Bode 500 - Application Note

Modeling Multi-Resonance Common-Mode Chokes

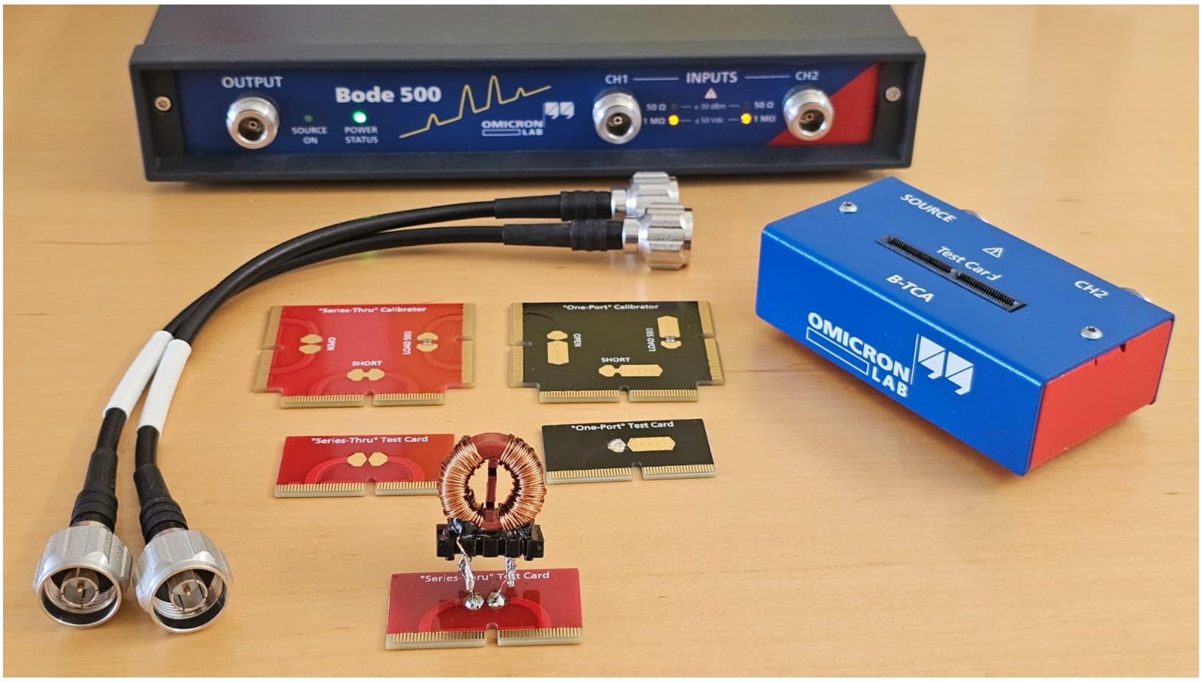

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Table of Contents

Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual available at:
[Bode 100, Bode 500 Vector Network Analyzer User Manual (omicron-lab.com)]

Note: All measurements in this application note have been performed using the Bode Analyzer Suite V3.51 Use this version or a newer version to perform the measurements shown in this document. You can download the latest version at
[Bode Analyzer Suite - Download Area - OMICRON Lab (omicron-lab.com)]

1 Executive Summary

In modern power electronics, common-mode (CM) chokes are essential for mitigating electromagnetic interference (EMI) and ensuring system stability. Characterizing their impedance goes beyond simple impedance measurements; it requires capturing frequency-dependent behavior and parasitic effects for reliable EMI simulations and robust filter design.

This application note describes the measurement of CM chokes using the Bode 500 in impedance analysis mode with the B-TCA fixture [1]. It covers setup, calibration, and acquisition of impedance magnitude and inductance data. The results enable precise modeling based on the behavioral modeling method introduced by Ivica Stevanovic in “Behavioral Modeling of Chokes for EMI Simulations in Power Electronics” [2]. This technique captures frequency-dependent characteristics and parasitic effects, including higher-order resonances, enabling EMI simulations and robust filter design. Neglecting this analysis may lead to poor EMI suppression, regulatory failures, and unstable designs.

2 Measurement Task & Setup

The objective of this measurement is to characterize the impedance behavior of common-mode chokes in common-mode (CM) and differential-mode (DM) configurations over frequency.

The measurement focuses on obtaining impedance magnitude and equivalent inductance across a wide frequency range to capture frequency-dependent characteristics and parasitic effects.

Dedicated measurement configurations are applied for CM and DM to ensure reliable results.

2.1 Measurement Setup

2.1.1 Common-Mode Choke DUT

Figure 1 illustrates the WE-CMB common mode choke used for the measurement. This component was sourced from Würth Elektronik’s Design Your EMC Filter kit [3] and is identified by part number 744824220 [4].

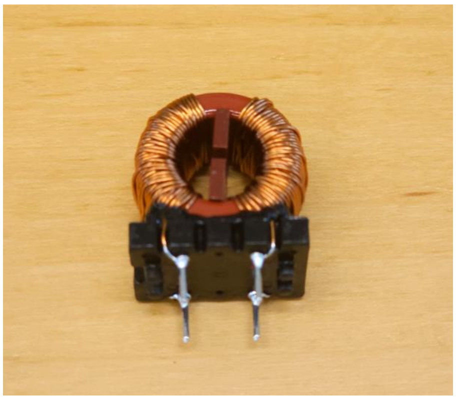


Figure 1: Device under test (DUT): common-mode choke

2.1.2 Measurement Setup using the Bode 500 & B-TCA

The measurement setup consists of the Bode 500 used in combination with the B-TCA test fixture, providing a controlled environment for impedance characterization of the choke under test.

The B-TCA minimizes parasitic effects and ensures stable and repeatable measurement conditions. It supports measurement configurations such as Shunt-Thru, Series-Thru, or One-Port, allowing impedance characterization across a wide frequency range and impedance range. The choke is connected to the B-TCA according to the selected configuration, as shown in Figure 2.

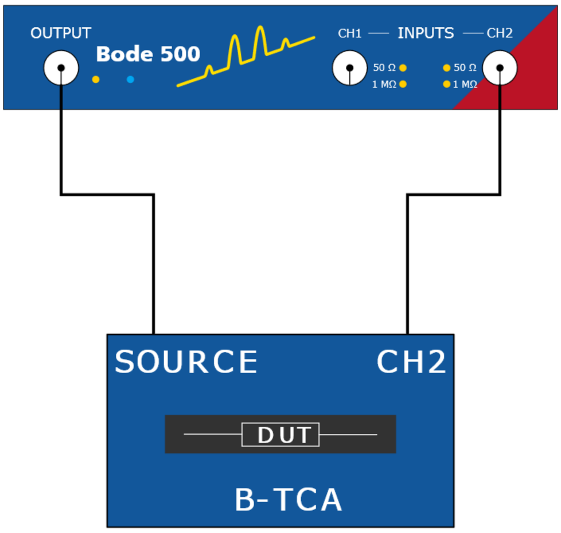


Figure 2: B-TCA test card adapter used for impedance measurements

2.1.3 Bode Analyzer Suite:

The Bode Analyzer Suite (BAS) is used to configure and control the Bode 500 during the measurements. It allows the definition of measurement parameters and the selection of different impedance measurement configurations, such as the Series-Thru and One-Port methods.

