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Common-Mode Choke Coils Characterization

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Abstract

Common-mode (CM) chokes are four-terminal devices with different CM and *differential-mode* (DM) characteristics. The paper reviews the models for two- and four-terminal inductors and presents two methods to obtain the CM and DM characteristics of four-terminal devices. More specifically, it shows how the insertion loss and π-equivalent circuits of a CM choke can be obtained using two- and four-port network parameters. However, these characterization methods are applicable not only to CM chokes, but to any four-terminal component or network, such as single-phase power filters.

The results show that second order linear circuit models cannot describe accurately the CM and DM characteristics of a CM choke over a wide frequency range. For the studied example, the DM characteristics were more complex than the CM ones.

1 Introduction

The components in a passive power filter can be two-, three-, or four-terminal devices. Among these, the resistors and capacitors have relatively stable *high-frequency* (HF) characteristic and their HF models can be defined by a few parameters given in the manufacturers' datasheets. For example, a capacitor is pretty well characterized by its *equivalent series resistance* (ESR), *equivalent series inductance* (ESL), and *equivalent parallel resistance* (EPR). The inductive components, on the other hand, have a more complex structure and characteristics. Usually, two-terminal inductors are modeled by second order linear circuits, like in Fig. 1*a* [1] and Fig. 1*b* [2], but these are not linear models, because their parameters vary significantly. Even after ignoring the effects of environmental factors, like temperature, the inductance still changes with current, and both the inductance and the ESR are frequency-dependent. Four-terminal inductive devices, such as coupled *differential-mode* (DM) inductors (see Fig. 1*c*) and *common-mode* (CM) chokes (Fig. 1*d*), cannot be modeled with the equivalent circuits in

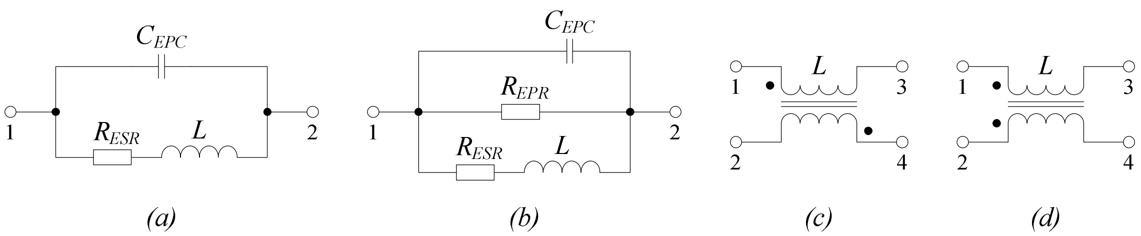

Fig. 1: *a*) Inductor model according to [1], *b*) according to [2], *c*) coupled DM inductor, *d*) CM choke.

Fig. 1*a* and *b* because in addition to all the parasitic couplings found in a two-terminal inductor there are also magnetic and capacitive couplings between the two windings.

During the modeling and analysis of power filters it is often necessary to derive their CM and DM equivalent circuits. For example, consider the set up for measuring the conducted emissions from a single-phase electrical appliance, which is the *equipment under test* (EUT) in Fig. 2*a*. In theory, the CM and DM equivalent circuits should be as shown in Fig. 2*b* and Fig. 2*c* respectively. However, exactly how much a four-terminal inductor contributes to the suppression of CM and DM noise over a wide frequency is not a trivial question.

1.1 CM and DM equivalent inductances

Assuming that the two windings of a four-terminal inductor are identical, it can be shown that its coupling coefficient k, and CM and DM inductances are:

$$k = \frac{M}{\sqrt{L_1 L_2}} = \frac{M}{L} \quad L_{cm} = \frac{L \pm M}{2} \quad L_{dm} = 2\left(L \mp M\right) \tag{1}$$

where L is the inductance per winding, and M is the mutual inductance between the two windings. In (1), the upper sign in front of M is for CM chokes and the lower one is for coupled DM inductors. Although the latter are not the subject of this paper, it is worth nothing that according to (1), when $k = 1$, i.e. assuming $M = L$, then $L_{cm} = 0$ and $L_{dm} = 4L$. Therefore, a coupled DM inductor is very different from two decoupled DM inductors, which would result in $L_{cm} = L/2$ and $L_{dm} = 2L$.

There can be different objectives with regards to the coupling between the windings of a CM choke.

