω/ 0.1 Ω measurement system.

Unfortunately, these contributions were essentially ignored by the engineering community, and even by many EMC specialists.

In 1989, the authors felt the need for improved definitions of worst-case quantities [4], and offered a wide range of definitions, together with calculation methods. This paper introduces various improvements to the theory of the worst-case behavior of filters, related to definitions, calculation, and measurement techniques.

2. RELEVANCE OF WORST CASE CONCEPTS

Throughout this paper, the definitions shown on figure 1 will apply:

1) for the complex RMS voltages V_S, V_L, and V_{WF},

2) for the complex RMS currents I_S, I_L and I_{WF},

3) for the mean power P_S, P_L, P_{WF} and P_{MAX},

where "$_S$" stands for "source", "$_L$" stands for "load", and "$_{WF}$" stands for "without filter".

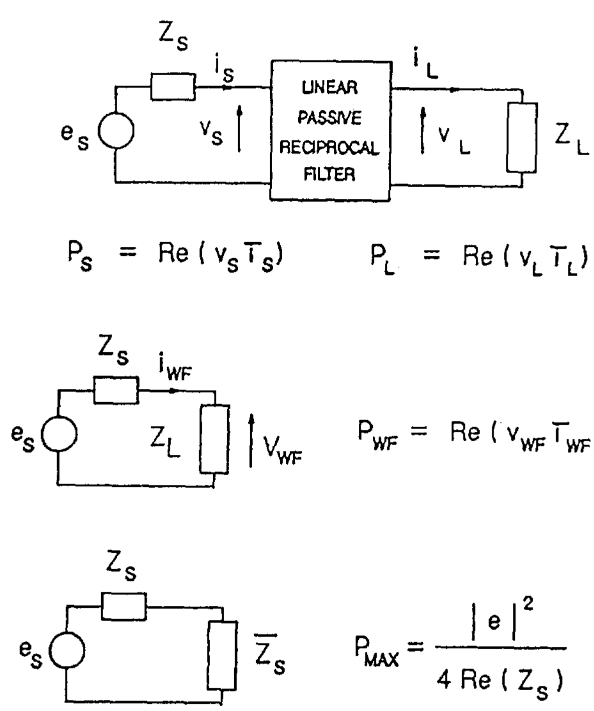

Figure 1: Definition for voltages, currents and powers.

Known Impedances			Worst Case		
Variable	Definition	elementary properties	at the input	at the output	at the input and the output
Insertion Loss	$I=\left(\frac{P_{WF}}{P_L}\right)^{1/2}=\left\lvert\frac{v_{WF}}{v_L}\right\rvert$	$I(Z_s,Z_L)=\left\lvert\frac{i_{WF}}{i_L}\right\rvert = I^{inv}(Z_L,Z_s)$	$I_i(Z_L)$	$I_o(Z_s)=I_i^{inv}(Z_s)$	I_{min}
Total Attenuation	$\mathcal{A}=\left(\frac{P_{MAX}}{P_L}\right)^{1/2}$	$\mathcal{A}(Z_s,Z_L)=\mathcal{A}^{inv}(Z_L,Z_s)$ $\mathcal{A}\geqslant I$	$\mathcal{A}_i(Z_L)==\mathcal{A}_o^{inv}(Z_L)=\mathfrak{A}(Z_L)$	$\mathcal{A}_o(Z_s)=\mathfrak{A}^{inv}(Z_s)$	M
Absorption Attenuation	$\mathfrak{A}=\left(\frac{P_s}{P_L}\right)^{1/2}$	$\mathcal{A}(Z_s,Z_L)\geqslant\geqslant\mathfrak{A}(Z_L)\geqslant 1$	$\mathfrak{A}(Z_L)$	M	M
Mismatch Attenuation	$\mathcal{B}=\left(\frac{P_{MAX}}{P_s}\right)^{1/2}$	$\mathcal{A}=\mathfrak{A}.\mathcal{B}$ $\mathcal{A}\geqslant\mathcal{B}\geqslant 1$	1	$\mathcal{B}_o(Z_s)$	1
Voltage Attenuation	$\alpha_V=\lvert v_s/v_L\rvert$	$\alpha_V(Z_L)=I(0,Z_s)$	$\alpha_V(Z_L)$	$\alpha_{V\,min}$	$\alpha_{V\,min}$
Current Attenuation	$\alpha_I=\lvert i_s/i_L\rvert$	$\alpha_I(Z_L)=I(\infty,Z_s)$	$\alpha_I(Z_L)$	$\alpha_{I\,min}$	$\alpha_{I\,min}$