The configuration settings applied in this application note are shown in Figure 4. All measurements were performed using Bode Analyzer Suite version 3.51. The procedure described is also applicable to newer software versions.

For detailed instructions on operating the Bode 500 and configuring measurements in the Bode Analyzer Suite, refer to the user manual [5].

2.2 Calibration

An open-short-load calibration is required to ensure accurate impedance measurements at high frequencies. Depending on the measurement configuration, either a Series-Thru or a One-Port calibration is applied using the B-TCA Test Card Adapter.

For common-mode (CM) measurements, a Series-Thru calibration is performed, as the expected impedance is relatively high and exceeds the recommended range of the one-port method (500 mΩ to 10 kΩ). In contrast, differential-mode (DM) measurements use a One-Port calibration since the impedance levels fall within its optimal range. Detailed calibration procedures for Series-Thru and One-Port methods using the B-TCA are described in the B-TCA manual [1].

All calibrations are performed using a logarithmic frequency sweep from 10 Hz to 80 MHz with a total of 401 points. These parameters are selected to match the intended measurement settings and ensure the validity of the user-range calibration.

Note: After performing the user-range calibration, any modification to the start frequency, stop frequency, sweep type, or number of points invalidates the calibration. Therefore, these parameters must remain unchanged during the subsequent impedance measurements to ensure the validity of the calibration.

Series-Thru Calibration & One-Port Calibration:

For common-mode measurements, a Series-Thru calibration is performed using the B-TCA fixture, as shown in Figure 3 (a). For differential-mode measurements, a One-Port calibration is applied, as illustrated in Figure 3 (b). In both cases, the calibrators are connected to the B-TCA test card adapter and the Bode 500.

(a)

(b)

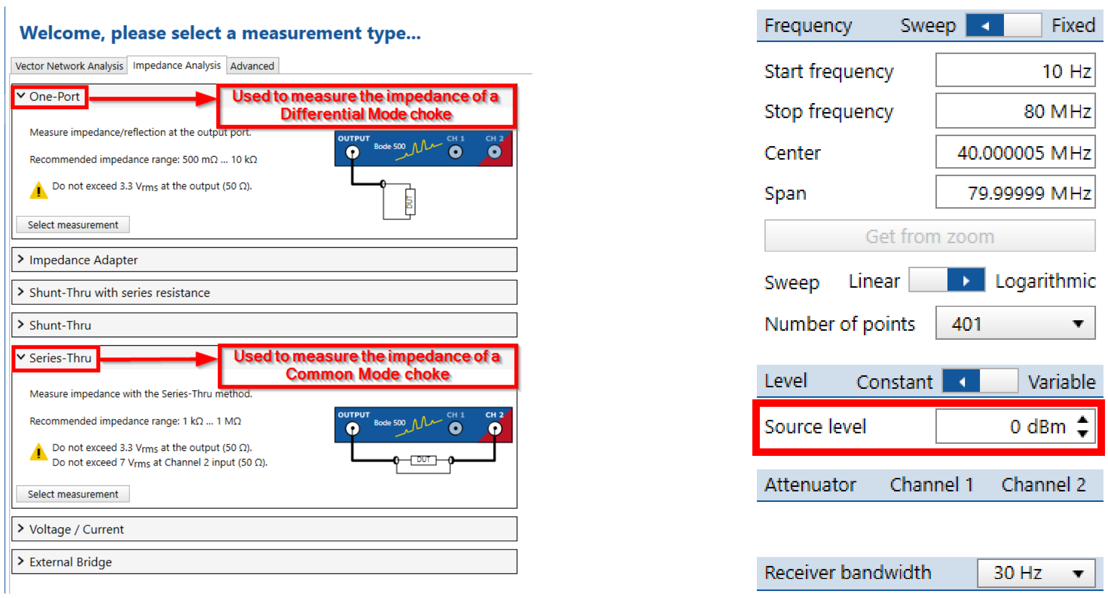
Figure 3: (a) Series-Thru Calibrator (Red) connected to the B-TCA test card adapter; (b) One-Port Calibrator (Black) connected to the B-TCA test card adapter.

2.3 Measurement Procedure

After calibration, the impedance measurements are performed using the B-TCA test card adapter. The choke under test is mounted on the dedicated test card. The measurement procedure is based on two impedance measurement methods. The measurements are then carried out in both common-mode (CM) and differential-mode (DM) configurations using the corresponding calibrated setups.

The same measurement parameters as defined in the calibration step are applied to ensure consistency between calibration and measurement.

The selected measurement methods and parameter settings in the Bode Analyzer Suite are shown in Figure 4.



(a) (b)

Figure 4: (a) BAS interface with selected impedance measurement methods; (b) parameter settings

2.3.1 Common-Mode Configuration (Series-Thru Method)

The Series-Thru method is recommended for impedance measurements when the expected impedance range is between 1 kΩ and 1 MΩ. For the common-mode choke referenced in [4], the impedance typically falls within this range at frequencies above 10 kHz.

The choke under test comprises two windings, each with two terminals. For common-mode measurement, terminals 1 and 3, as well as terminals 2 and 4, are short-circuited, forming the common-mode configuration, as illustrated in Figure 5.

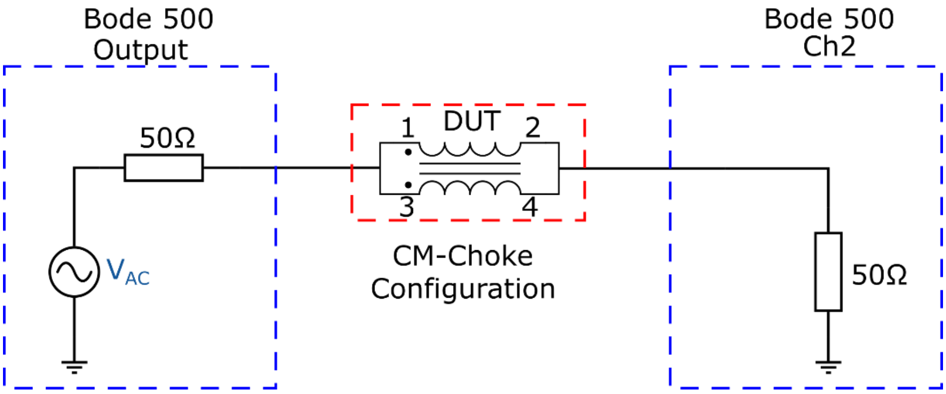


Figure 5: Common-mode choke in CM connection configuration in Series-Thru setup.

