Six-port scattering parameters of a three-phase mains choke for consistent modelling of common-mode and differential-mode response

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Abstract – The characterization of passive component properties over a wide frequency range is usually done using scattering parameters. This paper presents the measurement and modeling approach for two typical three-phase mains chokes $(3x100\mu H,$ 230V, 60A and 3x2.3mH, 230V, 65A) based on six-port scattering parameters using a common two-port vector network analyzer. The model allows to reproduce consistently common-mode and differential-mode response of a passive six-port device, covering a frequency range from 10Hz to 300MHz.

I. INTRODUCTION

In the past few years mainly two methods have been developed, which enable to use scattering parameter data for transient simulations and accomplish a transparent conversion simultaneously. These are the Convolution Method and the Rational Fit Method [1]. Both require frequency based models for passive devices. In this particular case a six-port device needs to be modeled. It is however difficult to distinguish common-mode and differential-mode stimulus in a realistic transient simulation scenario. As a result, a consistent model for common-mode and differential-mode response has to be used. The technique described here is using the symmetries of the three-phase mains choke to simplify the matrix of scattering parameters. Thus it becomes possible to use a standard twoport vector network analyzer to measure all unique scattering parameters. The measured data is then converted into the sixport scattering matrix by using a MATLAB script. After proofing passivity and rational fitting, the model is ready to be used in a transient simulation environment for consistent modeling of common-mode and differential-mode response. In the past, various papers have been published for the characterization of N-ports with a 2-port analyzer [2], [3]. Furthermore, there are publications [4], [5] and [6] that deal with the problems of error-correction and termination. This work is based on N-port scattering parameters provides a model readily to be used in simulation tools compared to mixed mode scattering parameter models [4].

II. MEASUREMENT REQUIREMENTS AND DUT-STRUCTURE

The requirements for the scattering parameter measurement have been defined as follows. Conducted emissions are generated in a frequency range from 9kHz to 30MHz. For characterization of passive components and suppression of this interference the measurement should be performed in the same frequency range. For safe eliminations of side effects it is recommended to simulate at least an order of magnitude above the highest conducted emission frequency. Due to the extremely frequency-dependent impedances the measurement setup for passive components should have a dynamic range of at least 100dB.

The connection of in dimension and design highly variable components to a measurement cable, should ensure, that the components are contacted as short as possible and sheath waves in the cable are suppressed by broadband ferrites. Amplitude and phase errors have to be eliminated by calibrating the network analyzer at the connection plane of the component.

Fig. 1 illustrates the three-phase mains chokes. The threephase mains chokes exhibit a rigid magnetic coupling, because all three windings have been applied on one core.



Fig. 1: Three-phase mains chokes (a: $3x100\mu$ H, 230V, 60A and b: 3x2.3mH, 230V, 65A)

For the fundamental frequency (50Hz) they can be considered as current-compensated. However, the value of parasitic capacitances and stray inductances influencing the behavior at higher frequencies is unknown. For this reason a consistent model valid in a broad frequency range is needed. Fig. 2 shows the equivalent circuit diagram of the three-phase mains chokes.



Fig. 2: Equivalent circuit diagram of the three-phase mains chokes

III. METHODOLOGY

The general definition of six-port scattering parameters allows a description of all permutational couplings for a component with a total of six ports. Equation (1) shows the common six-port scattering parameter matrix. It describes the reflection at each port on the main diagonal. On all other places the transmissions between the corresponding ports can be found.

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix}$$
(1)

Due to the highly symmetrical internal structure of the mains choke a simplification of the scattering parameter matrix is possible. The three-phase mains choke has a reciprocal response (2).

$$\mathbf{S}_{kj} = \mathbf{S}_{jk} \tag{2}$$

The component is a strictly symmetrical. This means that the reflection at all ports and all values at the main diagonal are equal. The following simplifications are therefore valid (3-6).

$$S_{11} = S_{22} = S_{33} = S_{44} = S_{55} = S_{66}$$
(3)

$$S_{12} = S_{21} = S_{34} = S_{43} = S_{56} = S_{65} \tag{4}$$

$$S_{13} = S_{31} = S_{24} = S_{42} = S_{35} = S_{53} = S_{46} = S_{64} = S_{51} = S_{15} = S_{62} = S_{26}$$
(5)

$$S_{14} = S_{41} = S_{23} = S_{32} = S_{36} = S_{63} = S_{45} = S_{54} = S_{61} = S_{16} = S_{52} = S_{25}$$
(6)

Because of the redundancy it continues to apply (7-8).

$$S_{15} = S_{51} = S_{26} = S_{62} = S_{31} = S_{13} = S_{42} = S_{24} = S_{53} = S_{35} = S_{64} = S_{26}$$
(7)

$$S_{16} = S_{61} = S_{25} = S_{52} = S_{32} = S_{23} = S_{41} = S_{51} = S_{63} = S_{36} = S_{54} = S_{45}$$
(8)

Equation (9) shows the simplification of the scattering parameter matrix of the three-phase mains choke.

