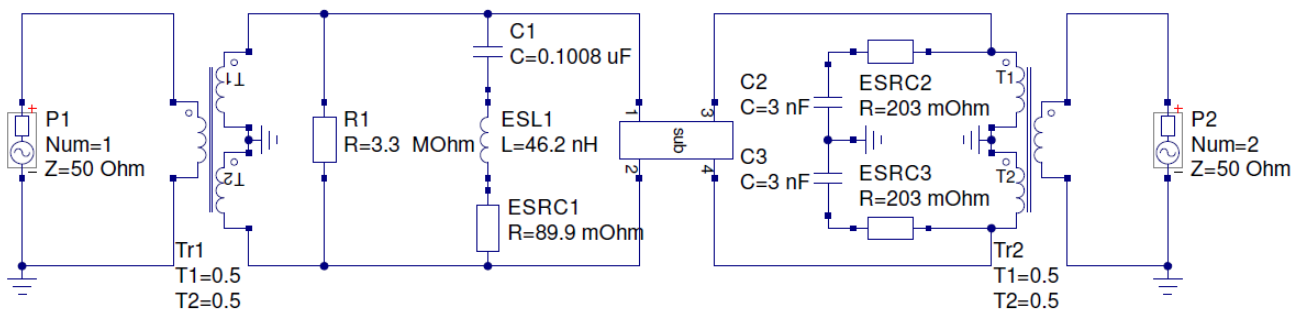


Bode 100 - Application Note

EMC Filter Insertion Loss Simulation

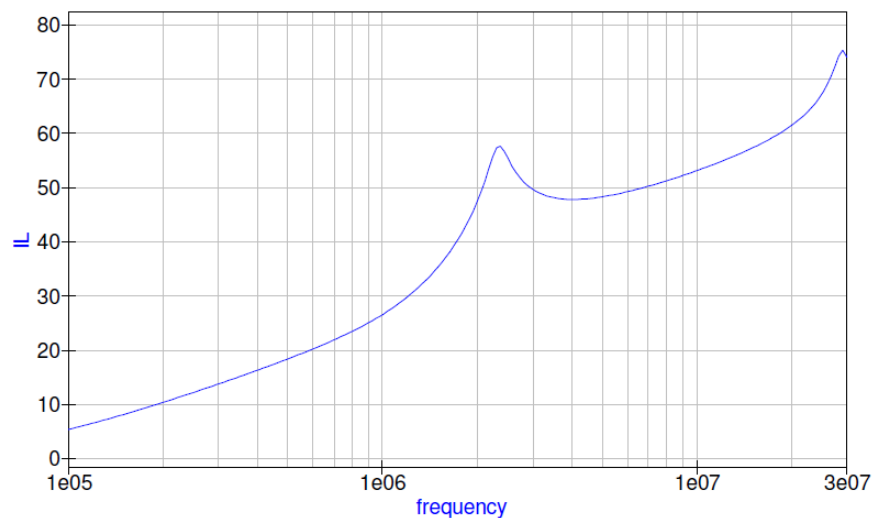


S parameter simulation

SP1
 Type=log
 Start=100 kHz
 Stop=30MHz
 Points=201

Equation

Eqn1
 $IL = -20 \cdot \log_{10}(\text{abs}(S[2,1]))$



By Benjamin Mößlang

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Table of Contents

1	EXECUTIVE SUMMARY.....	3
2	EMC FILTER COMPONENTS.....	3
3	SIMULATION MODEL	4
3.1	COMMON MODE CHOKE MODEL	4
3.2	CAPACITOR MODEL	5
3.3	BALUN TRANSFORMERS.....	5
4	MEASUREMENT AND PARAMETER CALCULATION	6
4.1	MEASUREMENT SETUP.....	6
4.2	MEASURING THE COMMON MODE CHOKE	7
4.2.1	<i>Winding Resistance Measurement.....</i>	7
4.2.2	<i>Common Mode Measurement and Calculation</i>	7
4.2.3	<i>Differential Mode Measurement and Calculation.....</i>	9
4.2.4	<i>Open-Mode Measurement and Calculations.....</i>	13
4.3	Y CAPACITOR MEASUREMENT	14
4.4	X CAPACITOR MEASUREMENT AND CALCULATION	16
5	SIMULATION	19
5.1	COMMON MODE CHOKE MODEL	19
5.2	COMMON MODE SIMULATION	20
5.3	DIFFERENTIAL MODE SIMULATION	21
6	CONCLUSION	22
7	REFERENCES.....	22
	VERSION HISTORY	22

Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at www.omicron-lab.com/bode-100/downloads#3

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.23. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

1 Executive Summary

This application note describes how to derive a wideband model of an EMC filter by using the Bode 100 vector network analyzer. In the application note “RFI Power Inlet Filter Insertion Loss Measurement” [1] (OMICRON Lab, 2016) the common mode and differential mode insertion loss of an EMC filter is measured. In this application note, the same EMC filter is modeled and simulated.

2 EMC Filter Components

To derive a model that fits the reality, the impedance of all the single components of the EMC inlet filter are measured. Therefore, the filter is disassembled.



Figure 1: RFI power inlet filter

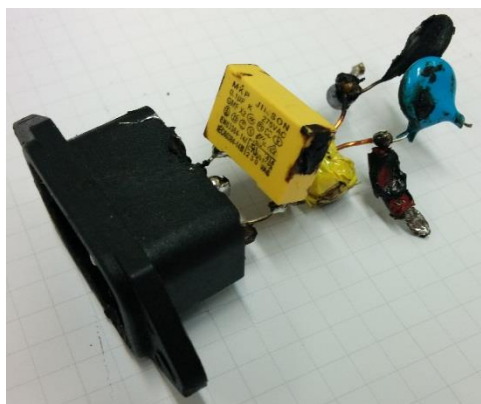


Figure 2: RFI power inlet filter, without housing

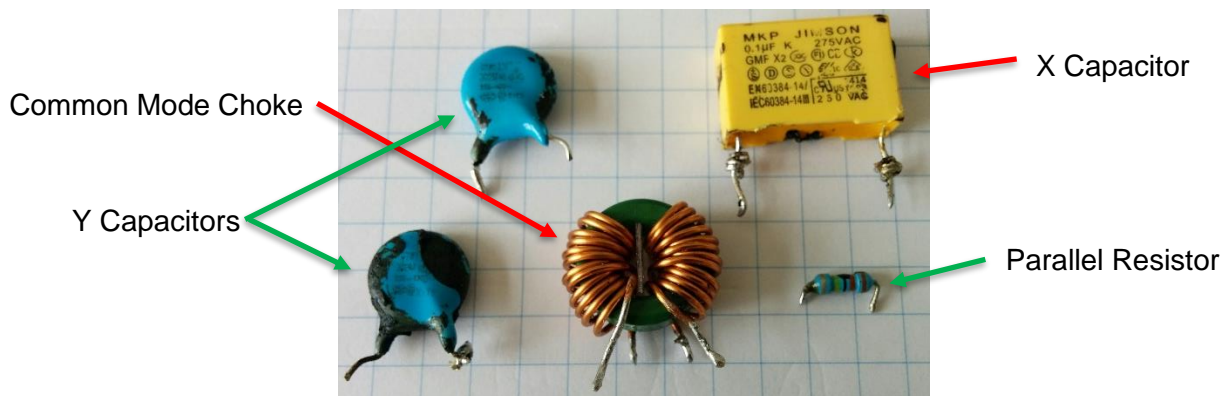


Figure 3: Disassembled parts

The following image shows the schematic diagram of the EMC filter.

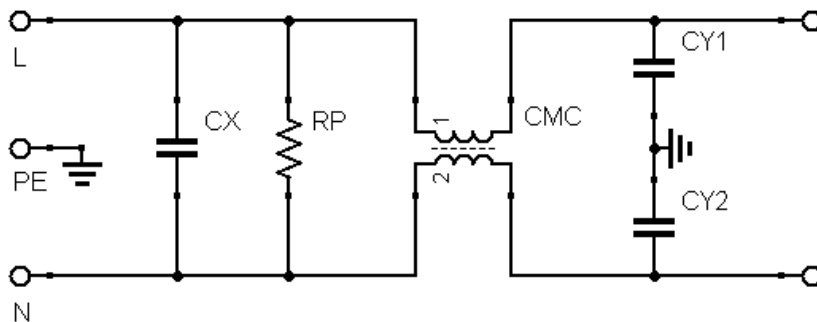


Figure 4: RFI Power Inlet Filter schematics

3 Simulation Model

To achieve an accurate simulation of the EMC filter, accurate behavior models of the used components were used. Note that the behavior model does not necessarily equal the physical model.