Figure 2: Definitions of basic caracteristics of filters and their associated worst-case quantities.

A summary of existing definitions is presented on figure 2, namely for the "basic" quantities

insertion loss I ,
total attenuation $\mathcal{A}$,
absorption attenuation $\mathfrak{A}$,
mismatch attenuation $\mathcal{B}$,
voltage attenuation α_V ,
current attenuation α_I ,

and their 9 non-trivial worst-case counterparts I_o, I_i, I_{min}, $\mathcal{A}_o$, $\mathcal{A}_i$, M, $\mathcal{B}_o$, α_{Vmin}, α_{Imin}.

Figure 2 also gives their most important properties, with the convention that the exponent "inv" always refers to the characteristic of the filter when its input and output ports are exchanged. Further explanations on these quantities can be found in earlier papers [4], [5].

The most commonly asked question about the basic and worst-case quantities is: which one should I choose for my application? This very sensible question requires careful thinking. First of all, the likelihood that a given disturbance produces an interference increase with its power or energy, in most cases. The voltage and current it produces on the susceptor will depend on the coupling path, on impedances, resonances, etc, and it is not easy to say anything about disturbance voltage and current values if the coupling mechanism itself is not completely specified. The power or energy however will be necessary smaller on the susceptor than on the source, once (passive) coupling has taken place. When a standard for emission says that the emission should not exceed the emission limit of 56 dBμV quasi-peak on a 50 Ω load, at a given frequency, what is really meant is that the emission should not exceed 39 dBpW whatever the load. If the designer of a system tries to achieve compatibility, not only compliance to existing standards, he should in many cases formulate his design limits in terms of power. Let us now review some examples.

Case 1: Around 4 MHz, a device of unknown impedance had its emission measured with a 50 Ω network analyzer and artificial mains network. The measured values was 64 dBμV. We want to guarantee that the output will never exceed 39 dBpW whatever the load impedance. What is the filter specification at that frequency?

Our answer is that we don't know the solution to this problem, because we cannot assess the available power from the source, nor the maximum voltage or current it may produce.

Case 2: The device of case 1 had its dynamic impedance measured as $Z_s \approx 8$ Ω+j 1000 Ω. How should the filter be specified?

Answer: The available power from the source can be computed as P_{MAX} = 75 dBpW, and the specification of the filter is therefore a total attenuation in the worst-case at the output such that $\mathcal{A}_o$ (8 Ω+j 1000 Ω)≥ 36 dB at 4 MHz.

Case 3: The device of case 1 was investigated, and we made sure that its emission will not exceed P_{MAX} = 75 dBpW, however we know that its structure and installation will differ from one site to the other and that the impedance seen by the filter around 4 MHz cannot be predicted. Can one still specify the filter?

Answer: The specification of the filter should be a minimum attenuation such that M≥ 36 dB at 4 MHz.

Three important remarks have to be made concerning the worst-case specification of a filter:

1) Insertion loss in the worst-case should not be used in most cases, because it tells you about the minimum improvement that the filter is going to bring you, but it gives you no idea of the worst-case value of output voltage or power. This is different from the specification between known impedances, where specifying the insertion loss or the total attenuation is equivalent.

2) The minimum voltage and current attenuation are of interest only in very special cases of specification.

