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Proceedings of the 7th International Zurich Symposium on EMC, 3-5 March 1987, pp. 393-398

DISSIPATIVE FILTERS FOR POWER ELECTRONICS APPLICATIONS

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The terminals of high power electronic apparatus are generally required to be free of unwanted signals, as defined in specific standards and regulations.
Low pass filters using reactive components can provide the needed attenuation but unfortunately exhibit a very unsatisfactory worst case behaviour under certain load impedance conditions.
This problem may be avoided by using filters that dissipate the unwanted signal.
This paper describes the design of one such dissipative filter and gives experimental data gathered in the 10 kHz - 30 MHz frequency range.

Introduction

This paper deals with the reduction of conducted emission produced by high power equipment in the kW range. Although the results presented may have various applications, this work was done principally for use with uninterruptible power supplies. The designer of a high power device faces two different kinds of conducted emission requirements:

1. Compliance with standards, usually specifying maximum emission levels at given frequencies, the measurement beeing made under well defined conditions.
2. Compatibility of the equipement with any electromagnetic environment that could be encountered in its normal use.

The second requirement is not mandatory and is therefore not always considered in the design of filters. Equipment complying with standards thus sometimes presents excessive conducted emission.
This is usually due to the exclusive use of non-dissipative elements in the power-line low-pass filters provided at the inputs and/or outputs of the considered power device. Such non-dissipative low-pass filters are known for the marked dependence of their behaviour on load and source impedance [1], [2].
At frequencies above a few tens of kHz, the impedance of a normal power outlet and of many types of linear power loads can take on almost any value in the complex plane. Thus, if such a source or load is not known accurately, its complex impedance should be considered as a random quantity, at any given frequency. A non-dissipative filter connected to this source or load will then exhibit random behaviour, sometimes showing insertion loss of a high or low value and sometimes showing insertion gain when ringing occurs.
This shortcoming may be avoided if losses are introduced in the filter [1], [3].
Two major differences between lossless and dissipative filters will be pointed out. Some properties of three different dissipative structures, made of lumped elements will then be discussed. Using those structures, we will describe an example of dissipative filter design for the 10 kHz-30 MHz frequency range.

Some fundamentals of 3-terminal filters

Let us consider a 3-terminal linear filter. With the notation used in Fig. 1, the filter is characterized by its chain matrix A defined by :

$$\begin{pmatrix} v_L \\ i_L \end{pmatrix} = A \begin{pmatrix} v_S \\ i_S \end{pmatrix} \qquad \ldots(1)$$

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \qquad \ldots(2)$$

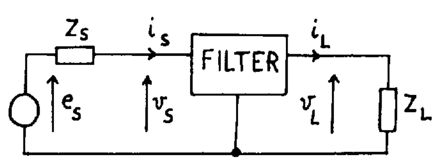

Fig. 1 - Notation

The quantities v_L, i_L, v_S, and i_S are complex amplitudes. The A matrix is a complex matrix and is frequency dependent. Since the filter contains no sources, it is well known that, due to reciprocity, the determinant of the chain matrix is [4] :

$$\det A = a_{11}\,a_{22} - a_{21}\,a_{12} = 1 \qquad \ldots(3)$$

Thus, the impedance Z'_L seen by the generator, defined as :

$$Z'_L = \frac{v_S}{i_S} \qquad \ldots(4)$$

is given by :

$$Z'_L = \frac{a_{22}\,Z_L - a_{12}}{a_{11} - a_{21}\,Z_L} \qquad \ldots(5)$$

This quantity is very important. It permits calculation of i_S and v_S, and therefore i_L and v_L, provided that e_S, Z_S and Z_L are known.

Considerations on lossless filters

Filters made of ideal inductors and capacitors are of course lossless. The active power at their inputs and outputs is equal. Since the active power reaching the load is given by :

$$P_L = \frac{|e_S|^2 \ \mathrm{Re}\,(Z'_L)}{|Z_S + Z'_L|^2} \qquad \ldots(6)$$

where Re ( ) represents the "real part of", the only way a non-dissipative filter can work is to create a severe mismatch between Z'_L and Z_S, at the appropriate frequencies.