The component is first soldered onto the test card and then connected to the B-TCA measurement setup, as shown in Figure 6.

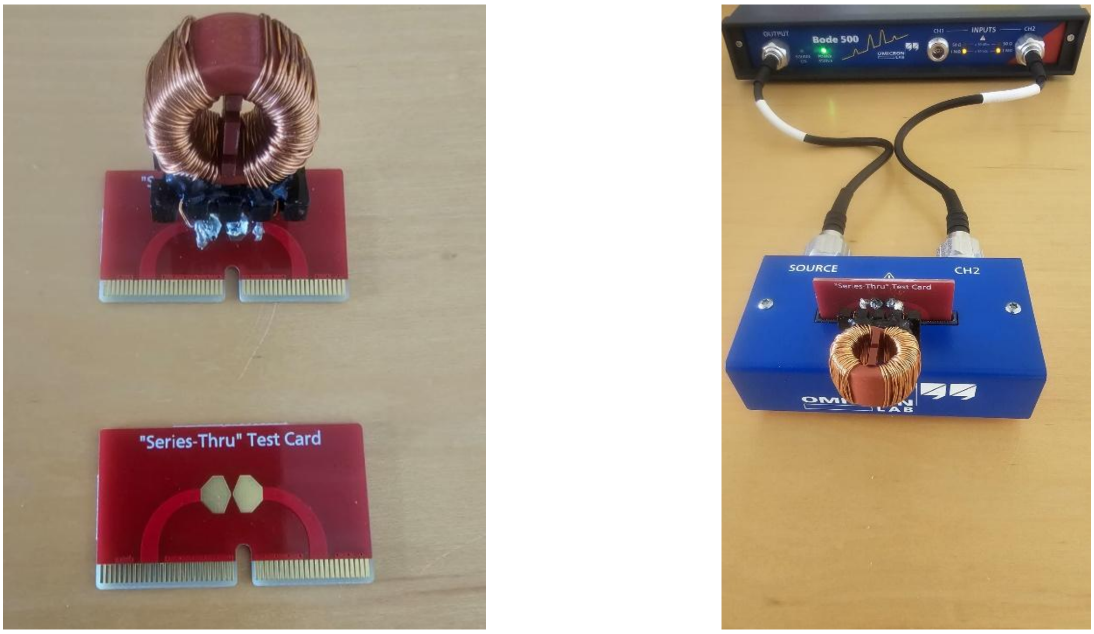


Figure 6: Common-mode measurement setup using the B-TCA test card adapter

A reduced source level of -30 dBm is configured in the Bode Analyzer Suite to ensure a small excitation of the common-mode choke therefore avoiding any non-linear behavior from saturation effects during the measurement.

2.3.2 Differential-Mode Configuration (One-Port Method)

For the measurement of the differential-mode configuration [4], the one-port impedance measurement method is used. This method is recommended when the impedance of the device under test (DUT) falls within the range of 500 mΩ and 10 kΩ.

The choke under test comprises two windings, each with two terminals. For differential-mode measurement, the excitation is applied between the windings. As illustrated in Figure 7, the output of the Bode 500 is connected to terminal 1, while terminal 3 is grounded. Terminals 2 and 4 are short circuited.

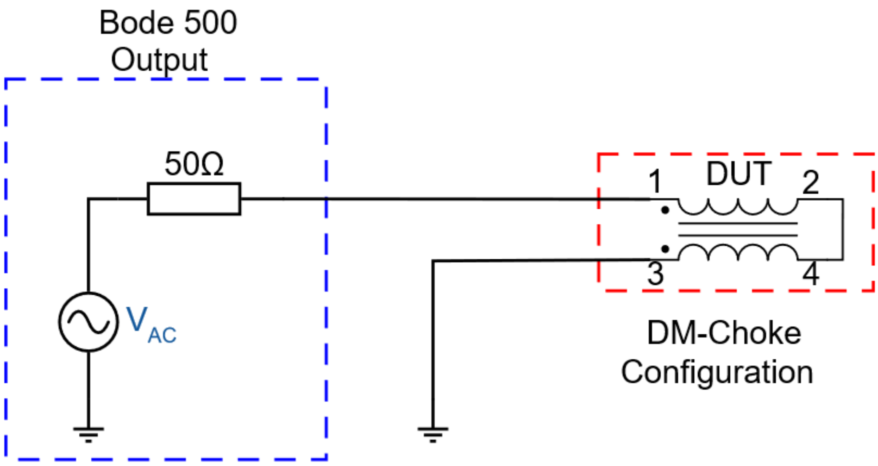


Figure 7: Common-mode choke in DM connection configuration in a One-Port setup.

The component is first soldered onto the test card and then connected to the B-TCA measurement setup, as shown in Figure 8.

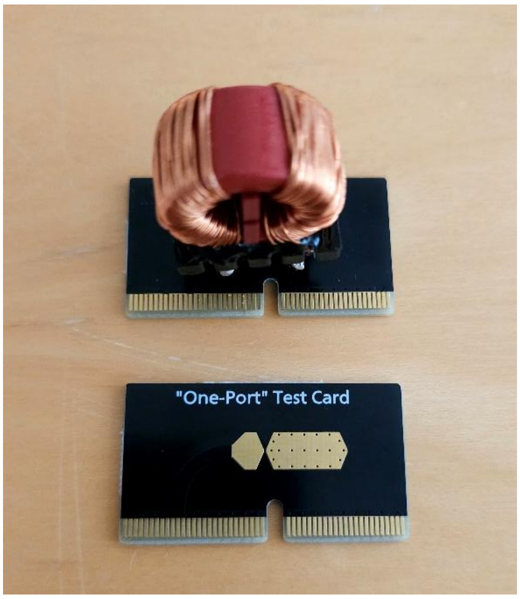


Figure 8: Differential-mode measurement setup using the B-TCA test card adapter.

A source level of 0 dBm is configured in the Bode Analyzer Suite to provide sufficient excitation of the differential-mode configuration, which is less sensitive to core saturation.

3 Measurement Results

3.1 Common-Mode Results

The measurement results for the common-mode (CM) configuration show the expected impedance behavior of a common-mode choke. At low frequencies, the impedance increases proportionally with frequency, indicating inductive behavior. As the frequency increases further, a resonance peak is observed at approximately 164.8 kHz, caused by parasitic capacitances. Beyond this first self-resonance frequency (SRF), the impedance decreases, reflecting the capacitive dominance of the device. At higher frequencies above 10 MHz, the DUT shows multiple resonance effects.

These results confirm that the measurement setup effectively captures the frequency-dependent characteristics and parasitic effects of the common-mode choke, as illustrated in Figure 9.

