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

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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 2-port scattering parameters has been described in detail. The particular mains chokes investigated here provides sufficient common-mode suppression only up to few MHz. The loss of common-mode suppression is caused by the parasitic winding capacitances. Differences between the model behavior and a rigorous impedance measurement of the DUT are most likely caused by parasitic winding capacitances and coils asymmetries.

I. Introduction

- Using scattering parameters for consistent impedance modeling
- Model used for conducted emissions simulations (9kHz – 30MHz)
- Here: simplified 6-port scattering parameter model
- Measuring all unique scattering parameters by a standard 2-port network analyzer
- Consistent modeling of common-mode and differential-mode response in a realistic transient simulation scenario

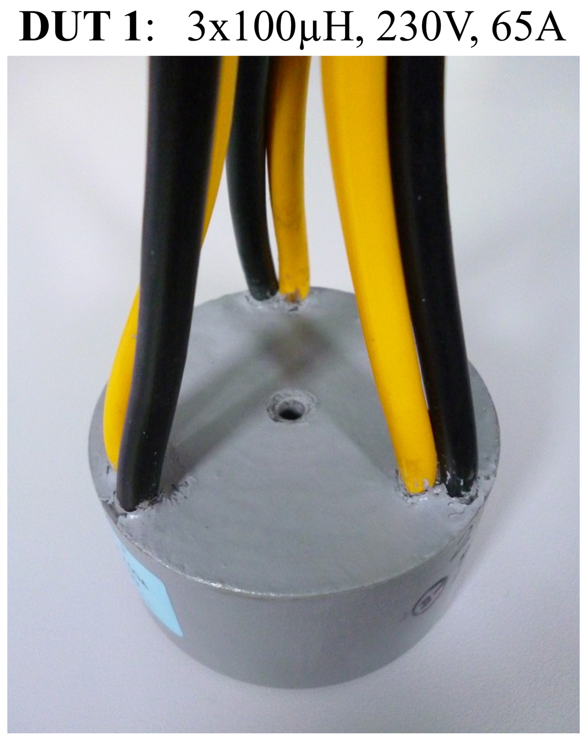
II. Measurement Requirements

- Frequency range 10Hz to 300MHz to cover fundamental frequency (50Hz)
- Dynamic range ≥ 100dB to cover interesting impedance range
- Using broadband ferrites to suppress sheath waves on coaxial measurement cables
- Calibration at the connection plane of the DUT
- Connection to DUT as short as possible

III. DUT-Structure

- Three coils on one toroidal ferrite core in one or multilayer structure
- Rigid magnetic coupling
- Current-compensated for fundamental frequency (50Hz)
- Unknown behavior at higher frequencies due to parasitic capacitances, stray inductances and asymmetries

DUT 1: 3x100µH, 230V, 65A



DUT 2: 3x2.3mH, 230V, 65A

IV. Methodology

- Scattering parameter matrix simplification due to symmetrical structure of the DUT:

1. Reciprocity:
$$S_{12}=S_{21}=S_{34}=S_{43}=S_{56}=S_{65}$$
$$S_{13}=S_{31}=S_{24}=S_{42}=S_{35}=S_{53}=S_{46}=S_{64}=S_{51}=S_{15}=S_{62}=S_{26}$$
$$S_{14}=S_{41}=S_{23}=S_{32}=S_{36}=S_{63}=S_{45}=S_{54}=S_{61}=S_{16}=S_{52}=S_{25}$$

2. Symmetry:
$$S_{11}=S_{22}=S_{33}=S_{44}=S_{55}=S_{66}$$

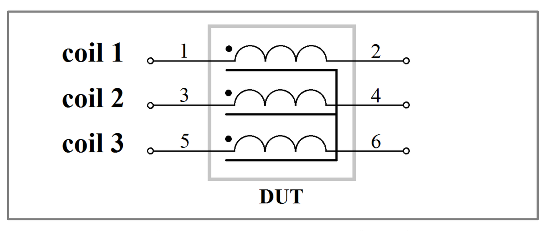
- Only four scattering parameters to be measured S11, S12, S13 and S14
- Assembling of the simplified 6-port scattering parameter matrix by a MATLAB script after the measurement

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

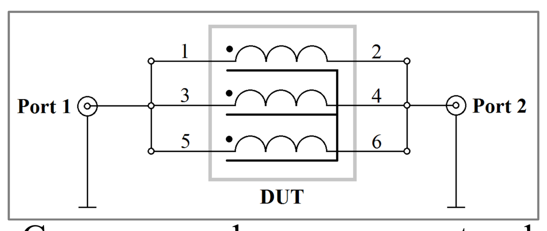
Simplified 6-port scattering parameter matrix of three-phase mains choke