Another important property of lossless filters is that, when propagation can be neglected, a_{11} and a_{22} are real numbers While a_{21} and a_{12} are purely imaginary numbers. This is the case in the 10 kHz-30 MHz frequency range and for filters of reasonable size. Thus the value of Z_L corresponding to a random value of Z'_L, given by

$$Z_L = \frac{a_{11}\,Z'_L + a_{12}}{a_{21}\,Z'_L + a_{22}} \qquad \ldots(7)$$

has a real part given by

$$\mathrm{Re}(Z_L) = \frac{\mathrm{Re}\,(Z'_L)}{|a_{21}\,Z'_L + a_{22}|^2} \qquad \ldots(8)$$

This is extremely important because it proves that Z'_L has a positive real part if and only if Z_L also has a positive real part.

In other words, if the load impedance Z_L is allowed to take on all physically possible values (i.e. values with a positive real part), the impedance Z'_L seen by the generator will also take on every possible value in the positive real part half complex plane. Eventually Z'_L will reach the value $\bar{Z}_S$ for which the maximum active power is sent from the generator to the load. When this occurs, the filter acts as a matching device. This is why lossless filters should not be used with a random load impedance Z_L.

Basic considerations on dissipative filters

As will be seen from the following examples, dissipative filters are quite different from their lossless counterparts in two important aspects :

1. The active power at the output is lower than the active power at the input. Sometimes it is even possible to guarantee that the ratio of these two quantities will be lower than a specified value smaller than one.
2. With a dissipative filter, the entire positive real part half complex plane cannot usually be swept by Z'_L when Z_L is randomized.

Let us now study the dissipative structures which display these properties. In the following, P_S and P_L will be the active power at the input and at the output of the filter respectively, i.e.

$$P_S = \mathrm{Re}\,(v_S\,\bar{i}_S) \text{ and } P_L = \mathrm{Re}\,(v_L\,\bar{i}_L) \quad \ldots(9)$$

The real part of Z_L and the real part of Z'_L will be R_L and R'_L respectively.

Examples of dissipative structures

The parallel RC branch

The parallel RC branch (see fig. 2) is already used for its dissipative properties in some power line filter designs [3], [5].

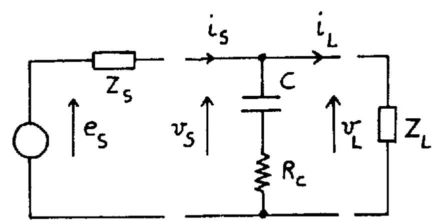

Fig. 2 : The parallel RC branch

It is usually seen as a damping device, to be used in conjunction with standard lossless filters. Our point of view is somewhat different. We see it as a filter, which at sufficiently high frequencies ($R_C \gg \frac{1}{\omega C}$), is characterized by two properties :

$$\frac{P_L}{P_S} \leq \frac{R_C}{R_C + R_L} \qquad \ldots(10)$$

and

$$\frac{R_C\,R_L}{R_C + R_L} \leq R'_L \leq R_C \qquad \ldots(11)$$

For this filter, the ratio $\frac{P_L}{P_S}$ has a maximum value of one if Z_L is allowed to take on any value with a positive real part.

The series RL branch

The series RL branch (see Fig. 3) is less frequently encountered in power line filters.

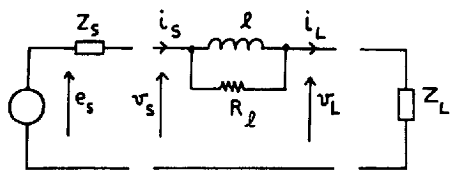

Fig. 3 : The series RL branch

It is a filter, which at frequencies such that $R_\ell \ll \omega \ell$, gives

$$\frac{P_L}{P_S} = \frac{R_\ell}{R_\ell + R_L} \qquad \ldots(12)$$

and

$$R'_L = R_\ell + R_L \qquad \ldots(13)$$

Here also $\frac{P_L}{P_S}$ has a maximum value equal to 1 if Z_L is allowed to take on any value with a positive real part.

The series-parallel dissipative low-pass filter

With a series RL branch and a parallel RC branch, a series-parallel dissipative low-pass filter can be obtained (see Fig.4)

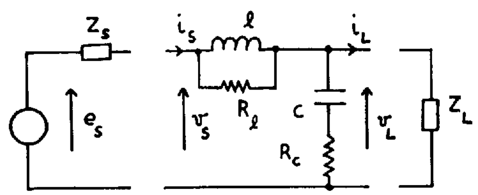

Fig. 4 : The series-parallel filter

For this filter, one can prove that, for frequencies such that $R_C \gg \frac{1}{\omega C}$ and $R_\ell \ll \omega \ell$

$$\frac{P_L}{P_S} \leq 1 + 2\frac{R_\ell}{R_C} - \left(\frac{|Z'_L|}{R_C} + (1 + \frac{R_\ell}{R_C}) \frac{R_\ell}{|Z'_L|} \right) \qquad \ldots(14)$$