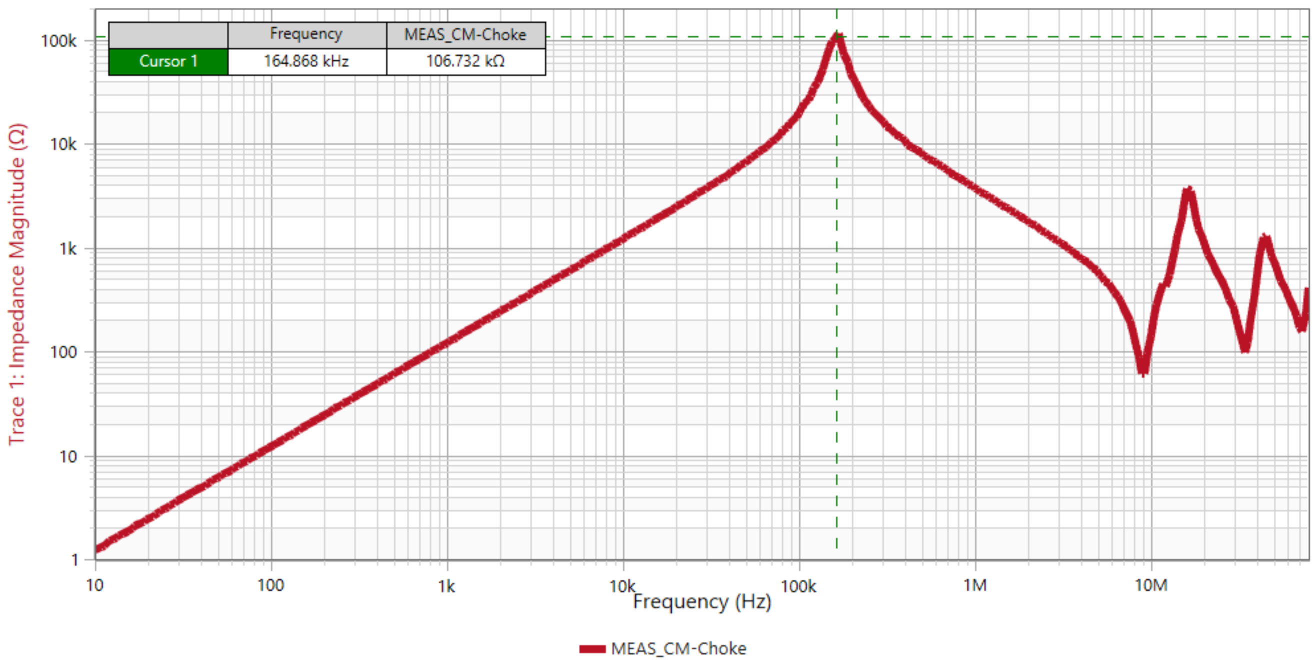


Figure 9: Measured CM impedance magnitude of the common-mode choke in CM configuration.

3.2 Differential-Mode Results

The measurement results for the differential-mode (DM) configuration were obtained over the same frequency range from 10 Hz to 80 MHz. Compared to the common-mode case, a significantly lower impedance is observed, as expected for a common-mode choke.

At very low frequencies (10 Hz to 100 Hz) the impedance is predominantly resistive. As the frequency increases, the behavior becomes inductive until a resonance occurs at approximately 3.89 MHz. Beyond this first self-resonance frequency (SRF), the impedance decreases, indicating capacitive behavior. Above 10 MHz, a second resonance appears. These results confirm that the common-mode choke provides limited impedance in differential-mode operation, while the measurement setup effectively captures its frequency-dependent characteristics, as illustrated in Figure 10.

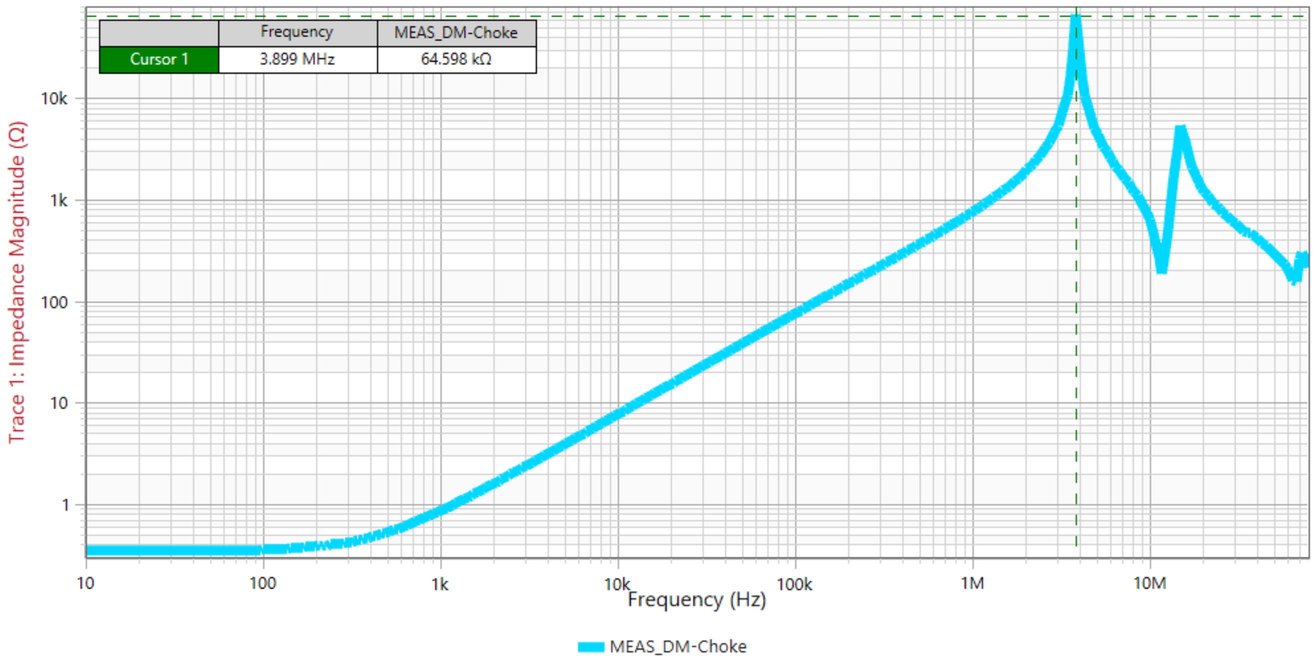


Figure 10: Measured DM impedance magnitude of the common-mode choke in DM configuration.

4 Equivalent Circuit Modeling

4.1 Circuit Fit

After completing the measurements, the Circuit Fit function in the Bode Analyzer Suite (BAS) was used to enable more accurate analysis, evaluation, and simulation of the measured data. This feature allows the generation of an equivalent circuit model (network structure), which can be exported as a SPICE block for further simulation and analytical calculations. The Circuit Fit function can be accessed from the measurement ribbon by selecting “Add Circuit Fit” as shown in Figure 11.