3) When one "translates" specification on voltages or currents, as they can be found in many standards, into specifications on powers, and then into worst-case specifications, care should be taken that limits given in the standards may incorporate some kind of margin supposed to take into account possible mismatch in the voltage/available power conversion, or worst-case effect. Such margin should eventually be removed before defining the worst-case specification.

3. IMPEDANCE DOMAINS

The concept of impedance domain is very useful in the study of worst-case. An impedance domain is a set of impedance value, which in this paper will always be a subset of the positive real part half complex plane $\mathbb{C}_+$, i.e. we will only consider impedances with a positive resistance. An impedance domain will also have the topological property of being simply connexe, which means that its boundary is only one regular curve. In the particular case of a finite impedance domain, the curve is therefore closed. Figure 3 shows such a finite impedance domain.

The concept of impedance domain is useful in the study of worst-case because it allows a simple formulation of what we know and don't know about an impedance. If we know nothing about a given impedance, for instance the impedance of a power outlet at 30 MHz, then it may take on any value within the positive real part half complex plane, and it is described by an impedance domain equal to $\mathbb{C}_+$. If instead of considering a power outlet, we want to represent what we know of the impedance of an articial mains network, which is supposedly well defined, we may eventualy describe this impedance with an impedance domain equal to a disk of radius 10 Ω and center 50 Ω, or if we measured accurately this value, we may described it with the single value 54 Ω- j 8 Ω.

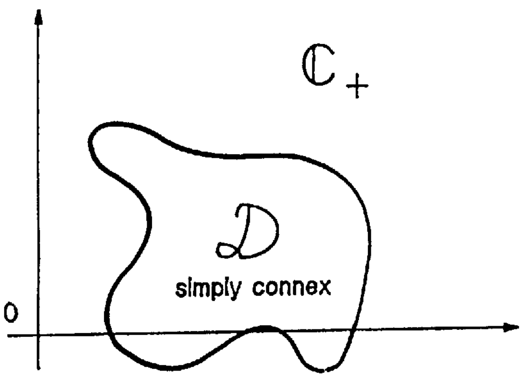

Figure 3: An example of impedance domain

A very interesting kind of impedance domain is the input impedance domain (IID) of a linear filter, which is the subset of $\mathbb{C}_+$, containing all the values of impedances that the input of a linear filter may take, when the output is allowed to be connected to any impedance with a positive real part. If D(f) is the IID of a linear filter, it is therefore defined as:

$$D(f) = \{ Z'_L(f) \mid Z_L \in \mathbb{C}_+ \} \qquad (1)$$

where $Z'_L(f)$ is the input impedance of the filter at the frequency f, when the load impedance Z_L is connected at its output.

It as already been proved [4] that the IID of a linear filter can only be $\mathbb{C}_+$, or a half plane obtained by translating $\mathbb{C}_+$ in the positive real direction, or a disk.

Figure 4 shows the 3 types of IID, together with filters having such IIDs.

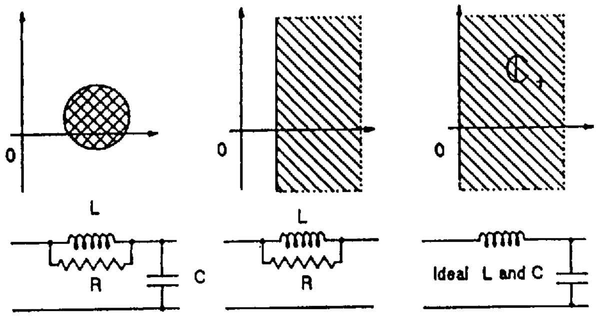

Figure 4: Impedance domain equal to the IID of a linear filter.

The IID of a lossless filter is always equal to $\mathbb{C}_+$, and this is the reason why such filters are completely ineffective in the worst case. As an example, we have computed the IID of two Artificial Mains Networks (AMN) used in CISPR standards. The schematic of those filters can be found on figure 5.