Maximizing the right hand side of equation (14) gives

$$\frac{P_L}{P_S} \leq 1 - 2\frac{R_\ell}{R_C} \left[\sqrt{1 + \frac{R_C}{R_\ell}} - 1 \right] \qquad \ldots(15)$$

This is an interesting result. The ratio $\frac{P_L}{P_S}$ has a maximum value less than 1, and independent of Z_L. Whatever the load provided at the output, this filter will always absorb at least a certain proportion of the high frequency power at its input. Note also that for frequencies such that $R_C \gg \frac{1}{\omega C}$ and $R_\ell \ll \omega \ell$, this filter gives:

$$R_\ell + \frac{R_C R_L}{R_C + R_L} \leq R'_L \leq R_\ell + R_C \qquad \ldots(16)$$

On the other hand, at frequencies low enough to satisfy $R_C \ll \frac{1}{\omega C}$ and $R_\ell \gg \omega \ell$, the losses become negligible, and the features described by equations (15)and (16)disappear. Let us define the quantity M representing the minimum attenuation of the filter where

$$M = -10 \log_{10} \left(1 - 2\frac{R_\ell}{R_C} \left[\sqrt{1 + \frac{R_C}{R_\ell}} - 1 \right] \right) \qquad \ldots(17)$$

If $\frac{R_\ell}{R_C} \gg 1$, which is desirable, then

$$M \simeq 10 \log_{10} \left(\frac{4R_\ell}{R_C} \right) \qquad \ldots(18)$$

This relationship is valid to within $^{+0}_{-0.5}$dB provided that $\frac{R_\ell}{R_C} > 5$

Dissipative filter design

To design a power line filter made of lumped elements that is really effective for any load, a series parallel dissipative low-pass filter is extremely suitable. Typical values of M attainable with a single filter are 10 dB to 30 dB. Unfortunately a series - parallel dissipative filter usually has an insertion loss under 50 Ω -source and 50 Ω - load conditions not markedly different from M, whereas a lossless low-pass LC filter using the same values of L and C gives a far more impressive insertion loss under the same conditions. Thus, under the same conditions (50 Ω), the same insertion loss will require the cascading of more dissipative than non-dissipative filters. This will probably deter some designers from using dissipative filters. Before making such a decision one should however consider the following advantages of a dissipative design :

a) A coil with losses is not a problem. One can therefore use cores of a lossy, high μ material, making coils cheaper and lighter.

b) High cost, high capacitance feed-through capacitors are not necessary. The only major requirement is that the reactance of a parallel RC branch be much smaller than its resistance, for correct dissipative behaviour.

c) Independent shielding of each coil is not as critical as for lossless filters, due to the strong loading of the coil by a small parallel resistance.

d) It is also possible to take advantage of the property described by equation (16), and use the dissipative filter to screen a lossless filter from load impedance variations.

A dissipative filter design example

We have designed an experimental dissipative filter to be used with a certain class of Uninterruptible Power Supplies. Our purpose was to eliminate the conducted emission from the UPS back into the mains supply; this being a major problem in the 10 kHz - 200 kHz frequency range, but of lesser importance in the 500 kHz - 30 MHz region, except around 6 MHz (see Fig. 5 and 6). Emission was mainly in the differential mode but the fundamental (at 25 kHz) and harmonics of the switching frequency were also present in the common mode. In the low frequency region, the differential mode emission had a low impedance (below 20Ω) and the common mode emission had a high impedance, mainly capacitive.
Taking these characteristics into account, we adopted the circuit shown in Fig. 7.
We used a low leakage design, for which the neutral line must be clearly marked [6]. Our filter was intended for a 2-line 2 kW unit.
The following points must be emphasized :

a) The cell containing L1, L1', L2, L2' and C1,..., C8 is a lossless low-pass filter. The differential mode load seen by this cell has its real part around 85Ω (see (16)) at frequencies above 10 kHz, and the presence of this load is negligible, due to the low impedance of C3 + C4.