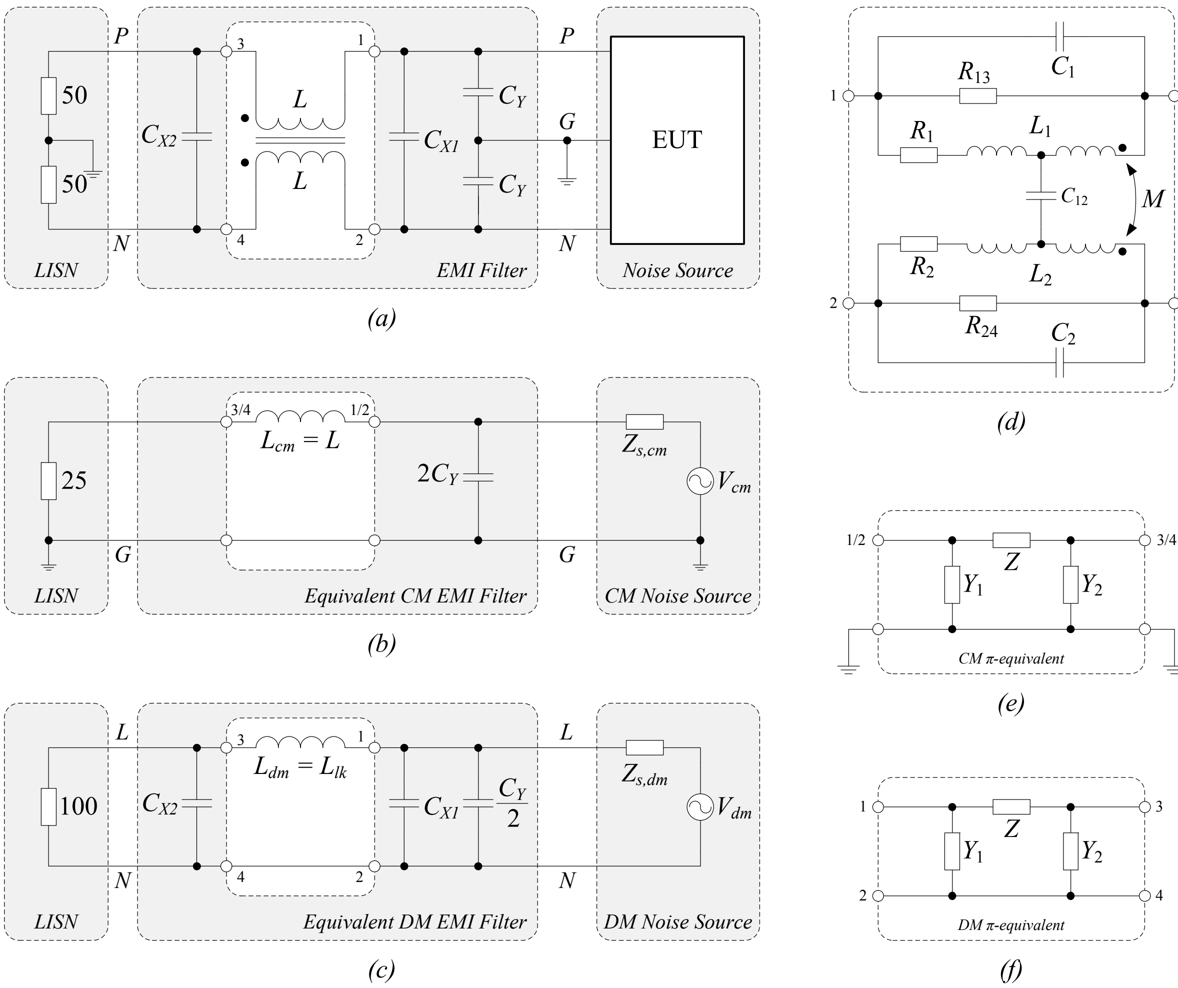

Fig. 2: *a*) Conducted emissions measurement set up, *b*) CM equivalent circuit, *c*) DM equivalent circuit; *d*) circuit model for CM chokes, *e*) CM π-equivalent circuit, *f*) DM π-equivalent circuit.

Sometimes the aim is to intentionally increase the leakage inductance [3] in order to achieve both the CM and DM suppression requirements with a single CM choke, thus minimizing the size and weight of the filter. In other cases the goal can be to boost the HF performance of the filter by cancelling the *equivalent parallel capacitance* (EPC) of the choke, which requires $k > 0.9999$ [4].

1.2 Circuit model for coupled inductors

The CM and DM equivalent inductances described in the pervious sub-section were caused by the magnetic coupling between the windings. Each winding is characterized not only by its inductance, but also by its ESR, EPC, and EPR, as in the models for two-terminal inductors (Fig. 1*a* and *b*). In addition to that, there is also parasitic capacitive coupling between the two windings. Thus the model for coupled inductors could be the circuit in Fig. 2*d*.

1.3 CM and DM characteristics

It was mentioned earlier that the models for two-terminal inductor are non-linear. Given the increased complexity of the coupled inductors model, it is reasonable to expect even more non-linear behavior. The CM and DM inductances alone cannot be accurate models of a CM choke in the equivalent circuits of a filter (Fig. 2*b* and *c*). Instead of only L_{cm} and L_{dm}, two π-type equivalent circuits of the CM choke (Fig. 2*e* and *f*) can be used in the equivalent circuits of the filter. Of course, each π-equivalent circuit can be converted to its T-equivalent, if necessary.

The following section describes two methods to obtain the CM and DM network parameters of a CM choke. In section 3 the same network parameters are used to calculate the CM and DM *insertion loss* (IL) as well as the elements of the CM and DM π-equivalent circuits of the same choke. These characterization methods can be used not only for CM chokes, but for any four-port network.