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{13} & S_{14} \\ S_{12} & S_{11} & S_{14} & S_{13} & S_{14} & S_{13} \\ S_{13} & S_{14} & S_{11} & S_{12} & S_{13} & S_{14} \\ S_{14} & S_{13} & S_{12} & S_{11} & S_{14} & S_{13} \\ S_{13} & S_{14} & S_{13} & S_{14} & S_{11} & S_{12} \\ S_{14} & S_{13} & S_{14} & S_{13} & S_{12} & S_{11} \end{bmatrix}$$
(9)

Network analyzers with six measurement ports are poorly available and expensive [2]. Therefore the six-port scattering parameters have been measured separately in a 500hm environment with a commercially available two-port network analyzer. The reflection and transmission factors of the first coil $(S_{11} \text{ and } S_{12})$ can be determined with one measurement simultaneously (Fig. 3). The transmission factors S_{13} and S_{14} respectively have to be measured separately (Fig. 4, Fig. 5). In all measurements the free ports have been terminated reflection-free with 500hm resistances. In [3] and [6] methods are described, which uses non-ideal or unknown terminations. For the frequency range used here (10Hz-300MHz) the 50Ohm terminations can be considered as ideal. Using a two-port network analyzer it is possible to characterize the three-phase mains choke with a total of three measurements completely. The final six-port scattering parameter matrix has to be assembled by use of a MATLAB script after the measurement.



Fig. 3: Measurement setup for determination of the six-port scattering parameters of the mains chokes (S11 and S12)



Fig. 4: Measurement setup for determination of the six-port scattering parameters of the mains chokes (S13)



Fig. 5: Measurement setup for determination of the six-port scattering parameters of the mains chokes (S14)

Fig. 6 and Fig. 7 show the simulation setup for the separate two-port common-mode and differential-mode impedance measurement and calculation with the simulation tool AWR MWO.



Fig. 6: Setup for common-mode impedance measurement and calculation



Fig. 7: Setup for differential-mode impedance measurement and calculation

IV. RESULTS AND DISCUSSION

Fig. 8 - Fig. 11 show an examples of the measured scattering parameters. They form the frequency dependent sixport scattering parameter matrix as described above.



Fig. 8: Six-port scattering parameter S11 (2.3mH mains choke)



Fig. 9: Six-port scattering parameter S12 (2.3mH mains choke)



Fig. 10: Six-port scattering parameter S13 (2.3mH mains choke)



Fig. 11: Six-port scattering parameter S14 (2.3mH mains choke)

The six-port scattering parameters can be used to derive frequency-dependent common-mode and differential-mode impedances. Fig. 12 shows the calculated six-port common-mode and differential-mode impedances of the $3x100\mu$ H three-

phase mains choke. These are compared against standard twoport common-mode and differential-mode measurements using the measurement setups as given by Fig. 6 and Fig. 7.



Fig. 12: Common-mode (Zeven) and differential-mode impedance (Zodd) of the three-phase mains choke 3x100uH by comparison of six-port and two-port approach

It can be clearly seen, that the mains choke are working properly only up to a frequency of about 600kHz. At this frequency the common-mode impedance reaches a maximum of 500Ohm, then reduces due to parasitic winding capacitance and finally crosses the differential-mode impedance at about 10MHz. The parasitic common-mode winding capacitance can be approximated to be 230pF (300Ohm@2.3MHz). Below 600kHz the common-mode impedance is about 2 orders of magnitude above the differential-mode impedance. The lower differential-mode impedance limit of 0.01Ohm is caused by the measurement principle using scattering parameters as a basis of the impedance calculation. They are limited to a dynamic range of about 100dB.

The differential-mode impedance shows a lower parasitic capacitance and thus a higher first resonance at about 25MHz. The maximum impedance is 1kOhm and is thus approximately twice as high compared to the maximum common mode impedance. The parasitic differential-mode capacitance can be approximated to 170pF (2000hm@4.5MHz).