3.1 Common Mode Choke Model

The used model is described in [2] (Stevanović & Skibin , 2010) and [3] (Stevanović, Skibin, Masti, & Laitinen, 2013). This model includes the common mode and the differential mode behavior of the common mode choke in one single model.

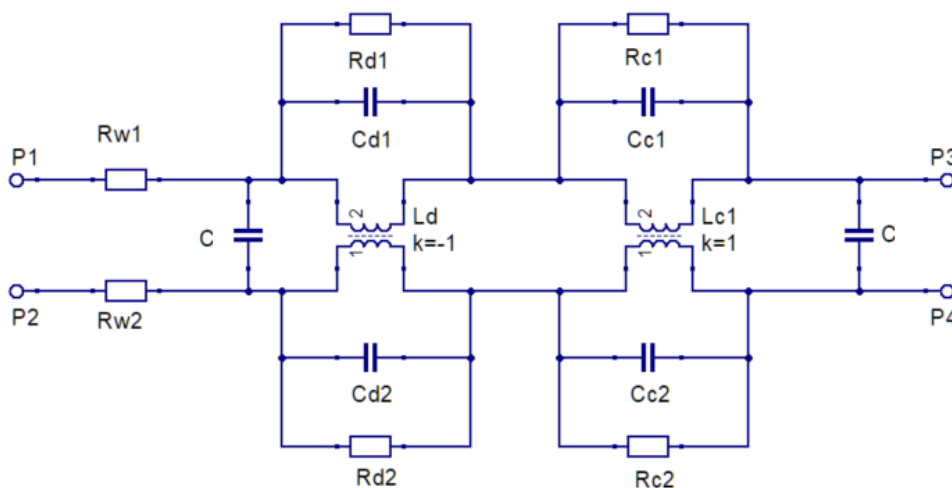


Figure 5: Common Mode Choke Model

R_{Wn} represents the resistance of the copper winding. Two times C represents the inter-winding capacitance (capacitance between the windings). The green section represents the differential mode part and the red section the common-mode part. R_{Dn} and R_{Cn} represent the loss of the core. C_{Dn} and C_{Cn} are the intra-winding capacitance (distributed capacitance of the winding). L_D is the differential mode inductance and L_C is the common-mode inductance. k_D is the differential mode coupling factor (-1) and k_C the common-mode coupling factor (+1).

3.2 Capacitor Model

The X and Y capacitors are modeled with the following simple equivalent series circuit.

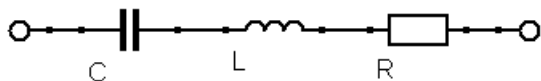


Figure 6: Capacitor series equivalent circuit

3.3 BALUN Transformers

The BALUN transformers used for the measurement are modeled as center-tapped transformers. The voltage transformation ratio for both secondary windings is $V_{SN}/V_P = 0,5$.

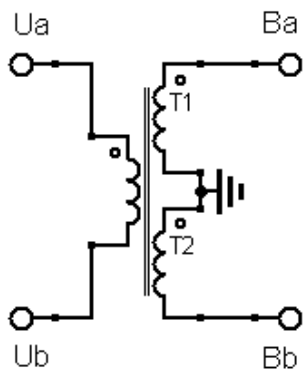


Figure 7: BALUN Transformer

4 Measurement and Parameter Calculation

4.1 Measurement Setup

The Bode 100 Vector Network Analyzer with the B-WIC impedance adapter is used. The connection of the B-WIC impedance adapter is shown in the following picture.

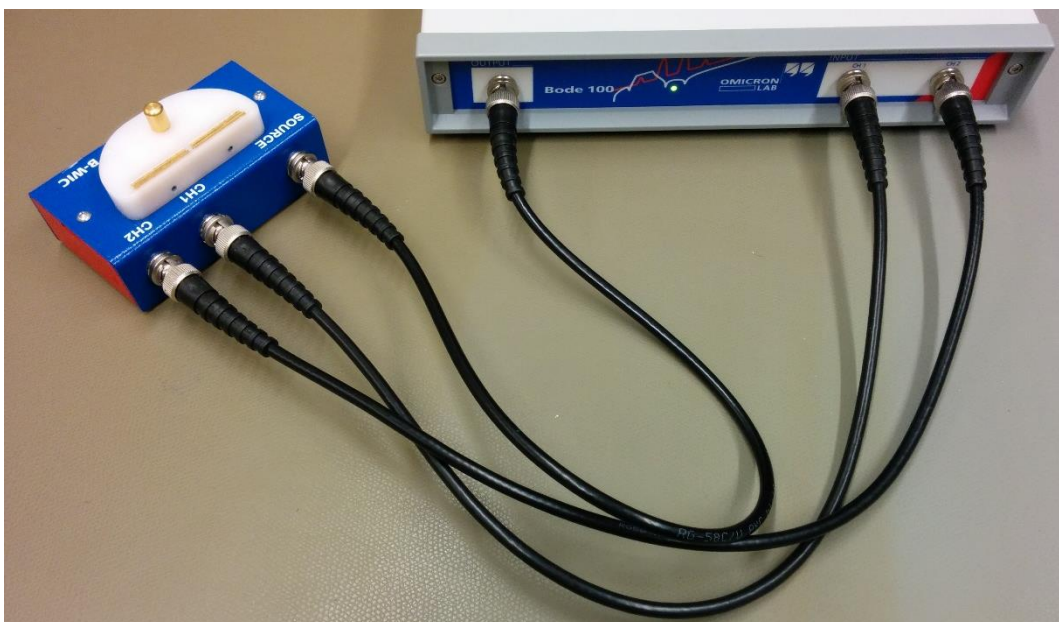


Figure 8: Bode 100 and B-WIC Setup

The measurements were performed in the “Impedance Adapter” measurement-mode of the Bode Analyzer Suite and the frequency range was set from 100 Hz to 50 MHz.

Vector Network Analysis Impedance Analysis

▼ One-Port

Measure impedance/reflection at the output port.

Recommended impedance range: 500 mΩ ... 10 kΩ

Start measurement

▼ Impedance Adapter

Measure impedance using the B-WIC or B-SMC component test fixtures.

Recommended impedance range: 20 mΩ ... 600 kΩ

Note: Calibration (open, short, load) is required.

Start measurement

Frequency Sweep Fixed

Start frequency

Stop frequency

Center

Span

Get from zoom

Sweep Linear Logarithmic

Number of points

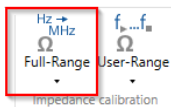
Level Constant Variable

Source level

Receiver bandwidth

Figure 9: Measurement configuration

Before the measurement can be started, an impedance-calibration must be performed. The Full-

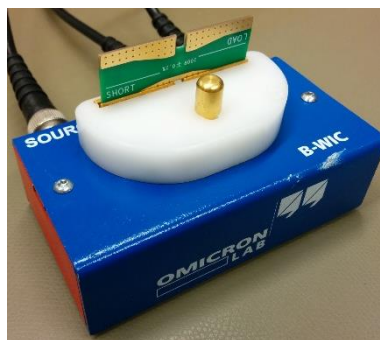


Range calibration is used. The calibration is done using the B-CAL board.



(a) Open calibration

Open



(b) Short calibration

Short



(c) Load calibration

Load

Figure 10: Calibration of the B-WIC using the B-CAL calibration board

4.2 Measuring the Common Mode Choke

To get all the required parameters of the model, four measurements must be performed. These measurements are all impedance measurements with different connection configurations and measurements with a digital multimeter. At first, the winding resistance is measured. The second measurement is the common mode measurement, where the two windings of the choke are connected in parallel. The third measurement is the differential mode measurement, where the two windings are connected in series. In the fourth measurement, the coil is in open mode, assuming a symmetric common mode choke.

4.2.1 Winding Resistance Measurement

The resistance of the winding is measured using a digital multimeter.

$$R_{w1} = R_{w2} = 0.1 \Omega \tag{1}$$

4.2.2 Common Mode Measurement and Calculation

To measure the common-mode impedance, the two windings are connected in parallel.

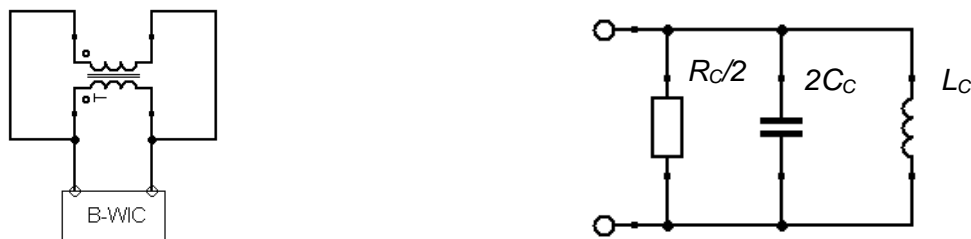


Figure 11: Common mode measurement. DUT configuration and corresponding equivalent circuit.