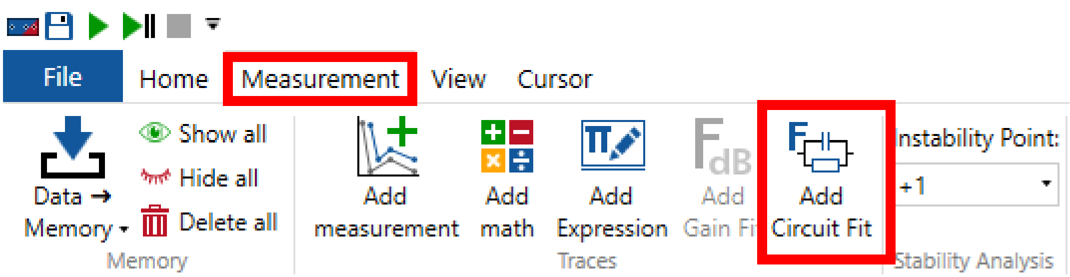


Figure 11: “Circuit Fit Function” in the Bode Analyzer Suite (BAS)

To configure the Circuit Fit for the measurements, a network-based model was selected. The network structure was defined as series, and the appropriate data source was chosen based on the available measurement data. Figure 12 and Figure 13 indicate the fit parameter settings, the DC resistor (Ro) and inductor (Lo) were deselected to improve the fitting accuracy within the frequency range of interest and allow easier matching to the structure of the approach proposed by Ivica Stevanovic in Behavioral Modeling of Chokes for EMI Simulations in Power Electronics [2]. Once the setup was completed, the fitting process was initiated using "Start Fit," allowing the extraction of the equivalent circuit parameters.

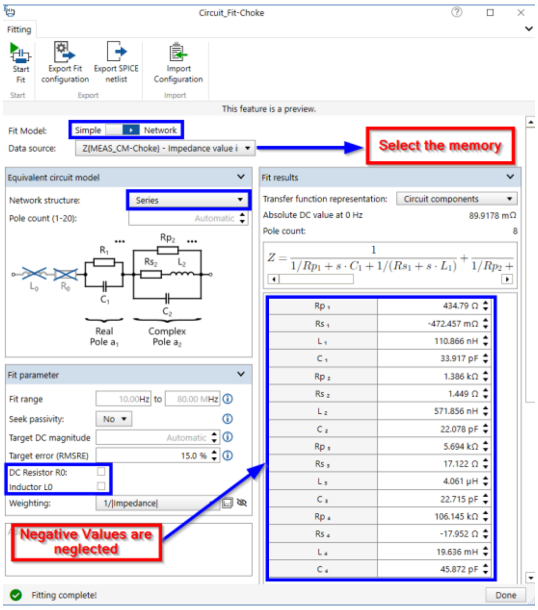


Figure 12: Circuit Fit configuration and fitting results for the CM configuration.

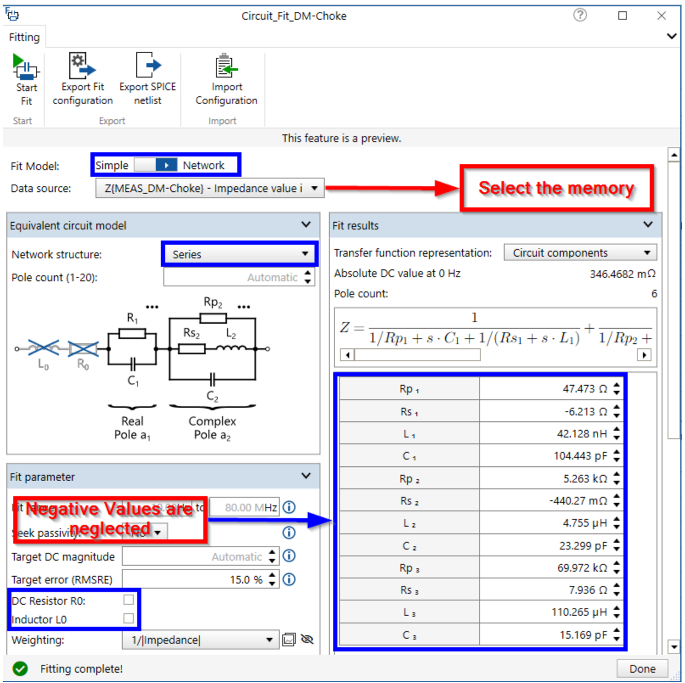


Figure 13: Circuit Fit configuration and fitting results for the DM configuration.

The approximation of the circuit fitting is illustrated in Figure 14 and Figure 15, where the measured impedance is compared with the fitted model for the CM and DM configurations, respectively.