Above 70MHz the common mode impedance and differential mode impedance equalize more and more, caused by the loss of magnetic coupling. Higher resonances at frequencies above 30MHz are caused by cable lengths of the windings acting as lambda/4 cable transformer.

Fig. 13 shows the relative errors between six-port and twoport approach of common-mode and differential-mode impedances of the $3x100\mu$ H mains choke. The differentialmode error below 20kHz is caused by the measurement method. But these are not relevant in this context, because conducted emissions to be examined are between 150kHz and 30MHz. Errors at high frequencies greater than 20MHz, especially in the differential-mode require further investigations and will not be considered here.

Fig. 14 shows the calculated six-port common-mode and differential-mode impedances of the 3x2.3mH three-phase mains choke. These are compared against standard two-port

common-mode and differential-mode measurements using the measurement setups as given by Fig. 6 and Fig. 7.



Fig. 13: Relative errors of common-mode and differential-mode impedances of the three-phase mains choke 3x100uH

At 300kHz the common-mode impedance reaches a maximum of 6kOhm, then reduce due to parasitic winding capacitance and finally crosses the differential-mode impedance at about 3MHz. The value of the parasitic common-mode winding capacitance is about 130pF (300Ohm@4MHz). Below 300kHz the common-mode impedance is about 2 orders of magnitude above the differential-mode impedance.

The differential-mode impedance shows a lower parasitic capacitance and thus a higher first resonance at about 5MHz. The maximum of the impedance is about 2kOhm and about half as high as the common-mode impedance. The parasitic differential-mode capacitance can be approximated to 30pF (500Ohm@10MHz).

Above 20MHz, the common mode and differential-mode impedances equalize to more and more, caused by the loss of magnetic coupling. The resonances above about 30MHz are caused by cable lengths of the windings acting as lambda/4 cable transformer.



Fig. 14: Common-mode (Zeven) and differential-mode impedance (Zodd) of the three-phase mains choke 3x2.3mH by comparison of six-port and two-port approach

Fig. 15 shows the relative errors between six-port and twoport approach of common-mode and differential-mode impedances of the 3x2.3mH mains choke. The differentialmode error below 20kHz is caused by the measurement method.



Fig. 15: Relative errors of common-mode and differential-mode impedances of the three-phase mains choke 3x2.3mH

The high common-mode error of the 3x2.3mH mains choke in the frequency range from 60kHz to 3.5MHz are explained more in detail.

Fig. 16 shows the mechanical design of a coil of the threephase mains choke 3x2.3mH and the multilayer structure of the windings. This multilayer structure results in an extended equivalent circuit shown for one coil in Fig. 17.



Fig. 16: Mechanical design of a coil of the three-phase mains choke 3x2.3mH

The common-mode impedance errors in the frequency range 60kHz to 3.5MHz can only be observed if, first, a double layer winding structure is given. Second, there must be an asymmetry between the three coils at the core, which is usually the case. Third, it is essential that the asymmetric coil has an inductance value which is lower than the inductance of the other two coils. In this case the inductance value is about 8% lower than the nominal inductance value.

If these prerequisites are given the inductance asymmetry acting as a differential-mode inductance is connected in series to the common-mode capacitance of about 3x130pF=360pF (falling slope of the common-mode impedance above the first resonance at 300kHz). The differential-mode impedance of the inductance asymmetry is increasing for increasing frequencies. This will cancel out the influence of the common-mode capacitance once it has reached the same impedance level (3500hm@3.5MHz).

The two-port common-mode measurement used for validation purpose doesn't reflect these asymmetries as the three coils are physically connected in parallel, suppressing any inductance asymmetry. It is however still in question which of the two approaches (i.e. six-port or two-port) is closer to a real application circuit.



Fig. 17: Extended equivalent circuit of one coil of the three-phase mains-choke 3x2.3mH

The error in the differential-mode at around 6MHz and errors at high frequencies greater than 25MHz require further investigations and will not be considered here.

V. SUMMARY

A consistent model of a three-phase mains choke for use in transient simulation environments has been developed. The measurement and model-building process based on standard two-port scattering parameters has been described in detail. In dependency of the specific application circuit, the particular mains choke investigated here provides sufficient common-mode suppression, only up to about 1MHz. The loss of common-mode and differential-mode suppression is caused the parasitic winding capacitances in the order of 50–250pF. Any errors that occur in the frequency range to be examined are caused by coils and parasitic winding capacitances asymmetries.

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