With a single sweep  the following result was obtained:

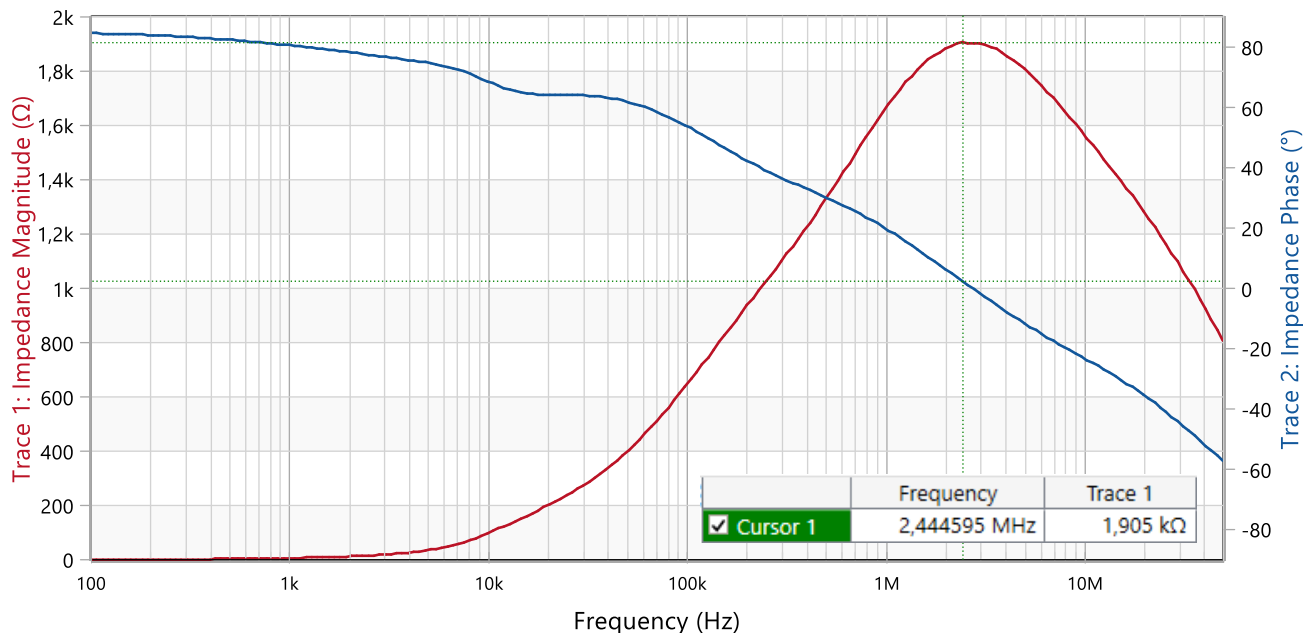


Figure 12: Common mode choke impedance measurement

Cursor 1 is placed at the resonance frequency. The resistance at this point is the double equivalent parallel resistor R_c of the coil.

$$f_{CR} = 2.445 \text{ MHz} \text{ and } R_c = 2 \cdot 1.905 \text{ k}\Omega = 3.81 \text{ k}\Omega \quad (2)$$

At low frequencies the inductive part of the choke is dominant. Therefore, it is measured from 100 Hz to 10 kHz. With this new frequency setting and the trace format set to “Ls” (series inductance), the inductance of the coil can be seen.

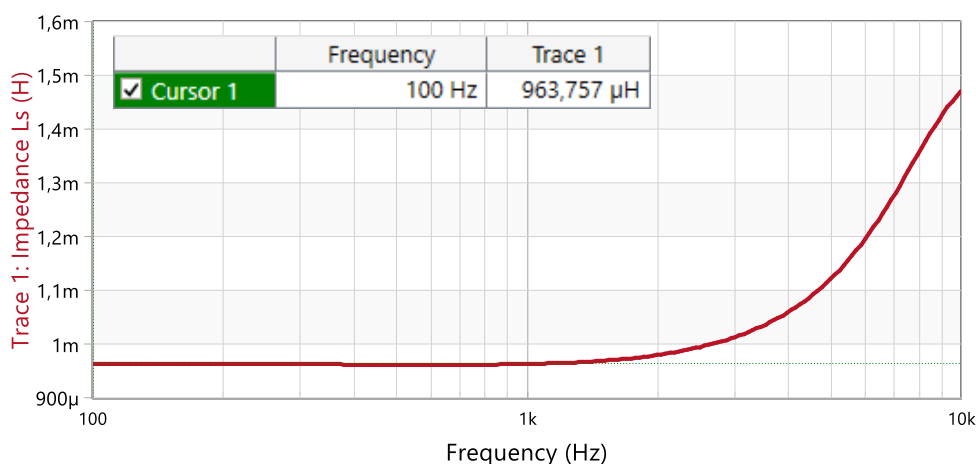


Figure 13: Common mode choke inductance measurement

The measured inductance at 100 Hz is:

$$L_C = 0.964 \text{ mH} \quad (3)$$

With the inductance and the self-resonance frequency the equivalent capacitance can be calculated:

$$C_C = \frac{1}{8 \cdot \pi^2 f_{CR}^2 \cdot L_C} = 2.198 \text{ pF} \quad (4)$$

4.2.3 Differential Mode Measurement and Calculation

To measure the differential mode impedance of the choke, the same settings as in the common mode measurement are used. To measure this impedance the two windings are connected in series.



Figure 14: Differential mode measurement. DUT configuration and corresponding equivalent circuit.

At first, the value of the inductance L_D is extracted. A single measurement leads to the following result:

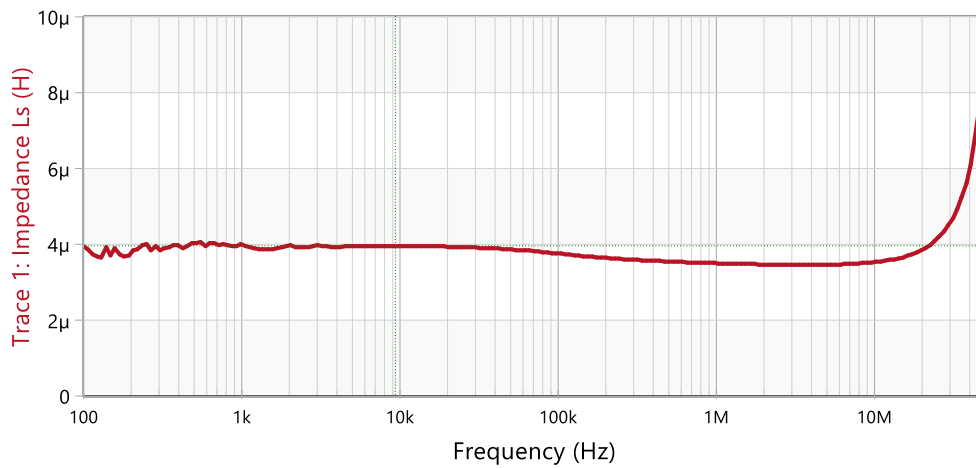


Figure 15: Differential Mode Inductance Measurement

The measured inductance is $3.9 \mu\text{H}$. Because measuring the two windings together and because of the coupling factor the inductance L_D is calculated with the following formula.

$$L_D = \frac{3.9 \mu\text{H}}{4} = 0.975 \mu\text{H} \quad (5)$$

Now, C_D of the common mode choke can be measured. To do so, the start frequency is set to 100 Hz and the stop frequency to 50 MHz. Additionally, the trace format is changed to magnitude.