2 CM and DM network parameters

Multi-port networks have different CM and DM characteristics, which can be described by the corresponding network parameters. There is one set of CM parameters, and depending on the number of ports, one or more sets of DM network parameters. Four-port networks have one set of CM and another set of DM network parameters, which can be measured directly or indirectly.

2.1 Direct measurement

The CM and DM network parameters can be measured in the asymmetrical (Fig. 3*a*) and symmetrical test circuits (Fig. 3*b*). These are the same test circuits used to measure the CM and DM IL according to CISPR 17 standard [5]. The measured CM and DM s-parameters of RN143-6-02 [6] are shown with red lines in Fig. 4 and Fig. 5 respectively. If it is necessary, these s-parameters can be converted to any

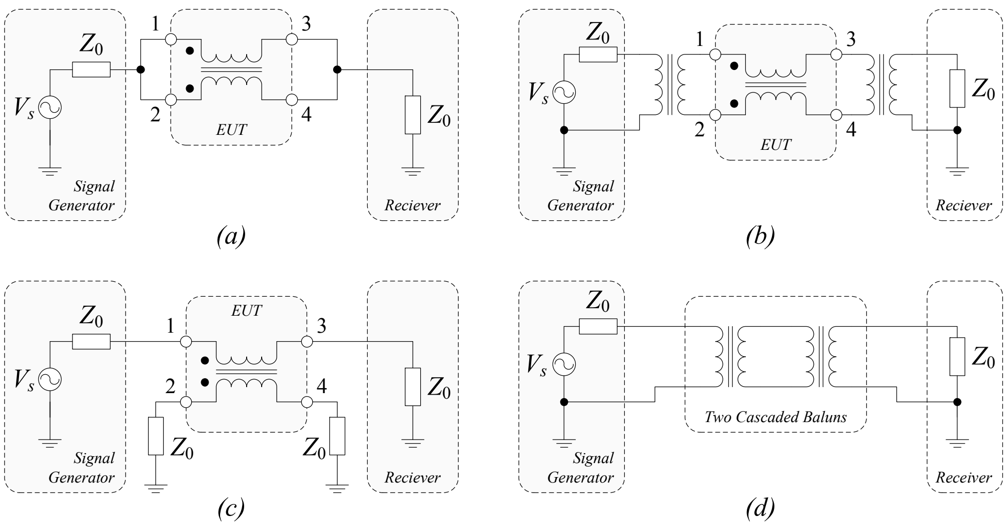

Fig. 3: *a*) Asymmetrical test circuit, *b*) symmetrical test circuit, *c*) test circuit for measuring the four-port single-ended s-parameters, *d*) the symmetrical test circuit without the EUT.

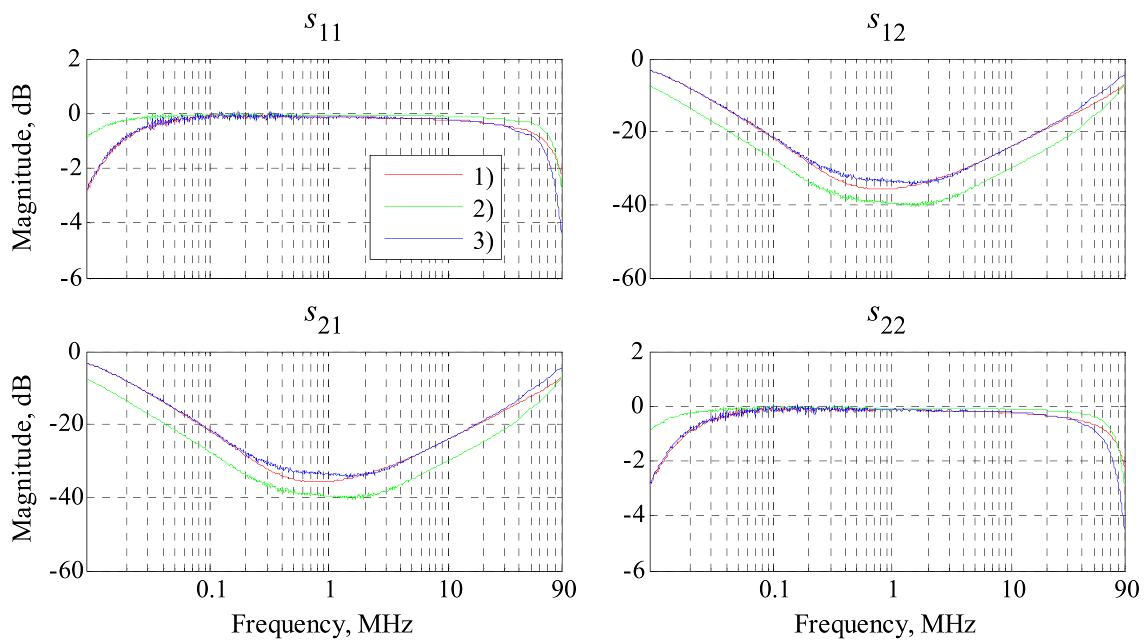

Fig. 4: CM s-parameters of RN143-6-02: 1) directly measured in the asymmetrical test circuit (Fig. 3*a*); 2) the CM sub-set from the mixed-mode s-parameters in Fig. 7 (note that $R_0 = 25\ \Omega$); 3) same as 2), but converted to $R_0 = 50\ \Omega$.

other type of network parameters: impedance z-, admittance y-, chain c-, or the hybrid g-, or h-parameters. Conversion tables between two-port network parameters can be found in many sources, e.g. in [7].