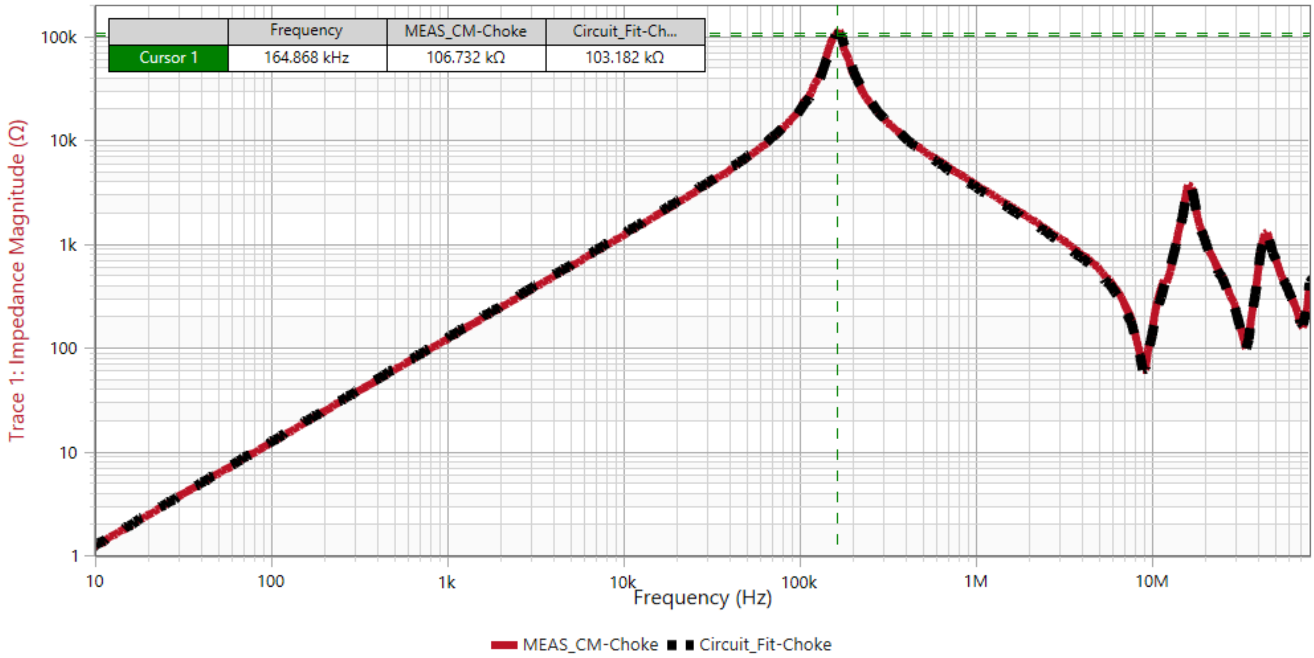


Figure 14: Measured and fitted impedance curves for the CM configuration

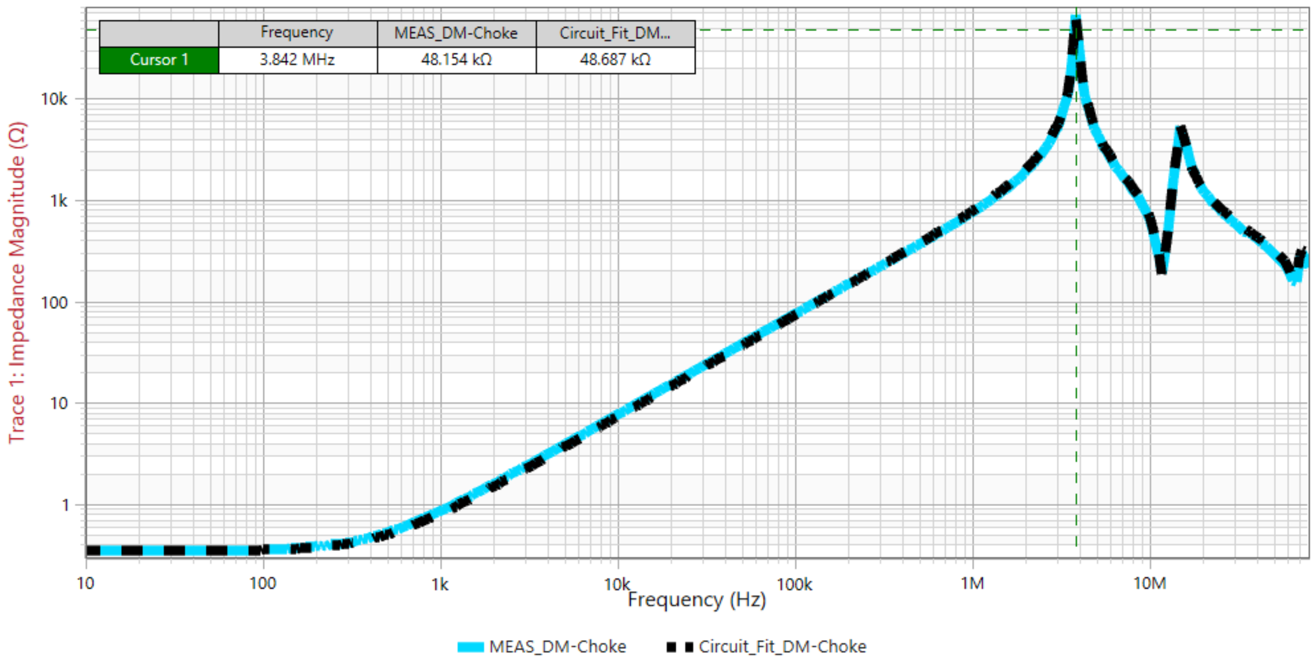


Figure 15: Measured and fitted impedance curves for the DM configuration

In general, a network configuration can be implemented using either a parallel or a series structure. In this work, the series configuration was selected to meet the requirements of the behavioral modeling approach. Further details are provided in the following section. Additional information about the Circuit Fit function can be found [6].

4.2 Extracting Model Parameters

The parameters of the equivalent Circuit Fit model were extracted using the Circuit Fit function in the Bode Analyzer Suite. These parameters describe the electrical behavior of the common-mode choke over the measured frequency range. The extracted values include the effective inductance, parallel resistance, and parasitic capacitances, which define the impedance response of the device.

In the common-mode configuration, a higher inductance is observed, resulting in a higher impedance at low frequencies. In differential-mode operation, the inductance is significantly lower, which explains the reduced impedance. The parasitic capacitances determine the self-resonant frequency (SRF) and the transition to capacitive behavior at higher frequencies.

For practical modeling purposes, non-physical parameter values (e.g., negative elements generated during the fitting process) were neglected. The resulting parameter set shows good agreement with the measured data.

The extracted parameters are summarized in Table 1.

Table 1: Extracted equivalent circuit parameters and mapping between Circuit Fit and simulation model for CM and DM configurations

Circuit Fit	Simulation	CM Value	Circuit Fit	Simulation Name	DM Value
Rp2	Rc3	1.386 kΩ	Rp1	Rd3	47.473 Ω
L2	Lc3	571.856 nH	L1	Ld3	42.128 nH
C2	Cc3	22.078 pF	C1	Cd3	104.443 pF
Rp3	Rc2	5.694 kΩ	Rp2	Rd2	5.263 kΩ
L3	Lc2	4.061 uH	L2	Ld2	4.755 uH
C3	Cc2	22.715 pF	C2	Cd2	23.299 pF
Rp4	Rc1	106.145 kΩ	Rp3	Rd1	69.972 kΩ
L4	Lc1	19.636 mH	L3	Ld1	110.265 uH
C4	Cc1	45.872 pF	C3	Cd1	15.169 pF

5 Simulation Model

The extracted parameters and equivalent circuit model were implemented in an LTspice schematic to validate the accuracy of the behavioral model. The implementation is based on the approach proposed by Ivica Stevanovic in Behavioral Modeling of Chokes for EMI Simulations in Power Electronics [2], which provides a method for modeling common-mode chokes for EMI simulations.