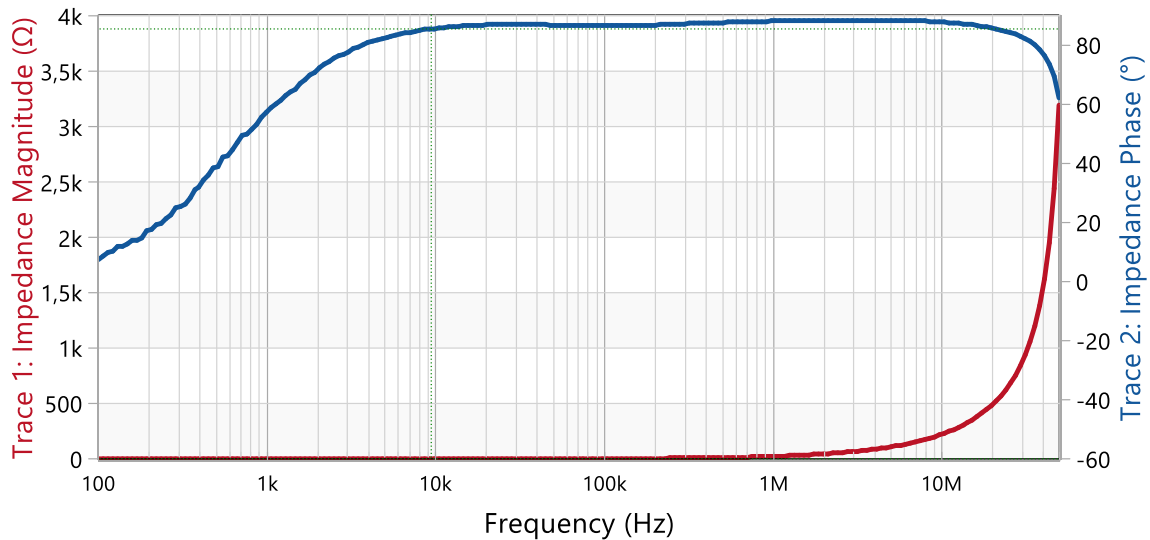
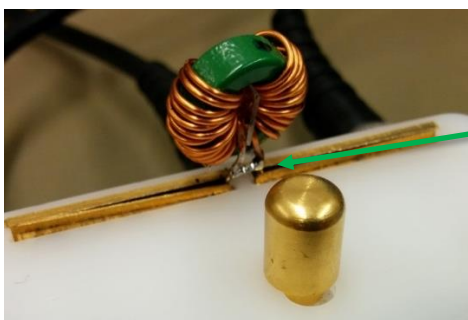


Figure 16: Differential Mode Impedance Measurement

The result shows that the resonance frequency of the differential mode impedance is above the frequency range of the Bode 100. But with a series inductance or a parallel capacitor, the resonance frequency can be shifted into the measurable frequency range to calculate the parasitic capacitance. A capacitor is chosen, because of the better RF¹ performance. The expected value of C_D is in the lower pico-farad range, so the parallel capacitor C_H is chosen in the same range. A higher parallel capacitance would lead to higher measurement uncertainty.

The capacitor is soldered directly to the common mode choke and the new resonance circuit is measured using the B-WIC Impedance Adapter.



Parallel Capacitor C_H

The capacitor is a 10 pF, 0603 ceramic chip capacitor.

Figure 17: Common Mode Choke with parallel Capacitor

¹ RF... Radio Frequency

Then, a single sweep is started which leads to a resonance frequency of ≈ 25 MHz.

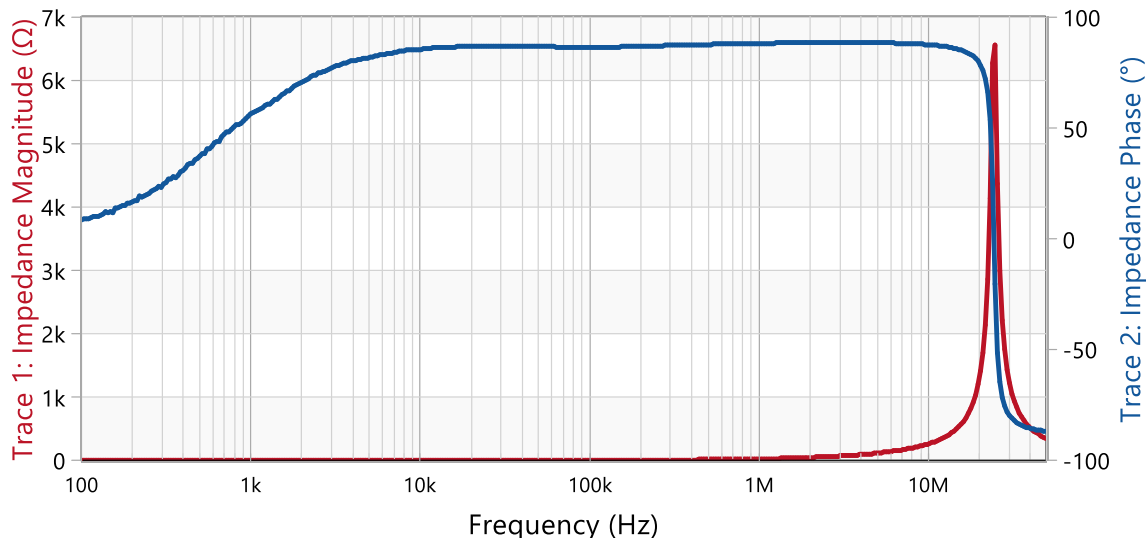


Figure 18: Differential Mode Impedance with a parallel capacitor

To get a more accurate result, one can zoom closer to the resonance.

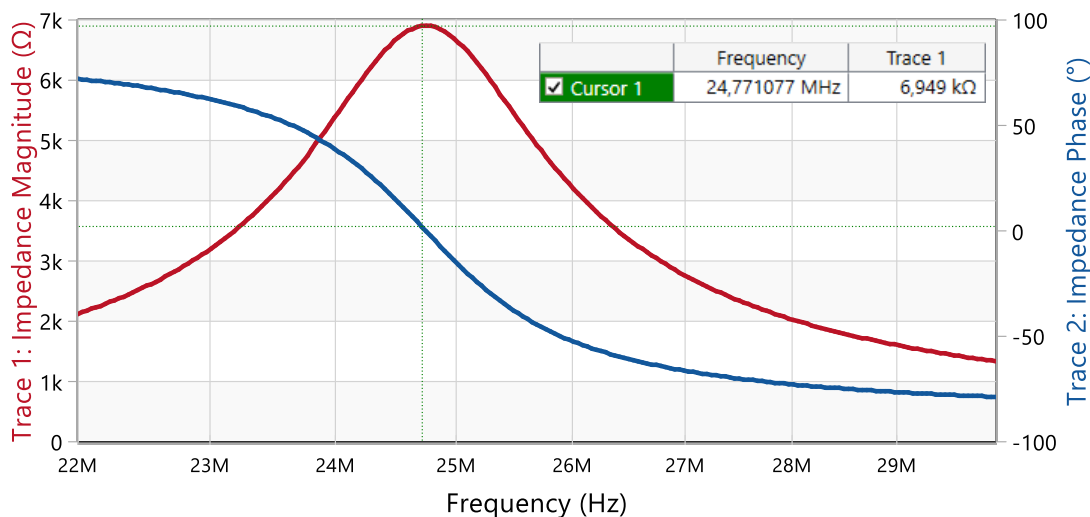


Figure 19: Differential Mode Impedance with a parallel capacitor, resonance

The cursor now marks the resonance at $f_{RD} = 24.771$ MHz

The resistance at this resonance is twice the parallel resistance R_D of the equivalent circuit.

$$R_D = \frac{6.949 \text{ k}\Omega}{2} = 3.475 \text{ k}\Omega \quad (6)$$

To get also an accurate value of the capacitor at the resonant frequency, the capacitance is measured using the B-SMC Impedance Adapter.

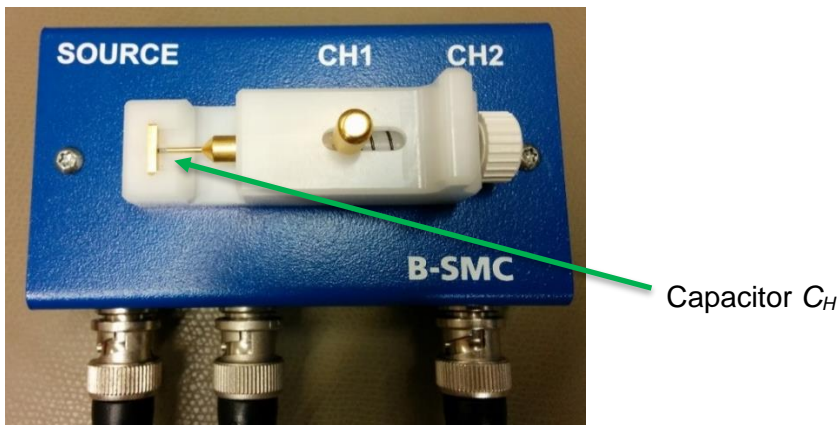


Figure 20: Parallel capacitor measurement with B-SMC

This leads to the following measurement.