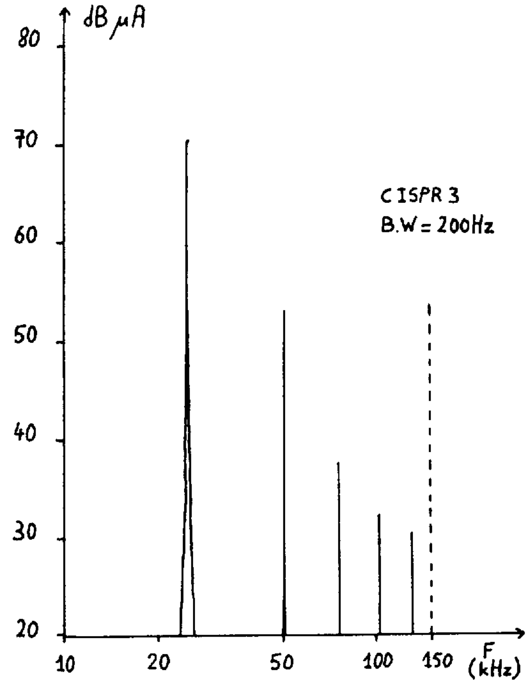

Fig. 6 : Conducted emission : Common mode current (2 x 10 μF feed through capacitor + current probe + 50 Ω receiver)

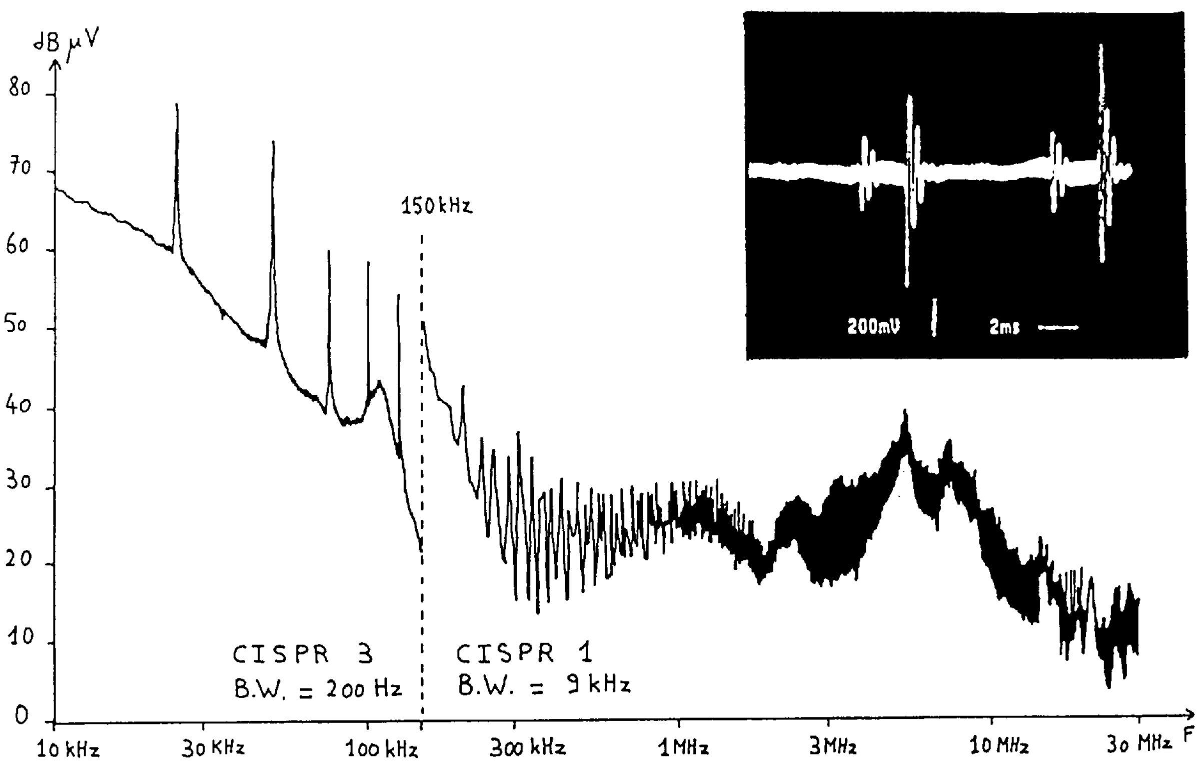

Fig. 5 : Conducted emission
5.a. Voltage between line and ground, 50Ω LISN + receiver
5.b. Voltage between line and ground, 50Ω LISN + oscilloscope

b) At low frequencies (≤ 1 kHz), L1,..., L6 operate only in the common mode.
At higher frequencies, these two transformers are wound in such a way that the increase in the reluctance of their cores decreases the coupling of their windings, and they therefore become really effective in the differential mode.

c) L7 - R5 constitutes a series RL branch operative in the common mode at low frequencies. This branch becomes inoperative at higher frequencies because it is effectively shorted by the stray capacitance betwen the UPS's case and the earth line or the ground.