The equivalent circuit model used for the analysis is shown in Figure 16 below:

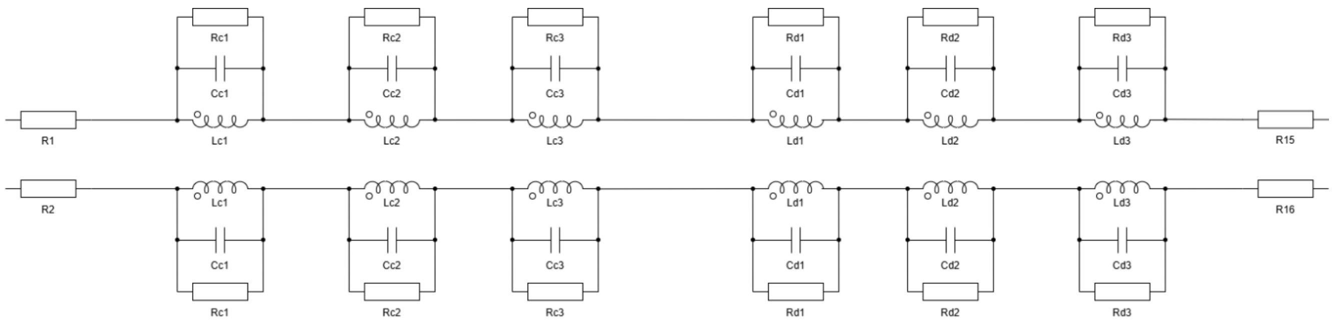


Figure 16: Equivalent circuit model of the common-mode choke used for simulation

To determine the resistance values for R1, R2, R15, and R16, additional considerations were applied. These values can be obtained using a DC kelvin measurement on either a common-mode or a differential mode configuration. Alternatively, the impedance of the differential-mode configuration at very low frequency (e.g., 10 Hz) can be used since the impedance is predominantly resistive in this region, allowing a direct estimation of the series resistance.

Table 1 lists the component values obtained using the circuit fit. The resonance frequencies associated with each group of components can be estimated using the LC resonance frequency formula $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

For instance, the common-mode (CM) values L4 and C4 in Table 1 correspond to a resonance frequency of approximately 168 kHz. As shown in Figure 14, the first measured resonance occurs at approximately this frequency. This correlation makes it possible to identify the component group associated with each resonance in the impedance characteristic.

Some extracted parameters, such as Rp1, L1, and C1, correspond to higher-order resonances (e.g., fourth resonance and above 80 MHz) that are outside the scope of this application note and were therefore not considered in the simulation.

The resistances Rc1, Rc2, and Rc3 are multiplied by a factor of two, while the capacitances Cc1, Cc2 and Cc3 are divided by a factor of two. These modifications ensure consistency between the fitted model and the equivalent circuit described in [2], which is why these parameters are adjusted accordingly in the simulation.

Similarly, for the differential-mode (DM) configuration, the equivalent circuit must also be adapted to align with the model presented in [2]. As a result, the inductances Ld1, Ld2, and Ld3 are divided by four, the capacitances Cd1, Cd2, and Cd3 are multiplied by two, and the resistances Rd1, Rd2, and Rd3 are divided by two.

Further details on the derivation and justification of these parameter adjustments can be found in [2]

Additionally, the magnetic coupling coefficients must be defined according to the configuration: k1, k2, and k3 are set to 1 for the common-mode choke configuration, whereas k4, k5, and k6 are set to -1 for the differential-mode configuration.

Several resistance elements obtained during the fitting process (e.g., Rs terms) were excluded from the final model because they either resulted in non-physical negative resistance values or contributed negligibly to the overall fitting accuracy. Since negative resistances are not physically meaningful for this system, omitting these parameters ensures a simplified model.

5.1 LTspice Model Implementation

Figure 17 shows the LTspice implementation of the equivalent circuit model of the common-mode choke based on the extracted parameters.

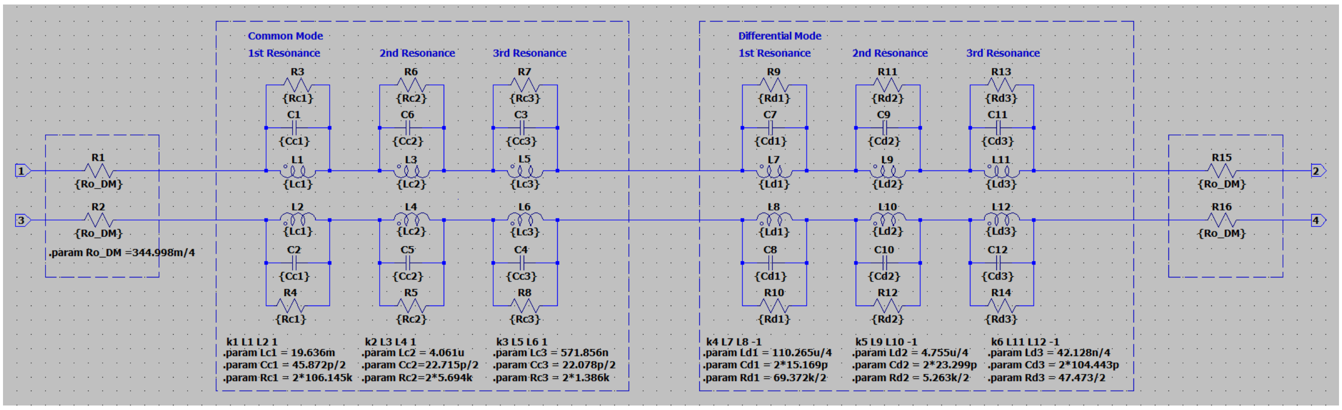
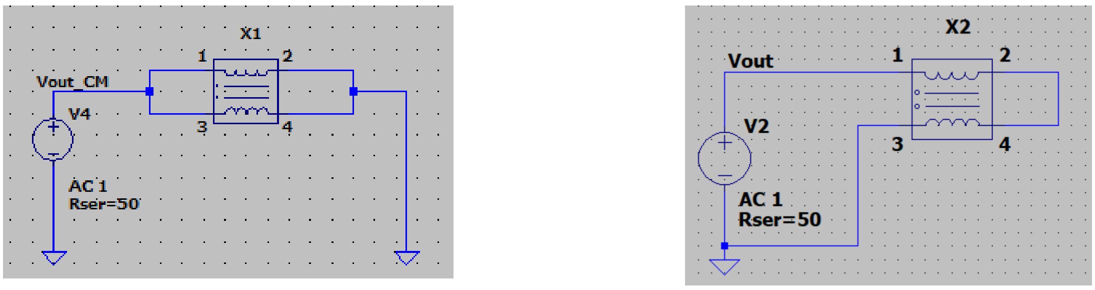


Figure 17: LTspice schematic of the common-mode choke using the behavioral model.

The obtained parameters were arranged in the circuit according to the order of the resonances observed in the measurement results. This ensures that each stage represents the corresponding resonance. Using this approach, a dedicated circuit block representing the common-mode choke was created.

Figure 18 shows the implementation of this block within the simulation environment for both common-mode (CM) and differential-mode (DM) configurations.



(a) (b)

Figure 18: Simulation of the common-mode choke block in (a) CM configuration; (b) DM configuration

This block can be reused in different simulation environments for further analysis and system-level simulations.

5.2 Simulation Results

The developed simulation model was validated by comparing the simulated impedance response with the previously obtained measurement and circuit fitting results. Figure 19 and Figure 20 show the comparison between the measured data, the Circuit Fit results, and the LTspice simulation for the CM and DM configurations, respectively.