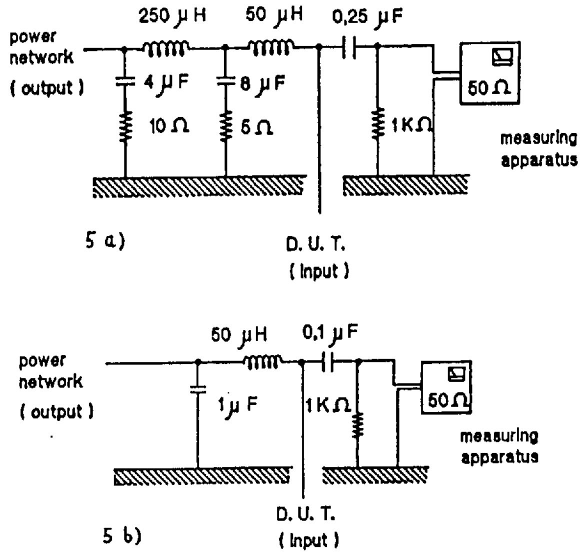

Figure 5: Two AMN used in CISPR publications.

Figure 6 and 7 present the IID of the two AMN of figure 5. As can be seen on figure 6, the AMN of fig. 5a) beautifully matches the CISPR specification whatever the impedance of the mains network. On the contrary, the AMN of fig. 5b) is only damped by the impedance of the measuring apparatus, and it shows a very inadequate IID. This means that this AMN cannot be used on a mains network of unknown or uncontrolled impedance.

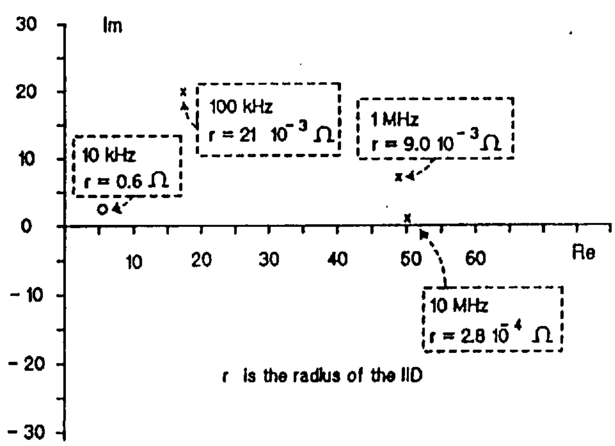

Figure 6: IID of the AMN of figure 5a).

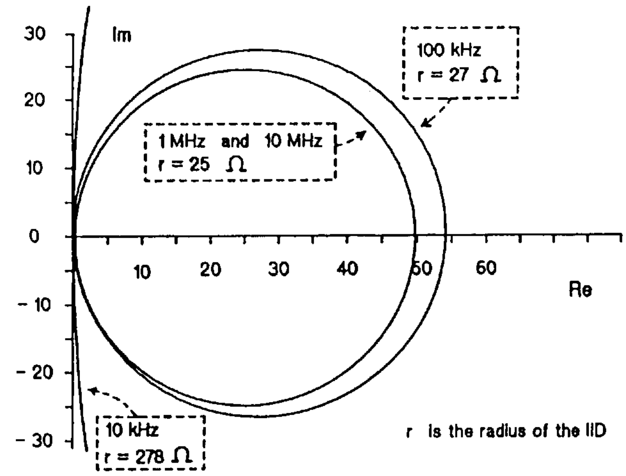

Figure 7: IID of the AMN of figure 5b).

The above impedance domains are the result of calculations. It is also possible to use a large number of measured impedances to build an impedance domain on a statistical basis. Unfortunately, too little data is available on this aspect up to now. Figure 8 shows the sketch of a frequency dependant impedance domain which we use for the design of filters to be inserted on the low voltage public network in residential areas, in the 10 kHz to 30 MHz frequency range. The figure only shows the boundary of impedance domains at three discrete frequencies, but we have produced a table of impedance domains versus frequency, in which impedance domains boundaries are either circles or ellipses, and interpolation is possible between tabulated frequencies. The data we used to produce our table is contained in [6], [7], [8] and [9].