Performance - The performance of the filter alone and connected to its UPS are summarized in Fig. 8 and 9.

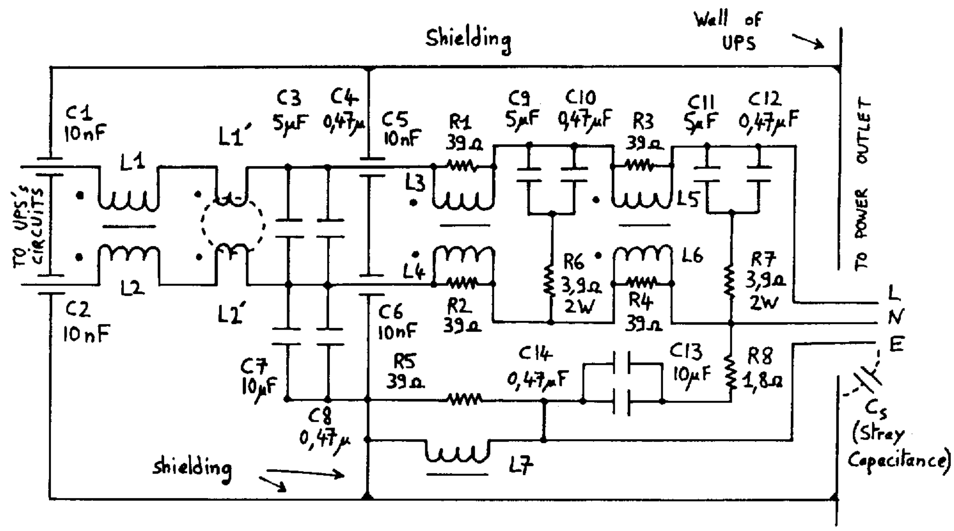

Fig. 7 : Dissipative filter circuit
L1 ≃ L2 ≃ ... ≃ L7 ≃ 1mH à 1 kHz (Iron core)
L1' ≃ L2' ≃ 50 µH à 1 kHz (Ferrite core)