2.2 Indirect measurement

CM and DM network parameters are four complex coefficients, arranged in a 2×2 matrix, which relate the corresponding voltages and currents, or incident and reflected power waves. The CM and DM parameters of a four-port network can be calculated from its four-port network parameters, which are

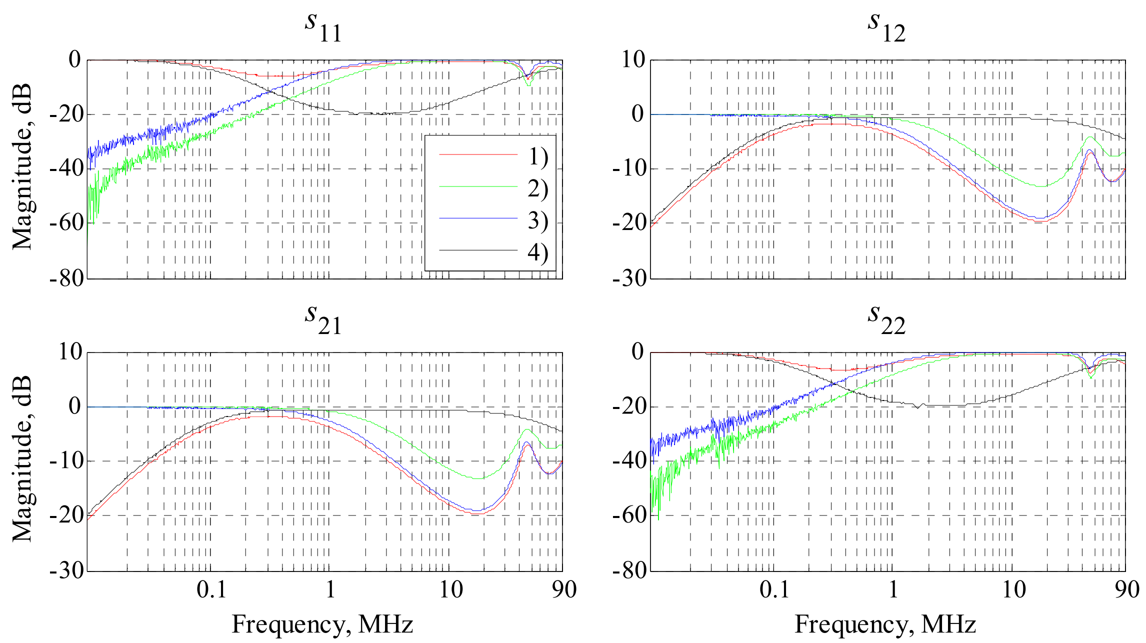

Fig. 5: DM s-parameters of RN143-6-02: 1) directly measured in the symmetrical test circuit (Fig. 3*b*); 2) the DM sub-set from the mixed-mode s-parameters in Fig. 7 (note that $R_0 = 100\ \Omega$); 3) same as 2), but converted to $R_0 = 50\ \Omega$; 4) the s-parameters of the two baluns measured as in Fig. 3*d*.

sixteen complex coefficients, arranged in a 4×4 matrix. The four-port network parameters can be z-, y-, or s-parameters. The c-, g-, and h-parameters are not defined for networks with more than two ports. For conversion between n-port network parameters refer to [8].

The test circuit for measuring the single-ended four-port s-parameters is shown in Fig. 3*c*. It should be noted that all ports must be terminated with the reference impedance and that the HF signal is applied not only to the first port, but to all ports in succession. In a four-port *vector network analyzer* (VNA) this process is automated, but with a two-port VNA there must be separate measurements for each pair of ports and external terminations must be used for the other two ports.

The single-ended four-port s-parameters of the same CM choke used in the direct measurements are shown in Fig. 6. They can be converted to mixed-mode s-parameters [9], two sub-sets of which are the CM and DM s-parameters. To continue the example with RN143-6-02, Fig. 7 shows the mixed-mode s-parameters, obtained from the single-ended s-parameters in Fig. 6. The CM s-parameters are the mixed-mode s-parameters with *cc*-subscript and the DM s-parameters are those with *dd*-subscript. It should be remembered that their reference impedances are different from that of the measured single-ended s-parameters. In the given example, where the single-ended four-port s-parameters have $R_0 = 50\ \Omega$, the CM mixed-mode s-parameters have half of that, i.e.25 Ω, and the DM mixed-mode s-parameters have double R_0, i.e. 100 Ω.

For comparison with the directly measured s-parameters, the mixed-mode CM s-parameters, but in dB, are plotted in Fig. 4 with green lines. Apparent the two differ, but the reason for that are the unequal reference impedances: 50 Ω for the direct measurement and 25 Ω in the indirect one. When the indirectly measured CM s-parameters are converted to 50 Ω reference impedance (the blue lines in Fig. 4) they are pretty close to the directly measured CM s-parameters (the red lines in Fig. 4).