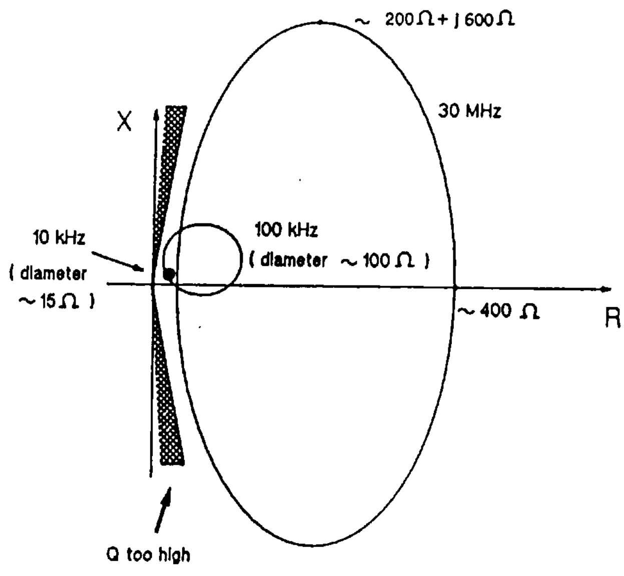

Figure 8: A frequency dependant impedance domain for low voltage power network in residential areas.

4. WORST CASE IN A SPECIFIED IMPEDANCE DOMAIN

Specifying a PLF with a total attenuation in a 50 Ω source and 50 Ω load measurement system is dangerously optimistic, because the filter performances will be completely different (far worse usually) when the filter is connected to a mains network.

On the other hand, it has been stated that designing a filter for worst-case performances is excessively pessimistic, because we take into account values of impedance which are not likely to occur on a power network: excessively high or low impedance values, or values with an unrealistic Q factor. The filter must then be strongly damped, and its cost increases.

The purpose of defining a worst-case in a specified impedance domain is to consider impedances taking on any values in a (frequency dependant) impedance domain, instead of $\mathbb{C}_+$.

For a quantity X dependant on Z_L, but not on Z_S (for instance X is either $\mathfrak{A}$, or α_V, or α_I), we define the minimum X in the load impedance domain D as

$$X^{D}_{min} = \mathrm{Inf}\ \{X(Z_L)\ |\ Z_L \in D\} \qquad (2)$$

and we call it minimum X in the impedance domain D.

For a quantity X dependant on both Z_L and Z_S (for instance X is either A , or $\mathcal{B}$, or I), we define X in the worst-case at the input in the source impedance domain D' as

$$X^{D'}{}_{I}(Z_L) = \mathrm{Inf}\ \{X(Z_S,Z_L)\ |\ Z_S \in D'\} \qquad (3)$$

We can also define X in the worst-case at the output in the load impedance domain D as

$$X^{D}{}_{I}(Z_S) = \mathrm{Inf}\ \{X(Z_S,Z_L)\ |\ Z_L \in D\} \qquad (4)$$

We can finally define X in the worst-case at the input in the source impedance domain D' and at the output in the load impedance domain D as

$$X^{D',D}_{min} = \mathrm{Inf}\{X(Z_S,Z_L)\ |\ (Z_S,Z_L) \in D'xD\} \qquad (5)$$

All quantities in (2) to (5) are frequency dependant, including the source impedance domains D and load impedance domain D'. Obviously the above definitions of worst-case in a specified impedance domain generalyse the worst-case definitions of figure 2. Once appropriate frequency dependent source or load impedance domains have been selected for a given environment, (for instance according to figure 8), an optimum PLF can be designed, which will only include the necessary amount of damping: its cost will therefore be optimized.