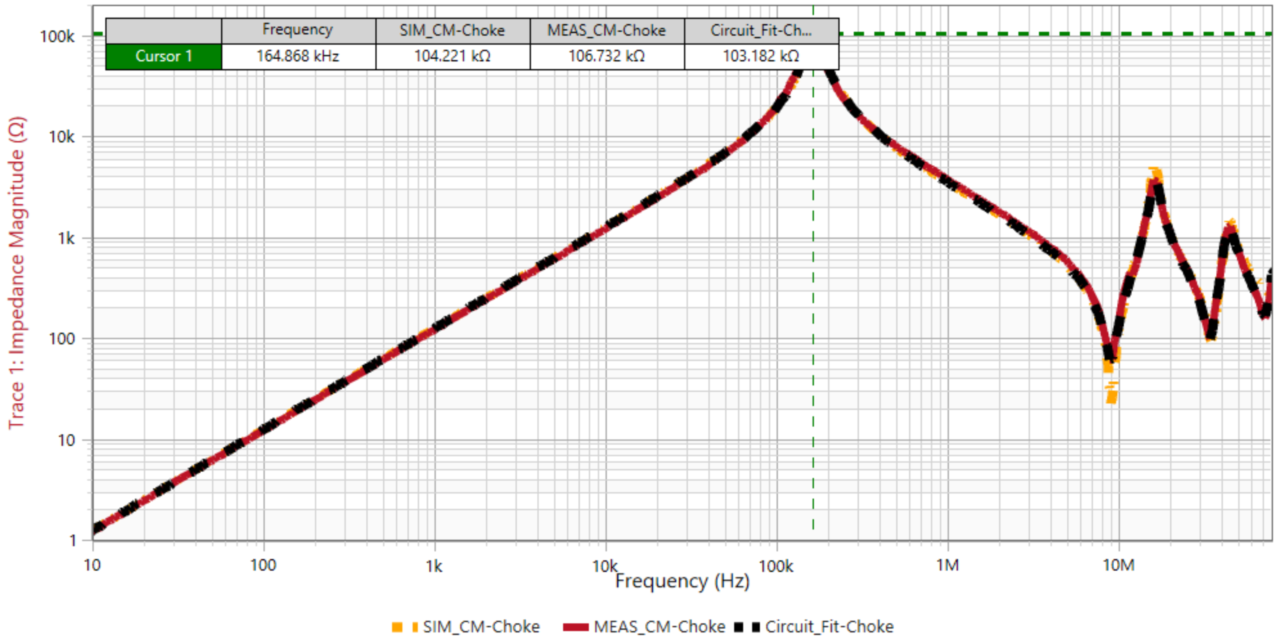


Figure 19: Comparison of measured data, Circuit Fit results, and simulation for the CM configuration

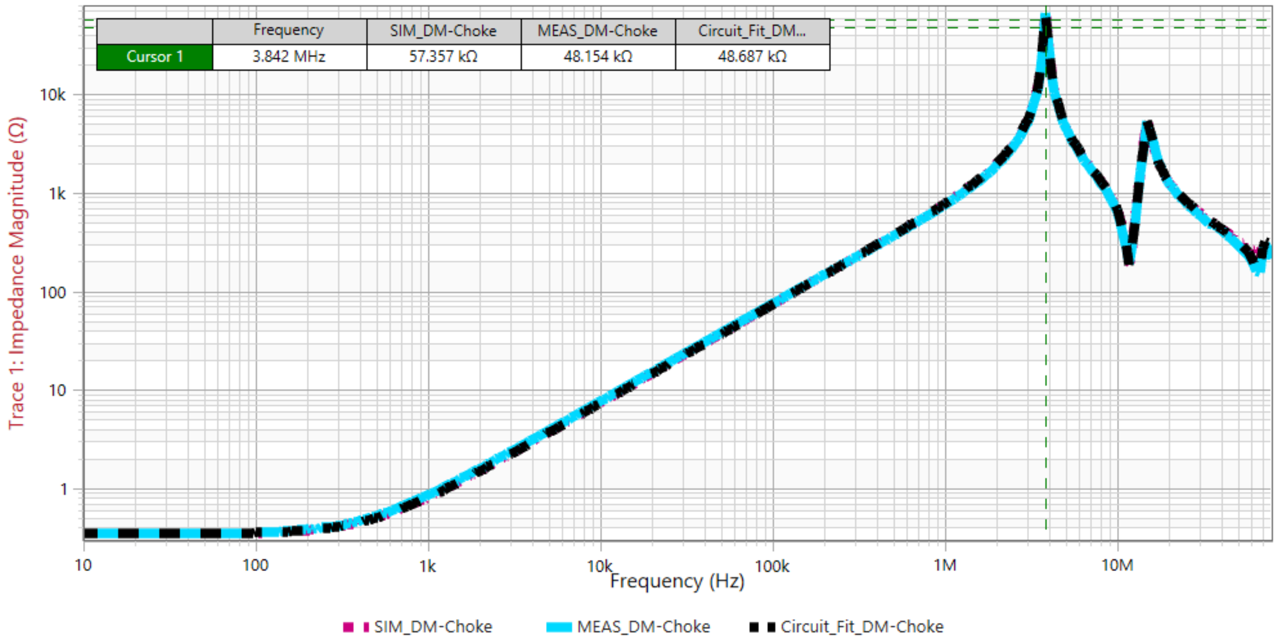


Figure 20: Comparison of measured data, Circuit Fit results, and simulation for the DM configuration.

A good agreement between the simulated and measured results can be observed over the relevant frequency range, confirming that the implemented model effectively represents the behavior of the common-mode choke.

6 Conclusion

The comparison between measurement, circuit fitting, and simulation results demonstrates good agreement across the analyzed frequency range for both common-mode (CM) and differential-mode (DM) configurations. The proposed modeling approach accurately captures the first, second, and third resonance points, providing a reliable representation of the impedance behavior of the common-mode choke.

The behavioral modeling method introduced by Ivica Stevanovic [2] proves to be an effective approach for representing multiple resonances. While this application note focuses on the evaluation up to the third resonance, the method can be extended to include higher-order resonances as required. The results confirm that the combination of impedance measurement and circuit fitting provides a practical and efficient method for extracting equivalent circuit models suitable for simulation and analysis.

The Bode 500 is a suitable instrument for measuring common-mode chokes across a wide frequency range up to 450 MHz. Similar measurements can also be performed using the Bode 100, with a maximum frequency range of 50 MHz.

7 References

[1] "B-TCA User Manual." [Online]. Available: https://www.omicron-lab.com/fileadmin/assets/Bode_100/Accessories/B-TCA/B-TCA_UserManual-ENU13020502.pdf

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