The same comparison is made in Fig. 5 for the DM s-parameters. Again the mixed-mode DM s-parameters in dB are plotted with green lines and the directly measured DM s-parameters with red

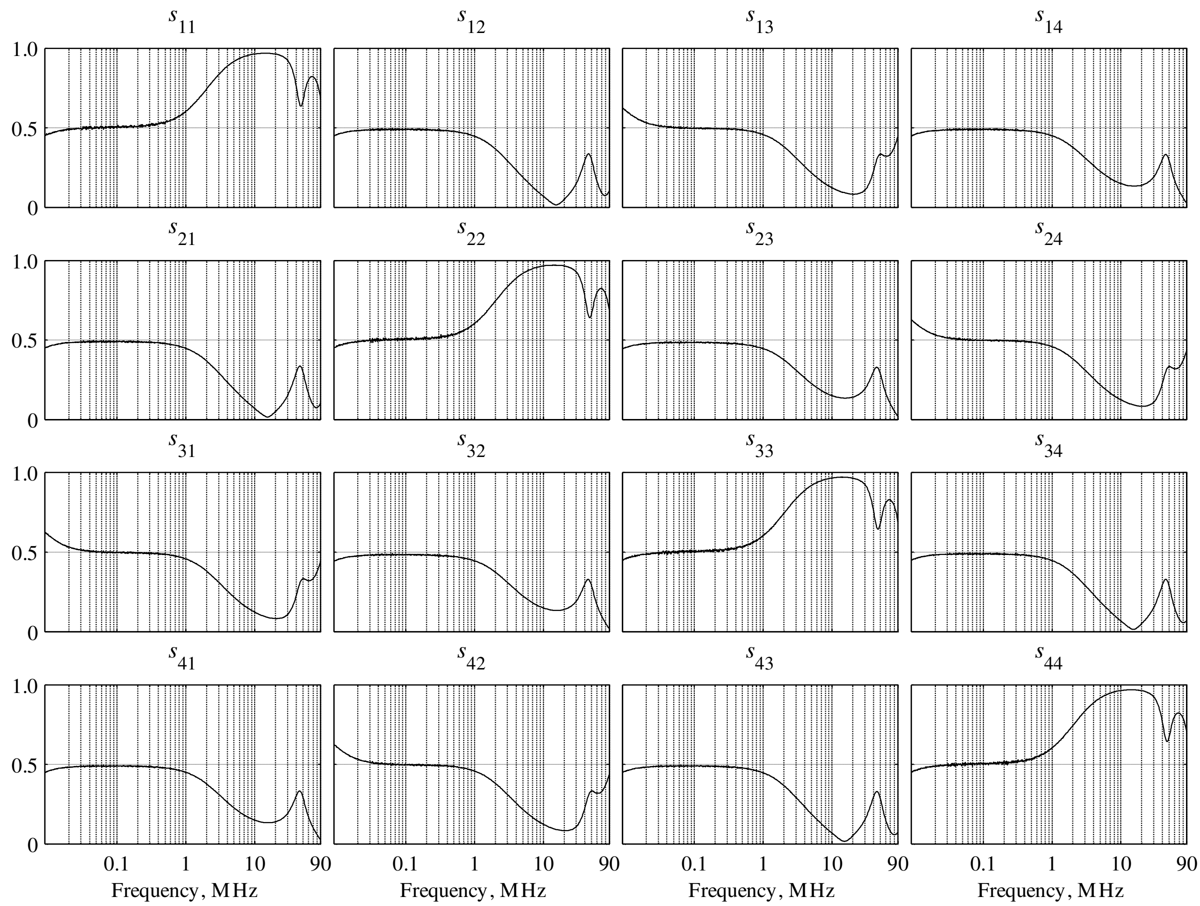

Fig. 6: Single-ended four-port s-parameters of RN143-6-02.