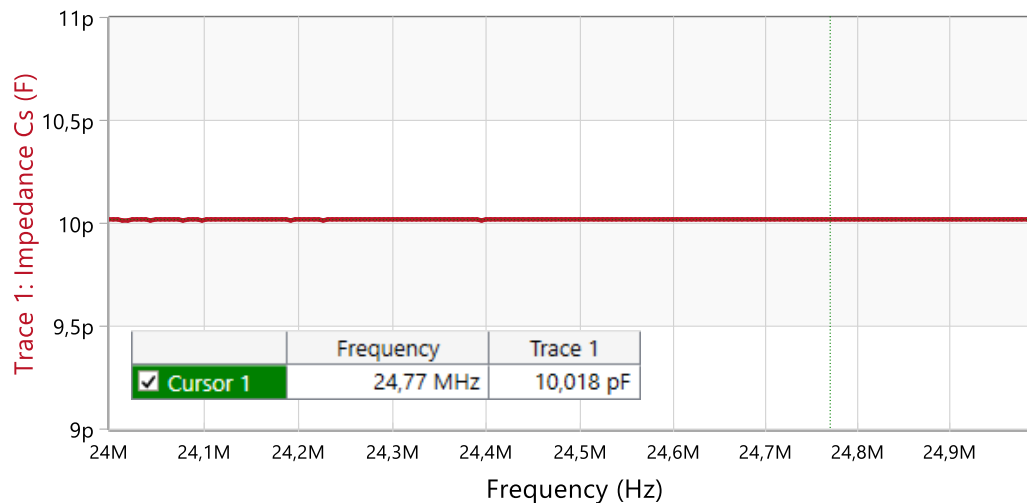


Figure 21: Parallel capacitor measurement

The measured capacitance is

$$C_H = 10.018 \text{ pF} \quad (7)$$

The intra-winding capacitance C_D is now calculated with the following formula. (Inter-winding capacitance $C=1.8 \text{ pF}$, measured in 4.2.4).

$$f_{DR} = \frac{1}{2 \cdot \pi \cdot \sqrt{(4 \cdot L_D) \cdot (\frac{C_D}{2} + C + C_H)}} \Rightarrow C_D = \frac{1}{8 \cdot \pi^2 \cdot f_{DR}^2 \cdot L_D} - 2(C + C_H) = \quad (8)$$

$$= \frac{1}{8 \cdot \pi^2 \cdot (24.771 \text{ MHz})^2 \cdot 0.975 \mu\text{H}} - 2 \cdot (1.8 \text{ pF} + 10.018 \text{ pF}) =$$

$$C_D = -2.47 \text{ pF} \quad (9)$$

Note that in this particular case the C_d capacitance is negative but this is not a problem for the behavioural model since the simulator can solve this and the total equivalent capacitance of the model will still be positive.

4.2.4 Open-Mode Measurement and Calculations

Instead of the open mode measurement as explained in the paper, we simply measure the total capacitance between the two windings. To do so, switch back to the B-WIC Impedance Adapter and connect the DUT as shown in the following picture.

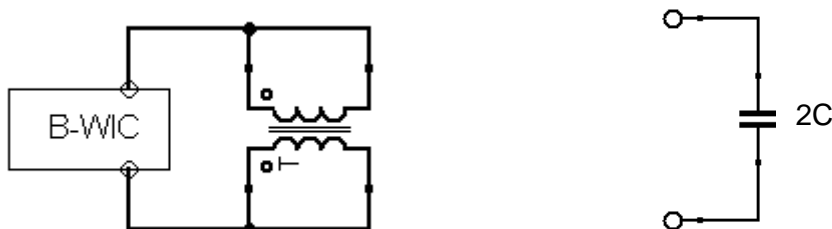


Figure 22: Open mode impedance measurement. DUT configuration and corresponding equivalent circuit.

Set the start frequency to 100 Hz and the stop frequency to 50 MHz. Trace 1 measures the impedance and displays the result as capacitance by choosing the Format “Cs”.

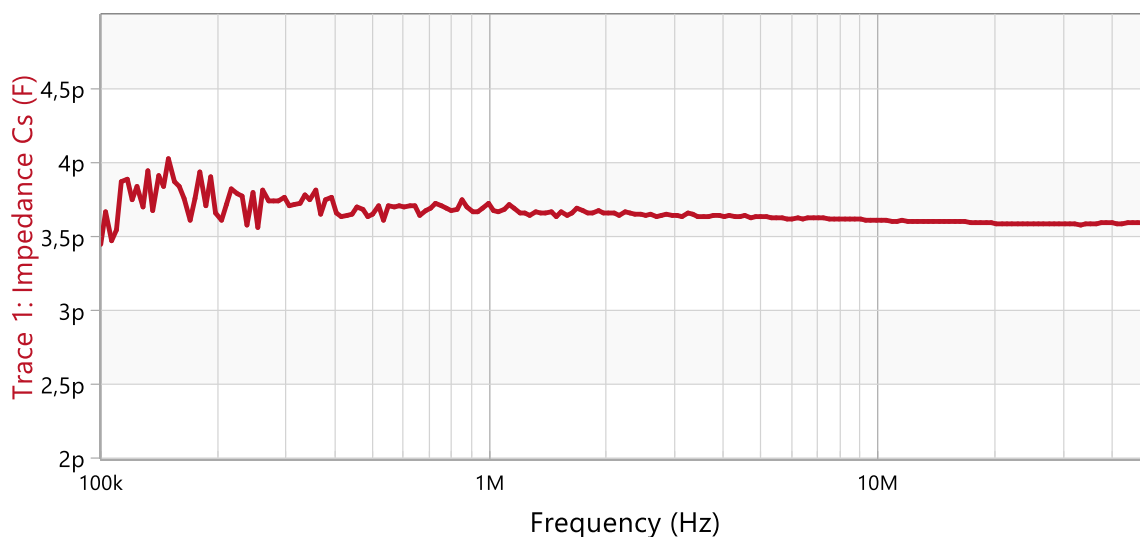


Figure 23: Inter-winding capacitance measurement

The here seen capacitance is the inter-winding capacitance of the choke.

$$\begin{aligned}
 2 \cdot C &= 3.6 \text{ pF} \\
 C &= 1.8 \text{ pF}
 \end{aligned}
 \tag{10}$$

4.3 Y Capacitor Measurement

To measure the Y capacitor, the start frequency is set to 100 Hz and the stop frequency to 50 MHz. Trace 1 displays the magnitude and Trace 2 the phase of the impedance.



Figure 24: Y capacitor measurement with B-WIC Impedance Adapter

Running a single sweep leads to the following chart:

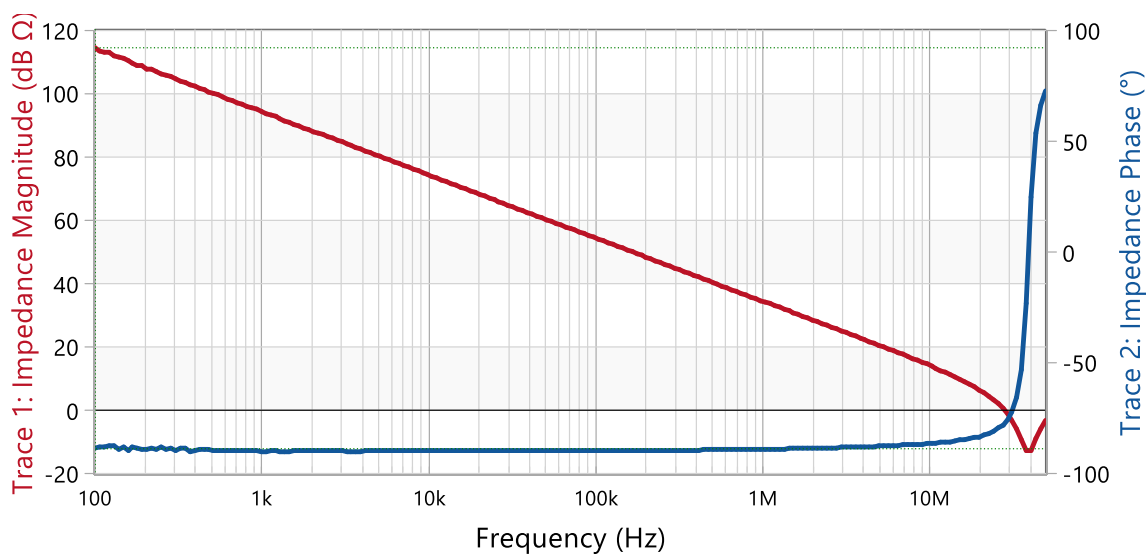


Figure 25: Y capacitor impedance measurement

As can be seen, the Y-capacitors start to get inductive close to 40 MHz. Therefore, the effects of the parasitic inductance in the simulation model can be ignored.