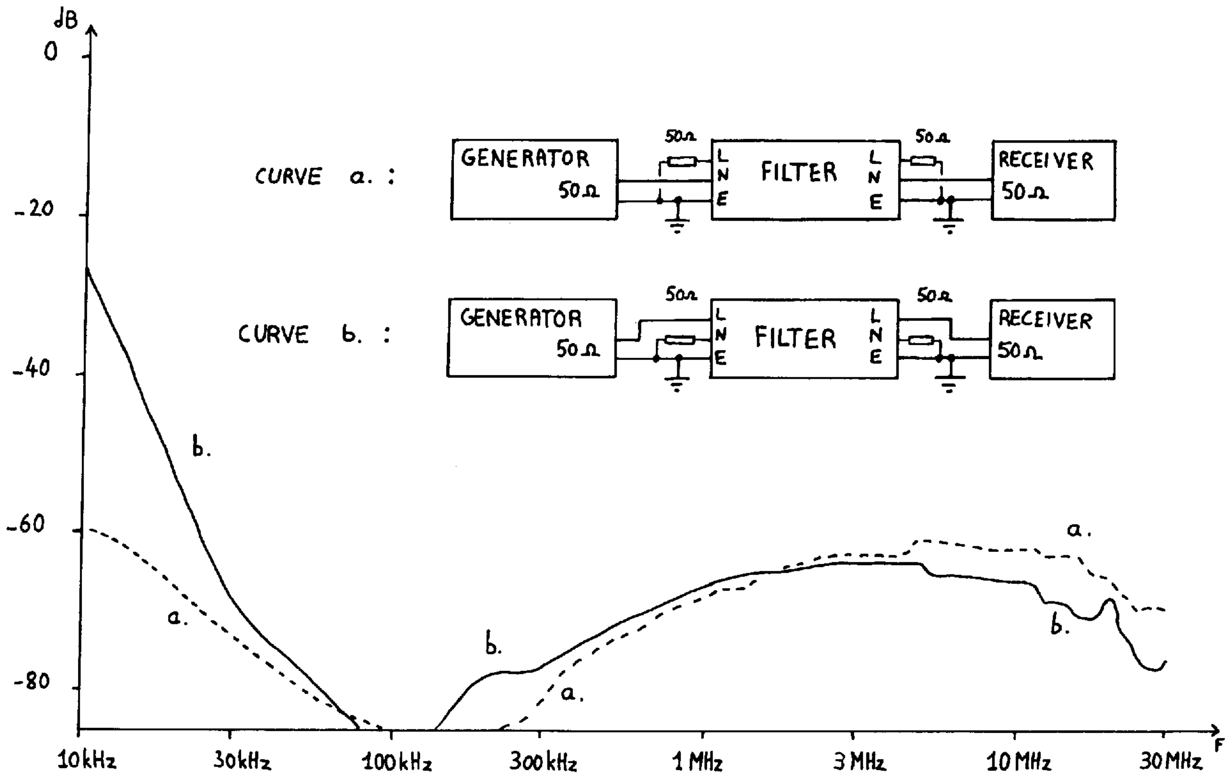

Fig. 8 : Insertion loss - 50Ω generator and 50Ω receiver

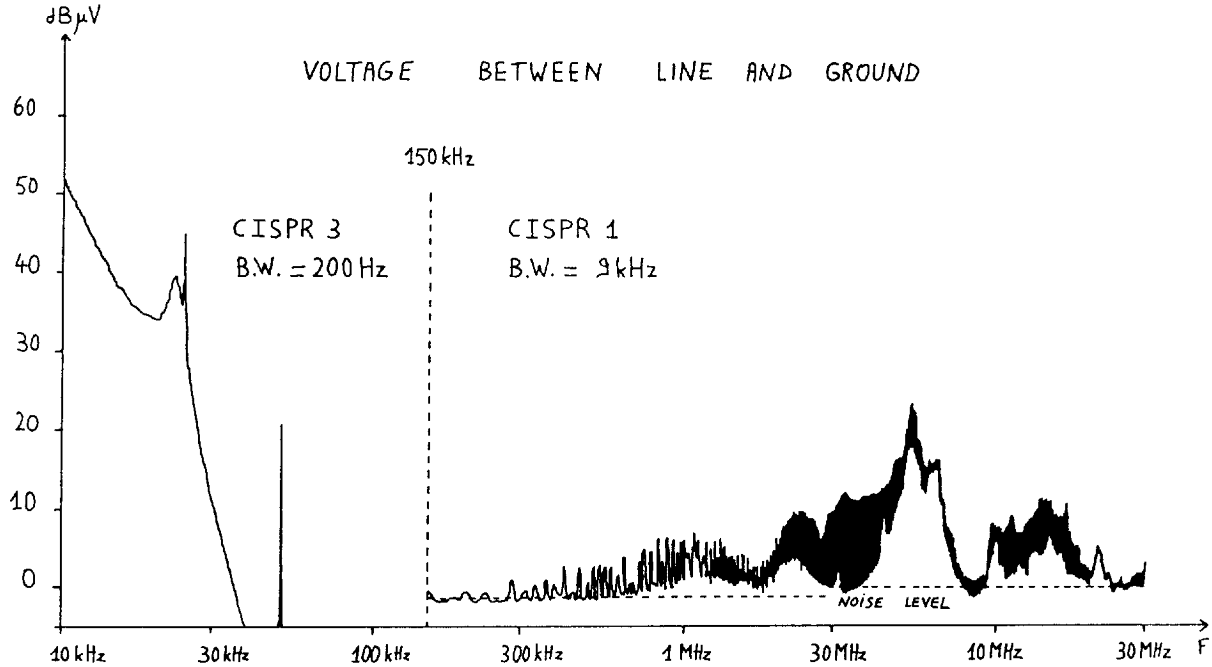

Fig. 9 : Conducted emission of the UPS with its dissipative filter. (50 Ω LISN + receiver). The remaining signal above 500 kHz is mainly due to the radiated emission of the UPS (inappropriate shielding)

The measurements were made with a 50 Ω LISN and receiver, and therefore do not show the independence of the behaviour of the filter versus its load impedance. However, we know from our calculations that this independence should exist. Unfortunately, we did not have the possibility of setting up an experiment to investigate this point [7], [8].

Conclusions

The design of a dissipative power line low-pass filter is a simple task.
The dissipative filters offer the extremely important property of providing at least a given attenuation when the load impedance takes on an arbitrary value.
Unfortunately these filters require a greater number of components than their non-dissipative counterparts for a given attenuation and given source and load impedances. They should nevertheless be made available to users wishing a high degree of equipment compatibility.

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