5. CALCULATION OF WORST-CASE QUANTITIES

We know analytical methods for computing all basic and worst-case quantities appearing in figure 2, except for I_{min} (which is of little interest anyhow). We also have analytical procedures for computing the IID of a filter [4]. All those procedure have been implemented in the early versions of our FILTREXPERT software, and examples of computation of worst-case quantities have already been presented [5] for a complex filter.

In the case of worst-case in a specified impedance domain, there was no possibility of analytical solution and we had to implement numerical procedures in FILTREXPERT. The current version 2.2 is able to compute:

- the minimum $\mathfrak{A}$, α_V et α_I in a load impedance domain D;
- the minimum A and I in the worst-case at the input in a source impedance domain D';

· the minimum A and I in the worst-case at the output in a load impedance domain D.

At any given frequency, D is specified as disk, or the surface bounded by an ellipse, or a single value.

For any frequency step of such a computation, FILTREXPERT has to find the minimum of a positive real function f of two real variable R and X on a bounded domain D the boundary of which is a closed curve included in $\mathbb{C}_+$ (see figure 9). It happens that all the functions to be considered have either one or zero local minimum in $\mathbb{C}_+$. If there exists such a local minimum, the procedure is to compute its coordinates z_1 (in complex format) and the value $f(z_1)$ of the minimum; in the case of figure 9, z_1 exists and lies outside D. We then look for the minimum value of f on the boundary ∂D of D, and its coordinates z_2. The result is either z_2 (as in the case of figure 9), or z_1 if and only if it exists, and is included in $D \cup \partial D$, and is smaller than z_1.

Because the above procedure is only one-dimensional, the exact algorithm is both straightforward and computationally efficient.

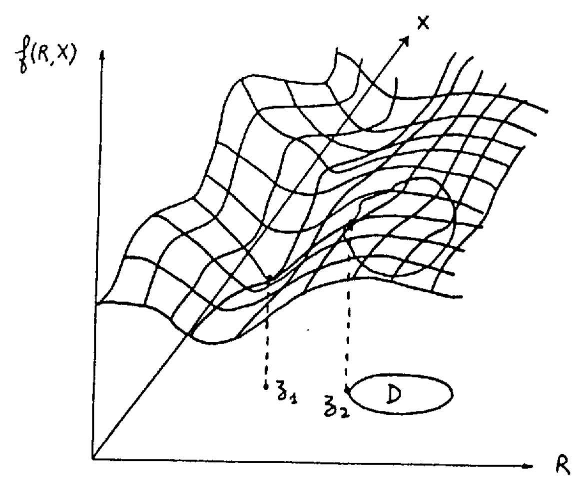

Figure 9: Principle for the calculation of worst-case quantities in a bounded domain.

6. MEASUREMENT OF WORST-CASE QUANTITIES EXISTING METHODS

Weidmann and McMartin [10] proposed in 1968 two worst-case insertion loss test methods. One of them (called series injection) has its principle represented on our figure 10: it includes a tunable source circuit and a tunable load circuit, used in conjunction with low-impedance series injection at the input and a current probe at the output. The other techniques (called parallel injection) used a high impedance parallel injection at the input and a voltage probe at the output. Because the worst-case insertion loss always occurs for purely reactive impedances, the designers of these test set-up where trying to obtain high-Q impedance at the input and at the output. Measurements could be made in the 10 kHz to 1 MHz frequency range.

The set-up presented on figure 10 is meant for the measurement of I_{min}, but it could be adapted to other worst-case measurements for which the minimum theoretically occurs with pure reactances: I_0, I_1, α_V, α_I. This impedance variation approach could be adapted to other frequency ranges, probably up to 100 MHz, but its frequency range would remain limited to approximatively two decades per set-up, because high quality factors are required. The main drawbacks of this approach are obviously: the limited range of achievable impedances, the limited frequency range, and the lengthy tuning procedure.