V. Measurement and Simulation Setups

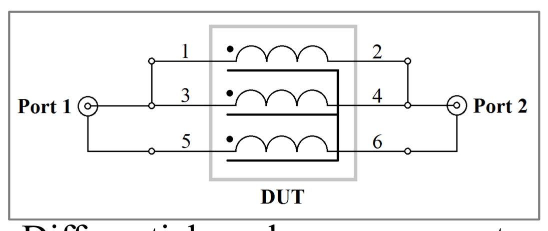
- Reflection-free termination of the free ports during measurements
- Comparison of the simulated impedances against standard 2-port measurements



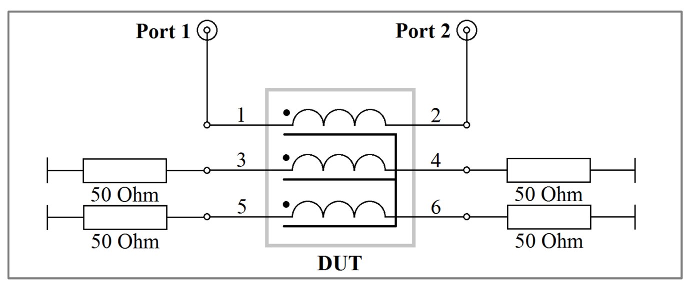
DUT assignment terminal to coil name



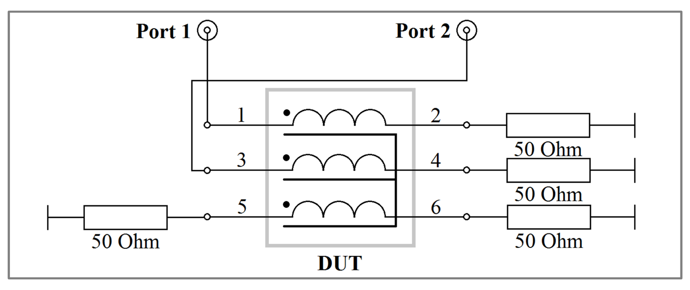
Common-mode measurement and simulation setup



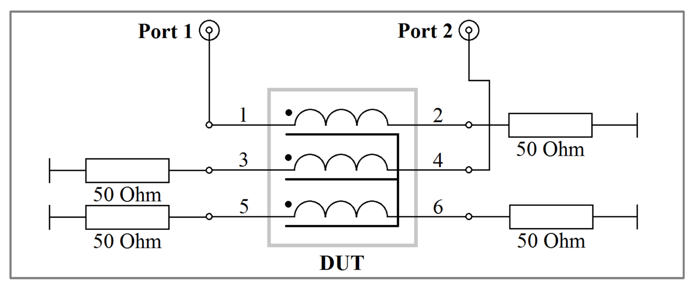
Differential-mode measurement and simulation setup



Measurement setup for determination of the 6-port scattering parameters of the mains chokes (S11 and S12)



Measurement setup for determination of the 6-port scattering parameters of the mains chokes (S13)



Measurement setup for determination of the 6-port scattering parameters of the mains chokes (S14)

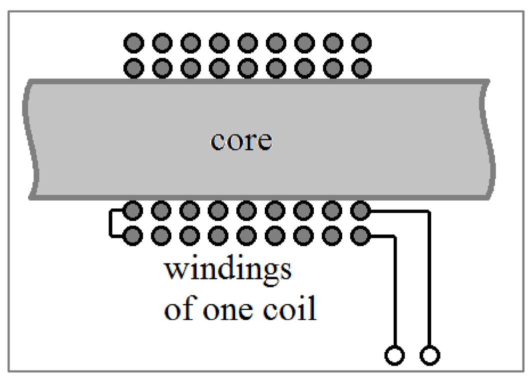
VI. Results and Discussion

- Results given as a graphical comparison between simulated 6-port and measured 2-port impedance curves separate in common-mode
  (simulated 6-port in blue traces and measured 2-port in brown traces)
  and in differential-mode
  (simulated 6-port in magenta traces and measured 2-port in red traces)
  by above setups
- Calculation of the relative error curves by subtraction of the simulation results with the measured results separate in common-mode (blue traces) and in differential-mode (red traces)