When the trace format is set to Cs, the curve of the capacitance can be seen:

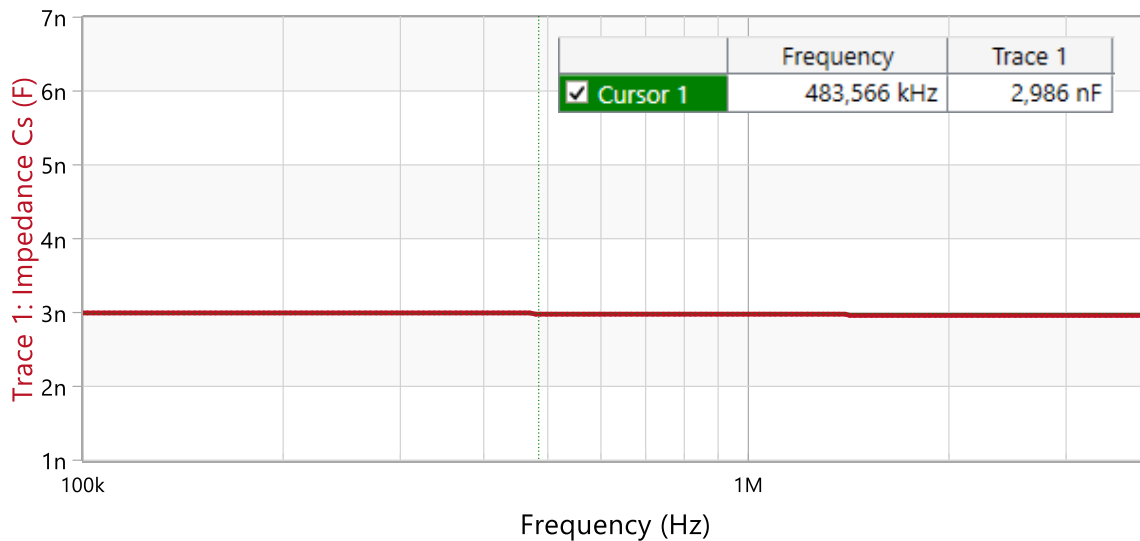


Figure 26: Y Capacitor measurement

The capacitance of the Y capacitor is:

$$C_Y = 2.99 \text{ nF} \tag{11}$$

To get the value of the equivalent series resistance, the trace format is set to Rs.

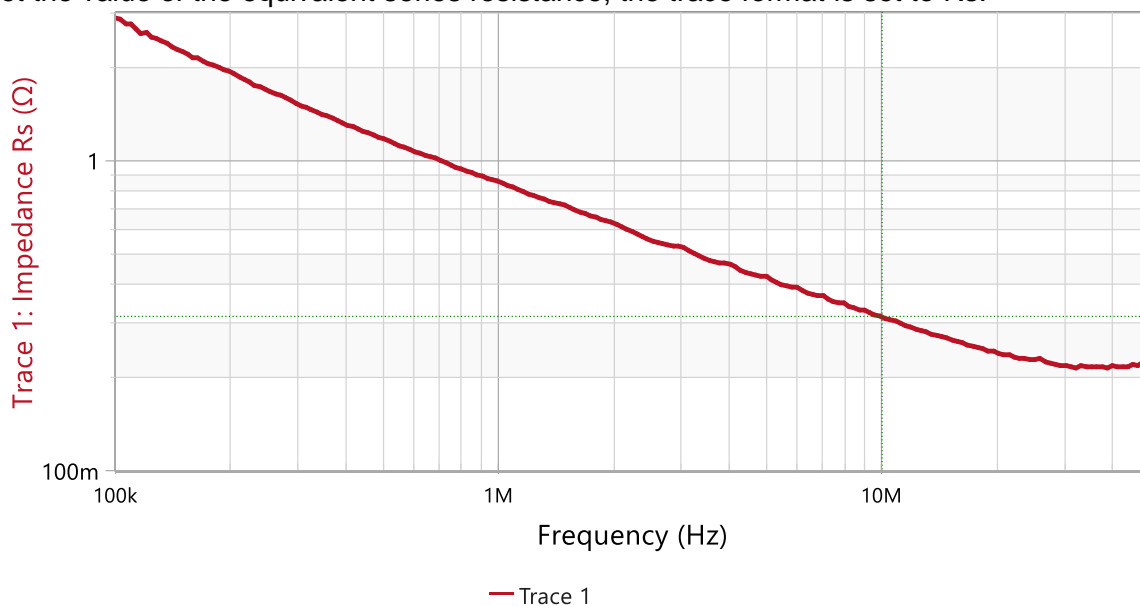


Figure 27: Y Capacitor measurement

This curve shows the frequency dependency of the equivalent series resistance. For the simulation, the value at 10 MHz is used.

$$R_Y = 300 \text{ m}\Omega \tag{12}$$

4.4 X Capacitor Measurement and Calculation

Now, the X Capacitor together with the power inlet is measured and modeled. Furthermore, the same connection leads as used in the insertion loss measurement were used.

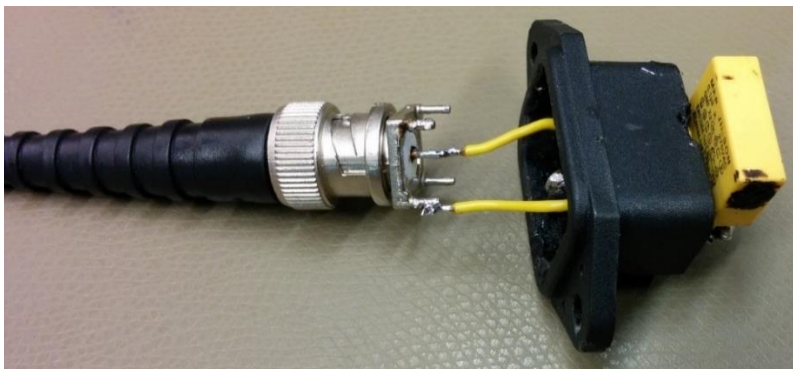


Figure 28: X capacitor with input circuit measurement

To measure the impedance of this input circuit, open a One-Port Impedance Measurement.

Vector Network Analysis **Impedance Analysis**

▼ One-Port

Measure impedance/reflection at the output port.

Recommended impedance range: 500 mΩ ... 10 kΩ

Start measurement

Frequency Sweep Fixed

Start frequency

Stop frequency

Center

Span

Sweep Linear Logarithmic

Number of points

Level Constant Variable

Source level

Attenuator Receiver 1 Receiver 2

Receiver bandwidth

Figure 29: Measurement configuration

The sweep settings are set to 100 kHz to 50 MHz.

The DUT is connected to the Bode 100 as in the following picture.



Figure 30: X capacitor with an input circuit measurement setup

Before performing the measurement, an impedance calibration (Full-Range) is performed.



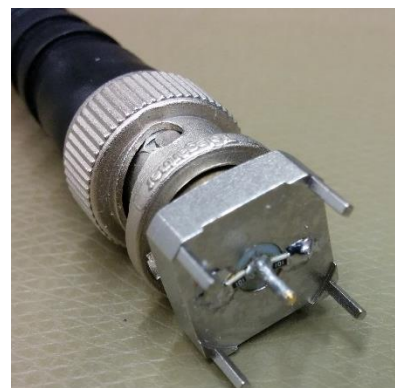
(d) Open calibration

Open



(e) Short calibration

Short



(f) Load calibration

Load

Figure 31: Probe calibration with BNC connectors

Trace 1 displays the magnitude and Trace 2 displays the phase of the impedance.

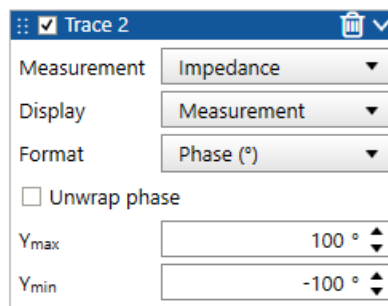
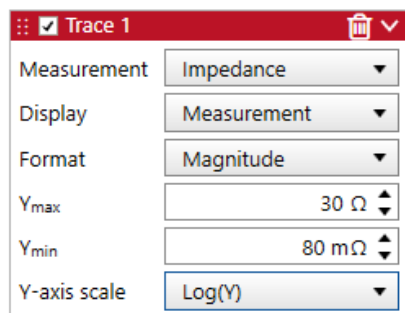


Figure 32: X capacitor measurement trace settings

A single sweep shows the following impedance spectrum.