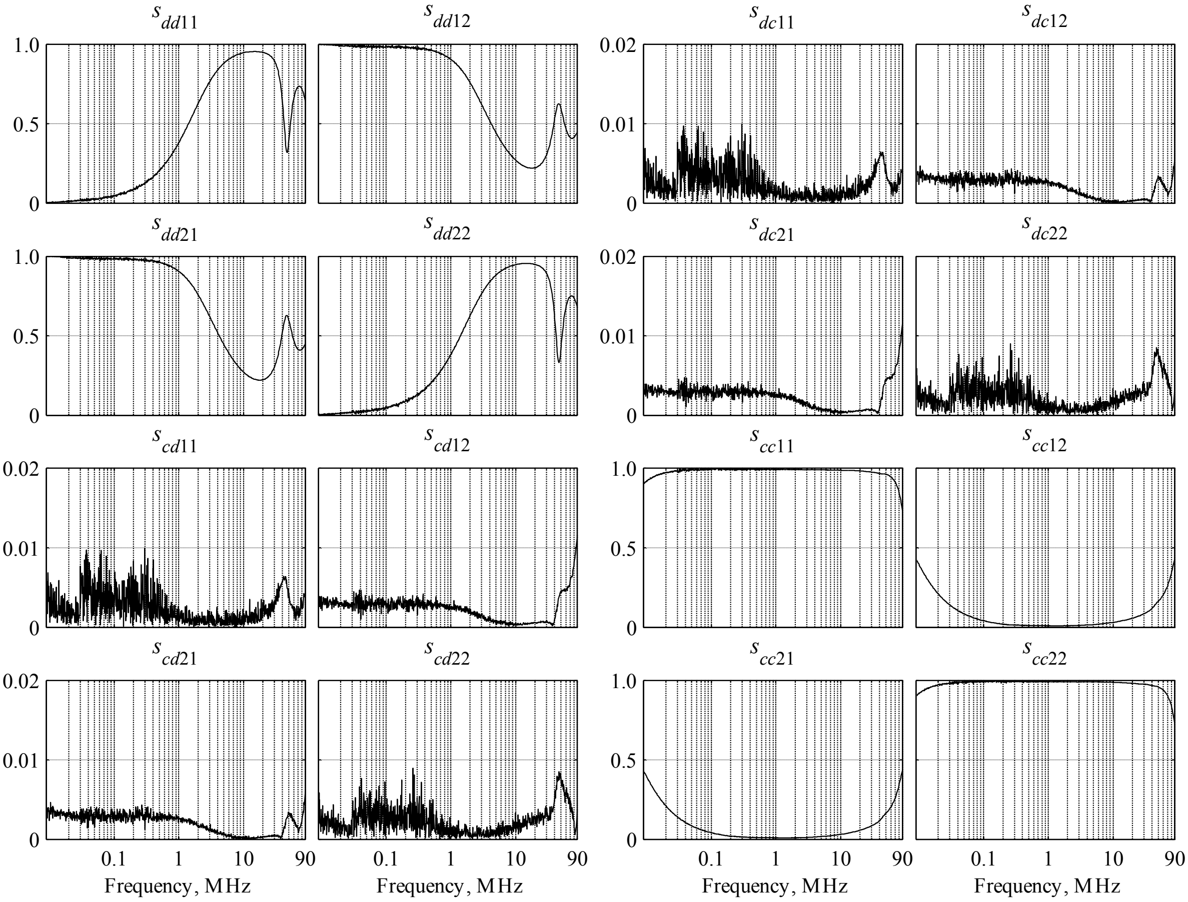

Fig. 7: Mixed-mode s-parameters, calculated from the single-ended four-port parameters shown in Fig. 6.

lines. In this case, even after the mixed-mode DM s-parameters are converted from 100 Ω to 50 Ω reference impedance (the blue lines in Fig. 5), they still differ significantly from the directly measured ones, especially up to about 500 kHz. This can be caused by the baluns in the symmetrical test circuit in Fig. 3*b*. If that is indeed the reason, then the direct DM s-parameter measurements have higher error than the indirect ones. To prove this point would require de-embedding, which we skip due to space restrictions. However, by looking at the s-parameters of the two baluns (the black lines in Fig. 5), which were measured as in Fig. 3*d*, it is obvious that the low values for the transmission coefficients up to a few hundred kHz are due to the baluns.

3 CM choke characterization

Traditionally, the IL has been used to characterize power filters or their elements. Unfortunately, the IL alone does not provide enough information for full characterization. In this section the CM and DM s-parameters, obtained as described in the previous section, are used to show how the IL and the elements of the π-equivalent circuit of a CM choke can be obtained.

3.1 CM and DM insertion loss

Most power supply engineers are aware that in real life power suppression filters and components do not provide the attenuation shown in the IL data published by manufacturers. The reason is that both the DM and CM IL are measured in the symmetrical and asymmetrical test circuits, Fig. 3*a* and *b* respectively, with the same source and load impedances, whereas in real life power filters operate under extreme mismatch conditions.

The IL at arbitrary source and load conditions can be obtained if all network parameters of the filter or component are known. In terms of two-port s-parameters it is given by the following equation [2]:

$$IL = 20 \cdot \lg \left| \frac{(1-\rho_s s_{11})(1-\rho_L s_{22}) - \rho_s \rho_L s_{12} s_{21}}{(1-\rho_s \rho_L) s_{21}} \right| \tag{2}$$

Where ρ_s and ρ_L are the source and load reflection coefficients respectively. They are related to the source and load impedances, Z_s and Z_L respectively, as follows:

$$\rho_s = \frac{Z_s - Z_0}{Z_s + Z_0} \quad \text{and} \quad \rho_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{3}$$

Thanks to its complex structure a CM choke has different CM and DM network parameters and consequently different CM and DM IL. If the s-parameters in (2) are the CM ones, the result is the CM IL, and if the s-parameters are the DM ones (2) yields the DM IL.