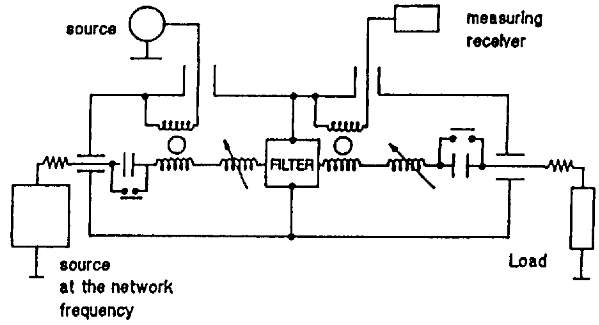

Figure 10: Impedance variation method

We will not present here the measurement method advocated by Schlicke in 1976 [11], which does not really measures any worst-case quantity, even though it was included in CISPR 17 as "the approximate method".

The method presented in figure 11 was introduced by Jarvis and Thomson in 1977, and is also included in CISPR 17 as "the quasi-analytic method". It requires two different measurements (a) and (b) at each frequency: (a) is a scalar measurement of transfer impedance, and (b) is a vector measurement of Thevenin impedance. The enormous advantage of this method over the impedance variation method is that it does not require any tuning. However, it can only be used for the indirect measurement of α_V. It may be implemented up to 100 MHz.

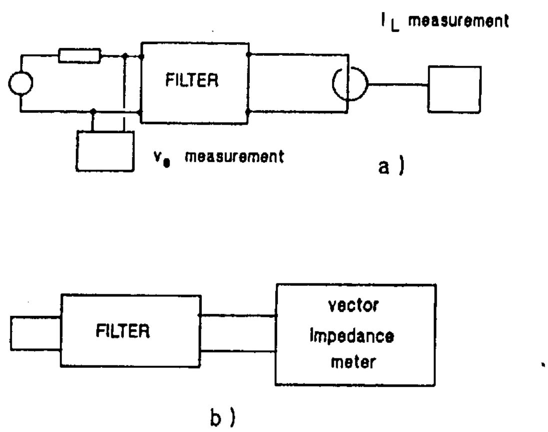

Figure 11: Measurement of the minimum voltage attenuation with the quasi-analytic method

7. MEASUREMENT OF WORST-CASE QUANTITIES NEW PROPOSALS

None of the existing measurement method for PLF offers a satisfactory solution to the determination of total attenuation in a worst-case and minimum attenuation, which are the normal design parameters. We present here several possibilities of development:

1) A first approach would be to implement the direct measurement of the components of the chain matrix of the PLF. At least 3 vector measurements would be required. The advantage would be that any quantities in the worst-case, even in a specified impedance domain, could be computed. A difficult question would be the determination of the final accuracy as a function of measured values.

2) A possible solution to the measurement of $\mathcal{A}_i$ and $\mathcal{A}_o$ is the measurement of the absorption attenuation $\mathcal{A}$ or $\mathcal{A}^{inv}$, as can be seen on figure 2. This would require power measurements at the input and at the output of the PLF. This could be achieved easily as shown on figure 12, at least up to 100 MHz with current and voltage probes connected to the output of a vector voltmeter. It should be noted that power measurement with a network analyser would probably be inadequate in this context because its directional couplers would be inaccurate with the usually high proportion of reflected power at the input of the filter.

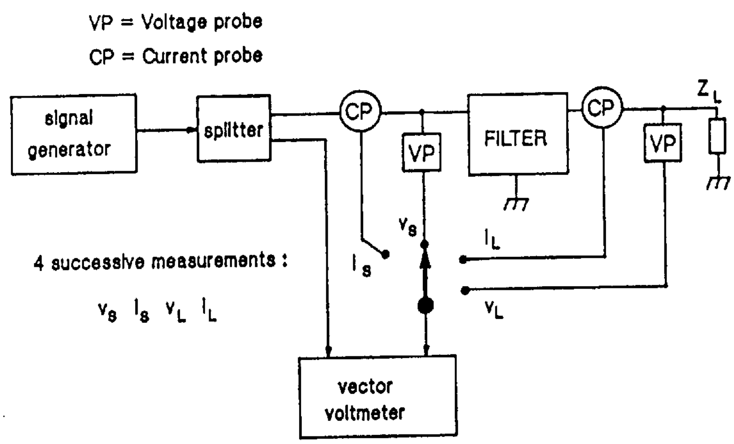

Figure 12: Direct measurement of absorption attenuation. The vector voltmeter is successively connected to the two voltage probes and current probes.