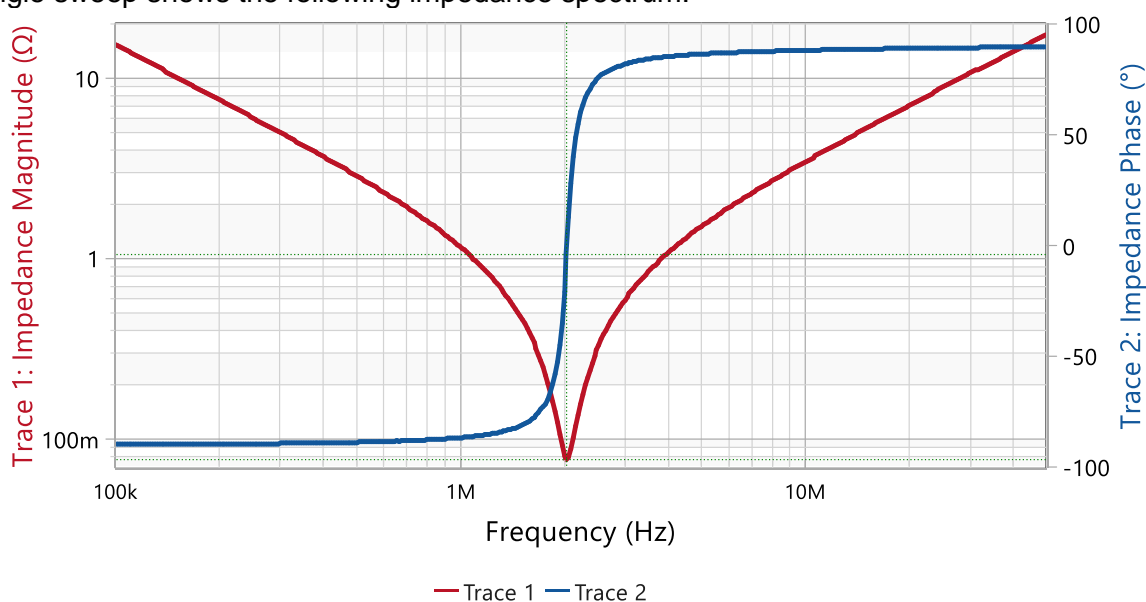


Figure 33: X capacitor with an input circuit, impedance measurement

As can be seen, the resonance of this input circuit is roughly at 2.2 MHz. This is the frequency where also the insertion loss measurement shows a peak (see [1] (OMICRON Lab, 2016)). This leads to the assumption that the measured peak in the differential-mode insertion loss measurement is caused by the parasitic effects of the input circuit.

To derive the values for the equivalent circuit components, the impedance below and above the resonance should be measured.

The ESR is the resistance at resonance.

$$R = 76.9 \text{ m}\Omega \tag{13}$$

Setting Trace 1 to Cs and Trace 2 to Ls, one can directly read the capacitance as well as the inductance of the capacitor as shown below:

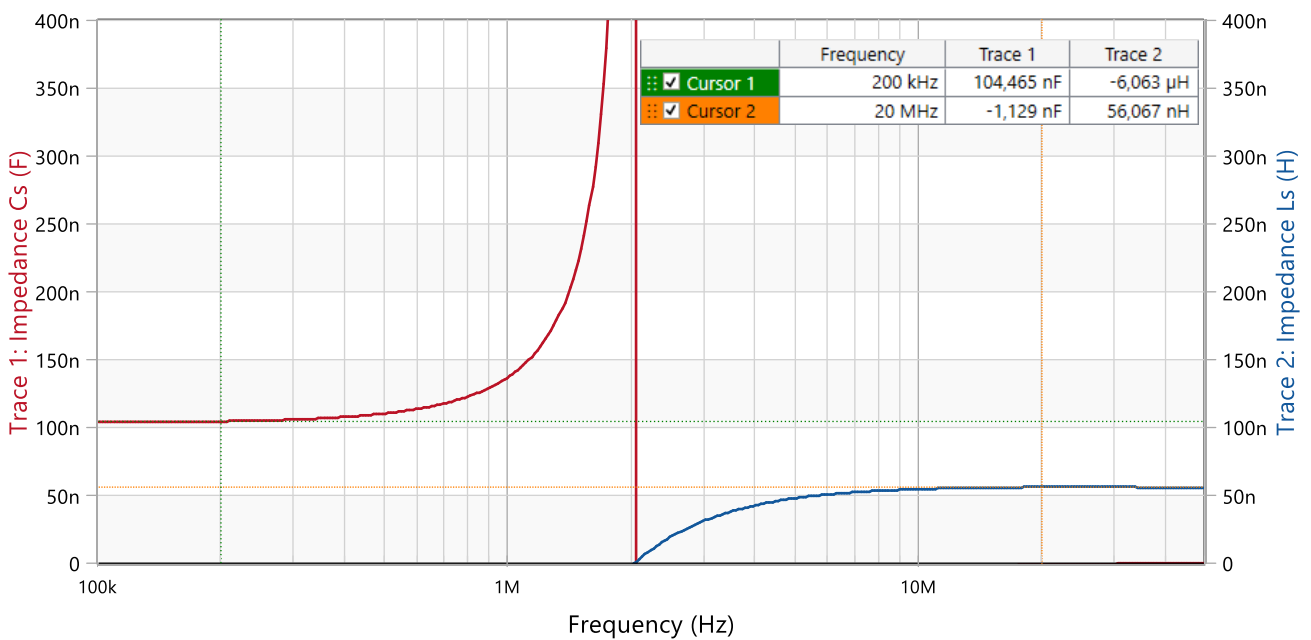


Figure 34: X capacitor Cs and Ls

Reading the values from the measurement leads to:

$$C = 104.46 \text{ nF} \tag{14}$$

$$L = 56 \text{ nH} \tag{15}$$

5 Simulation

With the gathered parameters from the measurement, the insertion loss of the filter can now be simulated. A common mode and a differential mode simulation are performed. To use the common mode choke model in both simulations, sub-circuits are used for the simulations. All the simulations are performed using *QUCS*². The $S[2,1]$ parameter is simulated and the insertion loss is calculated according to the following formula. Note that all simulation results are referenced to 50 Ω.

$$IL = -20 \cdot \log_{10} \left(|S[2,1]| \right) \quad (16)$$

S parameter simulation

Equation

Eqn1
 $IL = -20 \cdot \log_{10}(\text{abs}(S[2,1]))$

SP1
 Type=log
 Start=100 kHz
 Stop=30 MHz
 Points=201

Figure 35: S-parameter simulation settings and insertion loss formula

5.1 Common Mode Choke Model

In the following picture, the common mode choke model can be seen.

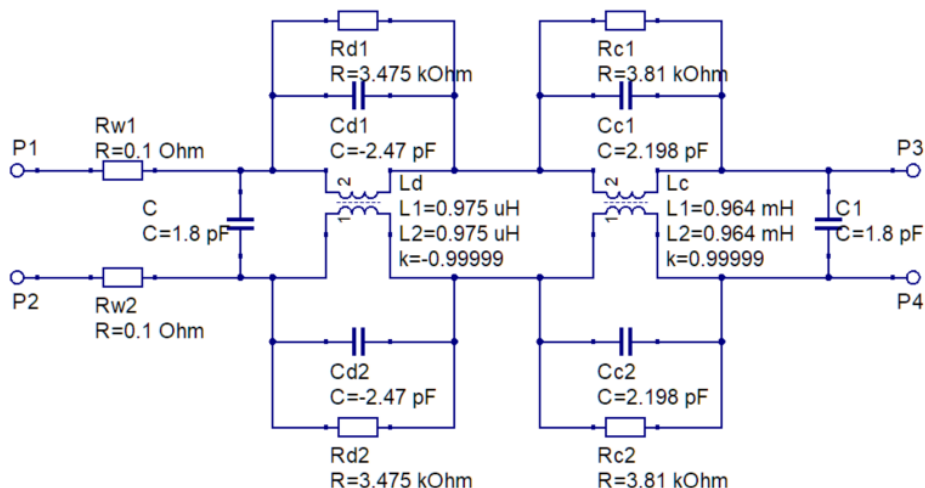


Figure 36: Common mode choke model

² [Qucs](#) is an open-source electronic circuit simulator. Version 0.0.19 was used for the simulations.

5.2 Common Mode Simulation

To perform the common mode insertion loss simulation, the following circuit is used.