Using network parameters does not mean loosing the IL data that are currently published by manufacturers. These are readily available from measured CM and DM s-parameters of the choke. Regardless of the measurement method (direct or indirect), the source and load impedances are equal, i.e. $Z_s = Z_0$ and $\rho_s = \rho_L = 0$. Then the IL in terms of the measured CM or DM s-parameters and equal source and load impedances is:

$$IL' = 20 \cdot \lg \left| \frac{1}{s_{21}} \right| = -20 \cdot \lg |s_{21}| \tag{4}$$

Therefore, the frequency plot of s_{21} in dB is an upside-down plot of IL′ for a given reference impedance, but the benefit of using network parameters is to be able to determine the IL when the source and load impedances are different. This cannot be done with the IL′ data alone.

The CM and DM IL can be expressed also in terms of four-port z- and y-parameters [10].

3.2 CM and DM π-equivalent circuits

The π- or T-equivalent circuits should be used cautiously, because they are valid only for reciprocal networks, i.e. networks with $s_{12} = s_{21}$. Strictly speaking networks containing anisotropic materials, such as ferrites, are non-reciprocal, but as the measurements in Fig. 4, Fig. 5, and Fig. 7 show, at least in small-signal sense the CM choke appears to be a reciprocal network.

3.2.1 Transfer impedance

If the chain c-, or as they are often called, ABCD-parameters of a two-port network are known, the c_{12} coefficient is exactly the transfer impedance Z in the π-equivalent of that circuit [11]. Using the conversion from chain to s-parameters [7] it follows that Z in Fig. 2*e* or Fig. 2*f* in terms of s-parameters can be calculated as follows:

$$Z = c_{12} = \frac{R_0 \left[(1+s_{11})(1+s_{22}) - s_{12} s_{21} \right]}{2 s_{21}} \tag{5}$$

When the arguments in (5) are the CM s-parameters, the result is the CM transfer impedance. Similarly, if these are the DM s-parameters, the result is the DM transfer impedance. Note that the reference impedance R_0 in (5) may differ depending on which s-parameters are used.

Fig. 8 shows the CM and DM transfer impedances obtained from the corresponding measurements of the RN143-6-02 choke. These measured CM and DM impedances are compared with the two-terminal inductor models that where shown in Fig. 1*a* and *b*. In the CM models the inductance and ESR values are the per path values given in manufacturer's datasheet. The EPR in model 2 is the maximum of the measured impedance. The EPC in both models is calculated from the frequency at which Z peaks, because it is not given in the datasheet.

It is even more difficult to extract the values for the DM models: the inductance and EPC values were obtained by curve fitting; the ESR is twice the published per path value; and the EPR in model 2 was selected in the same way as in the corresponding CM model, i.e. it is equal to the maximum of the measured DM transfer impedance.

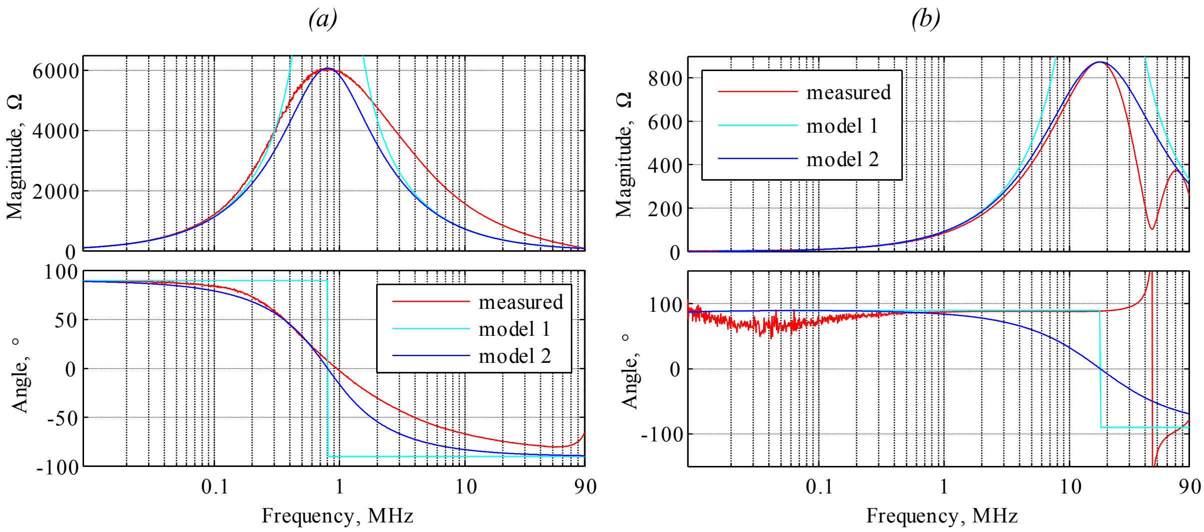

Fig. 8: *a*) Measured CM transfer impedance compared with the two-terminal models of inductors: model 1, shown in Fig. 1*a*, has $L = 1.8$ mH, $C_{EPC} = 22$ pF, and $R_{ESR} = 20$ mΩ; model 2, shown in Fig. 1*b*, is with $R_{EPR} = 6.1$ kΩ and the same L , EPC, and ESR as model 1; *b*) measured DM transfer impedance compared with model 1 ($L = 14.6$ μH, $C_{EPC} = 5.5$ pF, and $R_{ESR} = 40$ mΩ) and model 2 ($R_{EPR} = 875$ Ω and the same L , EPC, and ESR as in model 1.