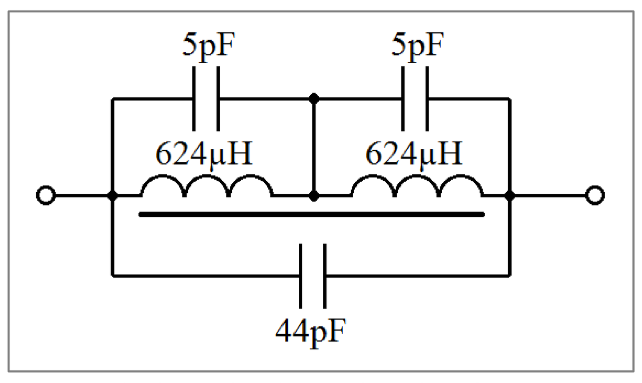
Key data of DUTs	DUT 1: 3x100uH, 230V, 65A		DUT 2: 3x2.3mH, 230V, 65A	
	common-mode	differential-mode	common-mode	differential-mode
First impedance maximum	500Ω@600kHz	1kΩ@25MHz	6kΩ@300kHz	2kΩ@5MHz
Parasitic winding capacitance	230pF (300Ω@2.3MHz)	170pF (200Ω@45MHz)	130pF (300Ω@4MHz)	30pF (500Ω@10MHz)
Maximum relative deviation in the relevant frequency range (150kHz-30MHz)	+0.5dB@30MHz	+5dB@30MHz	-9dB@350kHz	+13dB@7MHz

Explanation of the high common-mode difference in the frequency range from 60kHz to 3.5MHz of DUT 2 in detail:

- Higher inductance value leads to double layer winding structure and extended equivalent circuit
- Asymmetry between the three coils on the core
- Inductance value of coil 3 3.5% lower than coil 1 and coil 2
- The common-mode capacitance in series with the inductance asymmetry acting as differential-mode inductance decreases the simulated common-mode impedance level by about 60% compared to the rigorous common-mode impedance measurement
- Effect suspends at 3.5MHz when differential-mode impedance crosses common-mode impedance