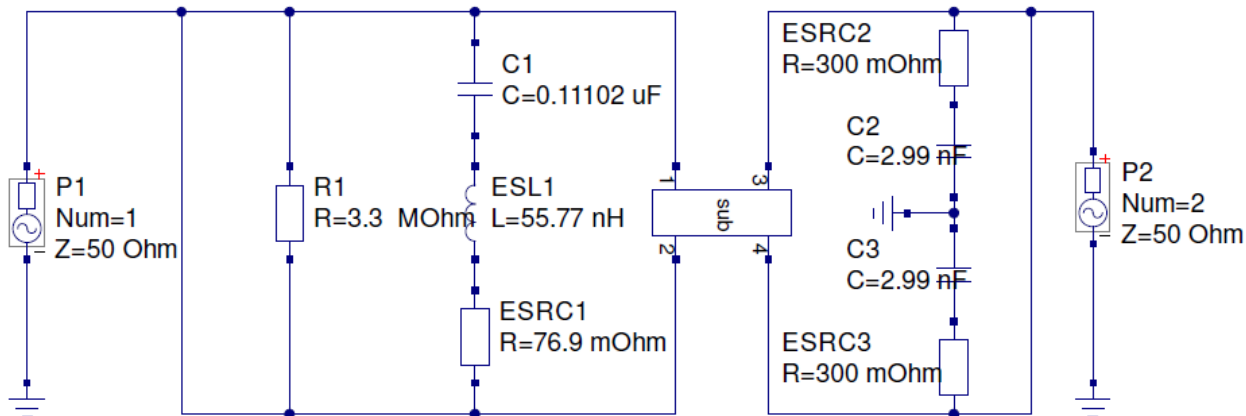


Figure 37: Common mode insertion loss simulation circuit

The following chart shows the simulated common mode insertion loss in comparison to the measured data.

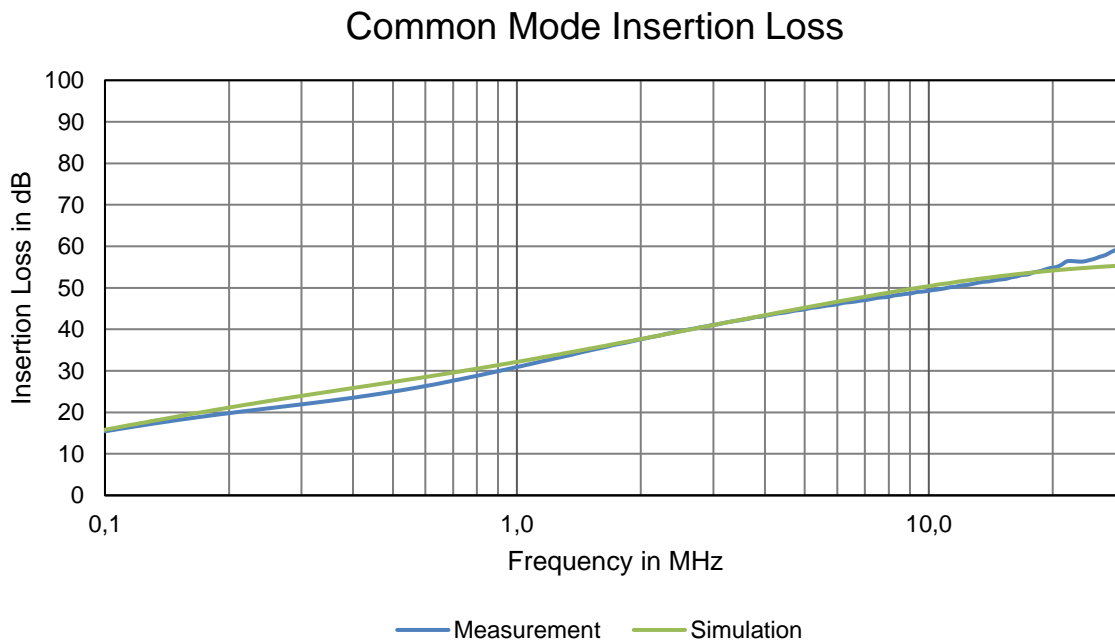


Figure 38: Common mode insertion loss simulation

The simulated data is very close to the measured data. And shows no unexpected behavior.

5.3 Differential Mode Simulation

To perform the differential mode insertion loss simulation, the following circuit is used.

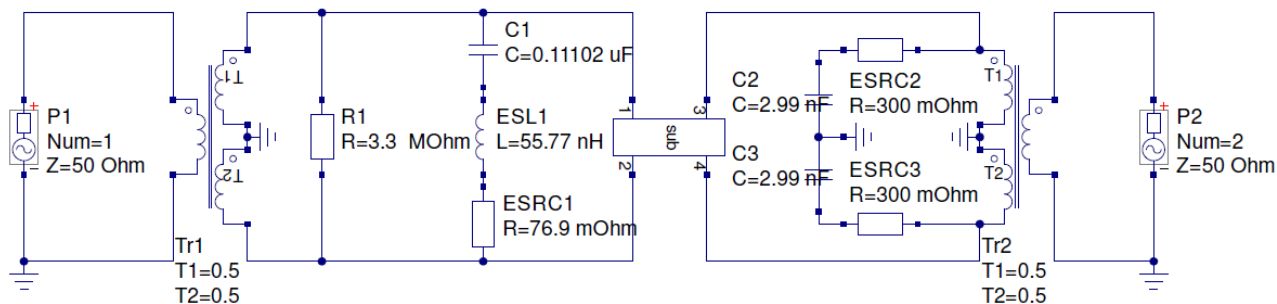


Figure 39: Differential mode insertion loss simulation circuit

The following chart shows the simulated differential mode insertion loss in comparison to the measured data.

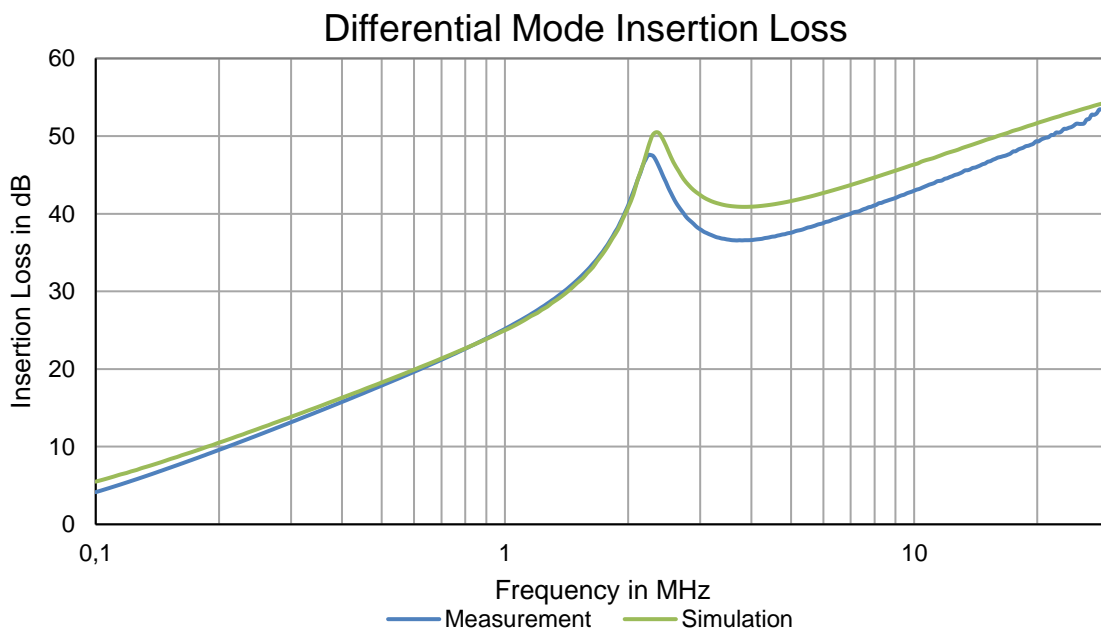


Figure 40: Differential mode insertion loss simulation

Comparing the measured and the simulated data shows that the peak above 2 MHz also occurs in the simulation. It is caused by a resonance at the input of the filter.

6 Conclusion

This application note shows that the Bode 100 Vector Network Analyzer in conjunction with the B-WIC and the B-SMC Impedance Adapters are perfectly suited to derive simulation models for electronic components. This test set provides an easy-to-use and accurate base for developing EMC filters.

7 References

- OMICRON Lab. (2016). *RFI Power Inlet Filter Insertion Loss Measurement*. Retrieved from OMICRON Lab "Smart Measurement Solutions": <https://www.omicron-lab.com/bode-100/application-notes-know-how/application-notes/rfi-power-inlet-filter-measurement.html>
- Stevanović , I., & Skibin , S. (2010). Behavioral Circuit Modeling of Single- and Three-Phase Chokes for EMI Simulations. *Power Electronics Conference (IPEC), 2010 International* (pp. 2867 - 2871). Sapporo: IEEE.
- Stevanović, I., Skibin, S., Masti, M., & Laitinen, M. (2013). Behavioral Modeling of chokes for EMI Simulations in Power Electronics (Volume:28 , Issue: 2) . *IEEE Transactions on Power Electronics*, 695-705.

Version History

Version	Date	Note	Edited by
1.0	2016-08-06	Initial version	Benjamin Mößlang
2.0	2020-07-21	Reworked to latest BAS 3.X	
2.1	2022-11-23	Fixed error in equation (8) Removed unnecessary coupling factor calculation	Florian Hämmerle



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