Despite the efforts to fit the models to the measured values, it is evident that they can deviate very significantly from the measured CM and DM impedance. This is an illustration of the non-linearity of inductive components and CM chokes in particular. This non-linearity is even more pronounced in the DM characteristics of the CM choke.

3.2.2 Admittances Y_1 and Y_2

It was shown in [11] that the c_{11} and c_{22} coefficients in the chain matrix of a π-circuit are:

$$c_{11} = 1 + Y_1 Z \quad \text{and} \quad c_{22} = 1 + Z Y_2 \tag{6}$$

where Z is already known. Solving for Y_1 and Y_2, expressing c_{11} and c_{22} in terms of s-parameters [7], and substituting Z from (5) gives the following equations for the admittances in the CM and DM π-equivalent circuits:

$$Y_1 = \frac{c_{11} - 1}{Z} = \frac{(1 - s_{11})(1 + s_{22}) + s_{12}s_{21} - 2s_{21}}{R_0\left[(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}\right]} \quad Y_2 = \frac{c_{22} - 1}{Z} = \frac{(1 + s_{11})(1 - s_{22}) + s_{12}s_{21} - 2s_{21}}{R_0\left[(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}\right]} \tag{7}$$

Again when the arguments in (7) are the CM s-parameters the results are the CM admittances, and when the arguments are the DM s-parameters (7) yields Y_1 and Y_2 for DM.

Fig. 9 shows the CM and DM admittances obtained from the CM and DM s-parameters of RN143-6-02. Ideally, for any CM choke, Y_1 and Y_2 should be zero. They are indeed very small, but depending on the required modeling accuracy and at very high frequencies, they might not be negligible. No attempts were made to model them as it was done with the transfer impedance.

4 Conclusion

This paper reviewed the models for two- and four-terminal inductors. The main focus was on the characterization of CM chokes, but the methods presented can be used without limitations to any four-port network, like single-phase power filters.

Two methods to obtain the CM and DM characteristics of a CM choke were demonstrated and compared. The indirect method requires measurements of the standard, single-ended, four-port s-parameters. With a four-port VNA this should be the fastest and most accurate method. Next the standard four-port s-parameters must be converted to mixed-mode s-parameters. It must be remembered, that as a result of that conversion the reference impedance changes. The elements of the CM and DM

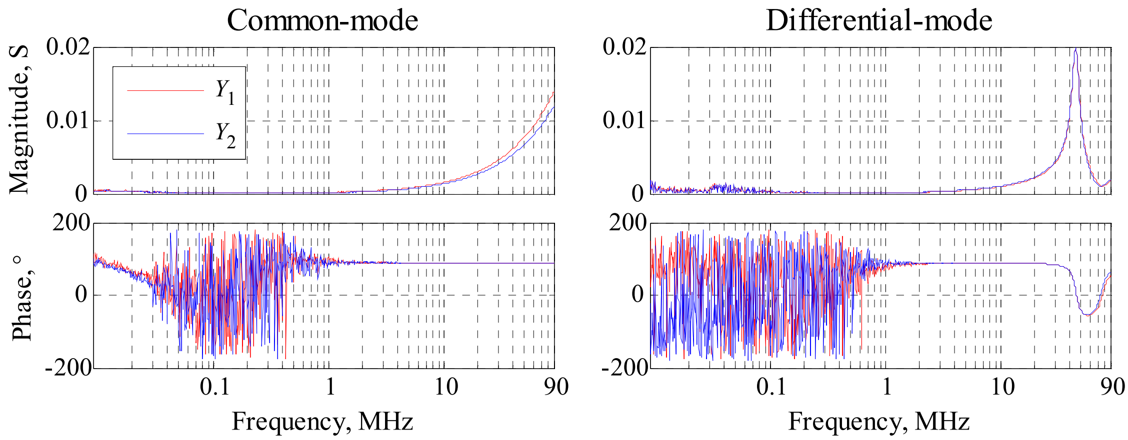

Fig. 9: Measured CM and DM Y_1 and Y_2 admittances in the π-equivalent circuit of RN143-6-02.

equivalent circuits, the corresponding IL, or other characteristics of the four-terminal filter or component, can be calculated from its CM and DM network parameters, which are sub-sets of the mixed-mode s-parameters.

The direct method requires two separate two-port s-parameter measurements: one for the CM and another for the DM s-parameters. When these are known, the remaining steps for deriving the corresponding CM and DM characteristics are analogous to the indirect method. The main disadvantage of the direct measurement method is that it requires auxiliary networks to convert the four-port device into a two-port one. The s-parameters of these auxiliary networks are part of the measured s-parameters and must be minimized in some way. In the CM measurement, keeping the connections as short as possible might be sufficient. In the DM measurement, however, that would not be enough, because the main error might not be from the length of the wires, but from the baluns, used to convert the balanced ports of the EUT to unbalanced ones.

The discrepancy between linear models and measured data demonstrates the non-linear characteristics of the CM choke coil under study. The model in Fig. 1*b* was found to be the better one among the two alternatives for two-terminal inductors.

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