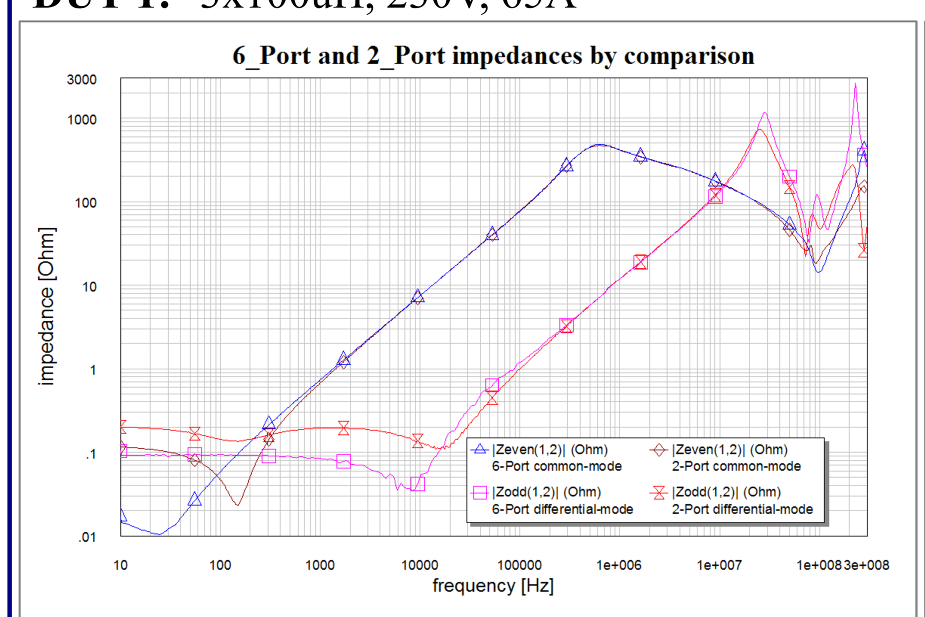


Mechanical design of a double layer coil

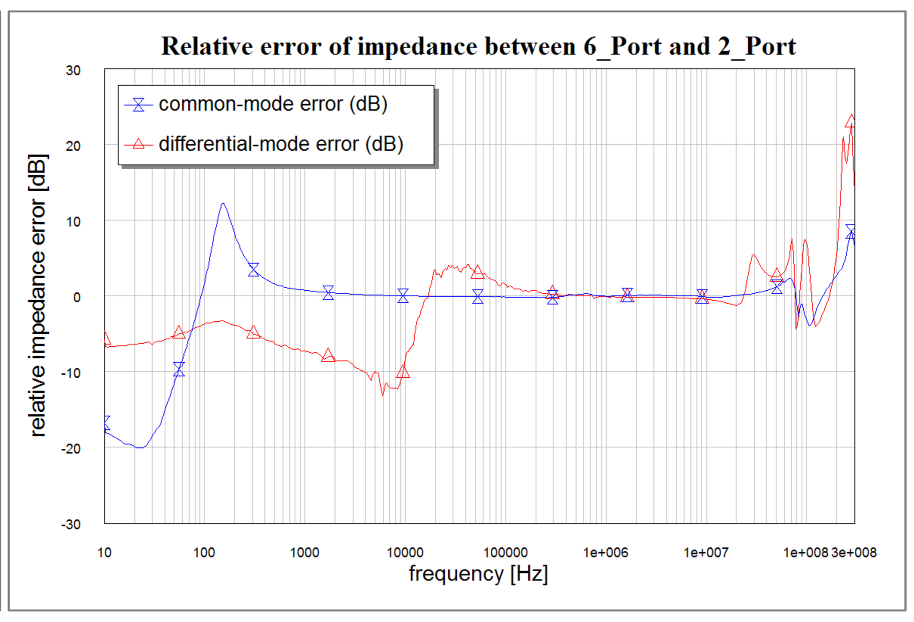


Extended equivalent circuit of one double layer coil of DUT 2

DUT 1: 3x100uH, 230V, 65A

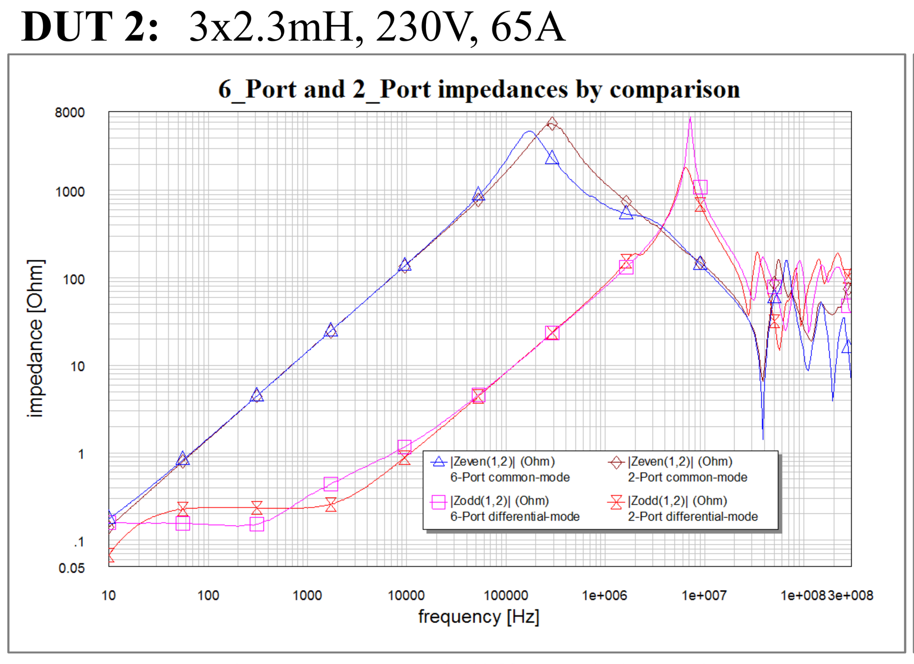


Common-mode (Zeven) and differential-mode impedance (Zodd) by comparison of 6-port and 2-port approach

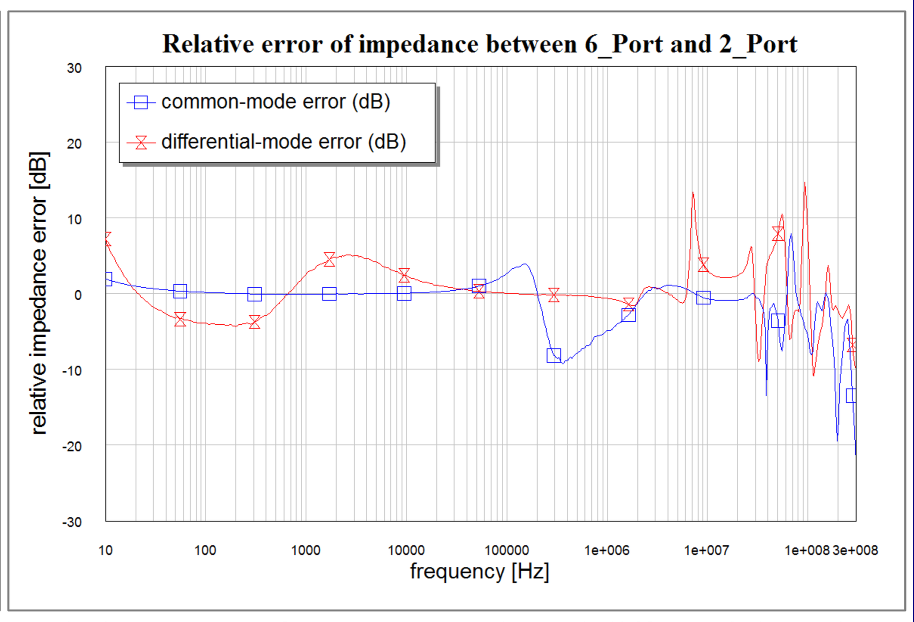


Relative errors of common-mode and differential-mode impedances

DUT 2: 3x2.3mH, 230V, 65A



Common-mode (Zeven) and differential-mode impedance (Zodd) by comparison of 6-port and 2-port approach



Relative errors of common-mode and differential-mode impedances

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