3) For the measurement of worst-case quantities in a specified impedance domain, the impedance variation method could be modified to accomodate one or two variable resistors. Because the relevant impedance domains would not exhibit extreme quality factors, the requirement on the Q of the set-up would be only moderate, and large frequency ranges would be achievable, probably 3 decades. The measurement system would have to be computer-controlled. Particular measurements (insertion loss for instance), in certain cases, would only require the scanning of the boundary of the impedance domains, and would therefore not be time consuming.

8. CONCLUSION

We have presented here some improvements to the theory of the worst-case behaviour of power line filters. This presentation focussed on the meaning of worst-case quantities, on new definitions, computational techniques and measurement methods. Obviously, much more work is needed on theoretical as well as experimental aspects. However, we feel that the most important need is to get data for complex network impedances. These data should be obtained by frequency scanning, not at discrete frequencies, because we have to know what extreme impedances are, and those extremes occur at narrow resonances.

9. REFERENCES

[1] W.R. HINTON, C.A. MEADOWS, L.C. CADDY :
"A theory for the Design and Analysis of Radio Interference Suppressors", Royal Aircraft Establishment Technical Report 66391, 1966.

[2] H.M. SCHLICKE, H.WEIDMANN :
"Compatible EMI filters", IEEE Spectrum, Oct. 1967, pp 59-68.

[3] CISPR Publication 17 :
"Méthode de mesure des caractéristiques d'anntiparasitage des éléments de réduction des perturbations radioélectiques et des filtres passifs", CEI 1981.

[4] F. BROYDE, E. CLAVELIER :
"Minimum Attenuation and Input Impedance Domain of a Linear Filter", proceedings of the 8th International Zürich Symposium on EMC, March 1989, pp 261-266.

[5] F. BROYDE, E. CLAVELIER :
"Atténuation minimale et domaine d'impédance d'entrée d'un filtre linéaire", proceedings of the 5ième Colloque International en Langue Française et Exposition sur la CEM", Evian 1989, communication BII-3.

[6] H.M. SCHLICKE :
"Filtering" in "Practical Design for Electromagnetic Compatibility", Edited by E. FICCHI, Hayden Book Comp., 1971, pp 93-132.

[7] J.R. NICHOLSON, J.A. MALACK :
"RF Impedance of Power Lines and Line Impedance Stabilisation Networks in Conducted Interference Measurements", IEEE Trans. on EMC, May 1973, pp 84-86.

[8] J.A. MALACK, J.R. ENGSTROM :
"RF Impedance of United States and European Power Lines", IEEE Trans on EMC, February 1976, pp 36-38.

[9] R.M. VINES et al :
Impedance of the residential Power-Distribution Circuit", IEEE Trans. on EMC, vol EMC-27, No.1, February 1985, pp 6-12.

[10] H. WEIDMANN, W.J. McMARTIN :
"Two Worst-Case Insertion Loss Test Methods for Passive Power-Line Interference Filters", IEEE Transactions on EMC, vol. EMC-10, No. 2, June 1968, pp 257-263.

[11] H.M. SCHLICKE :
"Assuredly Effective Filters", IEEE Trans on EMC, vol. EMC-18, No. 3, August 1976, pp 106-110 .

[12] M.L. JARVIS, J.M. THOMSON :
"Worst-Case Suppressor Testing Method -The Minimum Attenuation Concept", IEEE Trans. on EMC, May 1977, pp 99-101.