Bode 100 - Application Note

EMC Filter Insertion Loss Simulation

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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 CALCULATION .............................................................................6
  4.1 MEASUREMENT SETUP ...............................................................................................6
  4.2 COMMON MODE CHOKE .............................................................................................8
    4.2.1 Winding Resistance Measurement .......................................................................8
    4.2.2 Common Mode Measurement and Calculation ....................................................8
    4.2.3 Differential Mode Measurement and Calculation .................................................10
    4.2.4 Open Mode Measurement and Calculations ......................................................14
    4.2.5 Coupling Factor Measurement and Calculation ................................................15
  4.3 Y CAPACITOR MEASUREMENT ................................................................................17
  4.4 X CAPACITOR MEASUREMENT AND CALCULATION ..............................................19
5 SIMULATION .....................................................................................................................22
  5.1 COMMON MODE CHOKE MODEL ..............................................................................22
  5.2 COMMON MODE SIMULATION ..................................................................................23
  5.3 DIFFERENTIAL MODE SIMULATION ........................................................................24
6 CONCLUSION ....................................................................................................................25
7 REFERENCES ....................................................................................................................25

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 V2.43 SR1. 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) we measured the common mode and differential mode insertion loss of an EMC filter. In this application note, the same EMC filter is modeled and simulated.

2 EMC Filter Components

In order to derive a model that fits the reality we measure the impedance of all the single components of the EMC inlet filter. Therefore the filter is disassembled.

![RFI power inlet filter](image1.png)

![RFI power inlet filter, without casing](image2.png)

![Common Mode Choke](image3.png)

![X Capacitor](image4.png)

![Parallel Resistor](image5.png)

Figure 1: RFI power inlet filter

Figure 2: RFI power inlet filter, without casing

Figure 3: Disassembled parts
The following image shows the schematic of the EMC filter.

![Schematic of the EMC filter](image)

Figure 4: RFI Power Inlet Filter schematic

3 Simulation Model

To achieve an accurate simulation of the EMC filter, we use accurate behavior models of the used components. 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.

![Common Mode Choke Model](image)

Figure 5: Common Mode Choke Model

$R_{Wn}$ represent the resistance of the copper. $C$ is 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 and $k_C$ the common mode coupling factor.

### 3.2 Capacitor Model

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

![Capacitor series equivalent circuit](image)

Figure 6: Capacitor series equivalent circuit

### 3.3 BALUN Transformers

The BALUN transformers are modeled with central tapped transformers. The voltage transformation ratio for both secondary windings is $V_{Sn}/V_P = 0.5$.

![BALUN Transformer](image)

Figure 7: BALUN Transformer
4 Measurement and Calculation

4.1 Measurement Setup

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

![Bode 100 and B-WIC Setup](image)

The measurements are performed in the “Frequency Sweep (Impedance Adapter)” Mode.

![Bode 100 settings](image)

The settings for this impedance measurements are:

- Start Frequency: 100,000 Hz
- Stop Frequency: 40,000 MHz
- Center Frequency: 20,000 MHz
- Span: 39.999500 MHz
- Sweep Mode: Logarithmic
- Number of Points: 201
- Level: 13.00 dBm
- Receiver Bandwidth: 300 Hz

The start frequency is set to 100 Hz. And the stop frequency is set to 40 MHz.
Before the measurement is performed a probe calibration is executed. We calibrate with the B-CAL calibration board.

Figure 10: Device configuration

Figure 11: Calibration with B-CAL calibration board
4.2 Common Mode Choke

To get all required parameters of the model, we have to perform five basic measurements. These measurements are impedance measurements with different connection configurations and a measurement with a digital multi meter. At first we measure the winding resistance. 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. We assume a symmetric common mode choke. The fifth measurement is the measurement for the coupling factor.

4.2.1 Winding Resistance Measurement

We measured the resistance of the winding with a digital multi meter.

\[ R_{w1} = R_{w2} = 0.1 \, \Omega \] (1)

4.2.2 Common Mode Measurement and Calculation

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

![Common mode measurement](image)

Figure 12: Common mode measurement. DUT configuration and corresponding equivalent circuit.
With a single measurement the following result was obtained:

![Graph showing common mode impedance measurement with frequency on the x-axis and resistance on the y-axis.](image)

Figure 13: Common mode impedance measurement

We place the cursor at the resonance frequency. The resistance at this point is the double equivalent parallel resistor $R_c$ of the coil.

$$f_{CR} = 2.434 \, MHz \quad \text{and} \quad R_c = 2 \cdot 2399 \, \Omega = 4798 \, \Omega$$

At low frequencies the inductive part of the choke is dominant. Therefore we measure from 100 Hz to 10 kHz.

With this new frequency settings and the trace format set to we now can see the inductance of the coil.

![Graph showing common mode inductance measurement with frequency on the x-axis and inductance on the y-axis.](image)

Figure 14: Common Mode Inductance measurement
The measured inductance at 100 Hz is:

\[ L_C = 1.03 \, mH \]  

(3)

With the inductance and the resonance frequency we can calculate the equivalent series capacitance:

\[ C_C = \frac{1}{8 \cdot \pi^2 f_{CR}^2 \cdot L_C} = 2.075 \, pF \]  

(4)

### 4.2.3 Differential Mode Measurement and Calculation

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

At first we want to extract the value of the inductance \( L_D \). This inductance takes effect on low frequencies. Therefore the Start Frequency is set to 100 Hz and the Stop Frequency to 10 kHz. Trace 1 is set to Magnitude. A single measurement leads to the following result:
The measured inductance is $3.9 \, \mu H$. Because we measure the two windings together and because of the coupling factor the inductance $L_D$ is calculated with the following formula.

$$L_D = \frac{3.9 \, \mu H}{4} = 0.975 \, \mu H$$

Now we want to measure $C_D$ of the common mode choke. To do so we set the start frequency to 100 Hz and the stop frequency to 40 MHz. And the trace format to magnitude.

We can see 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 we can shift the resonance frequency in the measurable domain and calculate the resonance frequency.

We chose a capacitor, because of the better RF\textsuperscript{1} performance. The expected value of $C_D$ is in the lower pico-farad range, so we chose the parallel capacitor $C_H$ in the same range. A higher parallel capacitance would lead to a 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.

\textsuperscript{1} RF... Radio Frequency
We now start a single measurement. This leads us to the following trend.

![Image of Figure 19: Differential Mode Impedance with parallel capacitor]

The capacitor shifts the resonance to 25.54 MHz.

To get a more accurate result, we zoom in to the resonance.

![Image of Figure 20: Differential Mode Impedance with parallel capacitor, resonance]

The cursor now marks the resonance.

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

\[
R_D = \frac{6,430 \, \text{k}\Omega}{2} = 3,215 \, \text{k}\Omega
\]
To get also an accurate value of the capacitor at the resonant frequency we measure the capacitance using the B-SMC Impedance Adapter.

Before the measurement is performed, a probe calibration is executed. The Trace 1 is set to Format: Cp.

This leads us to the following measurement.

![Graph showing parallel capacitor measurement with B-SMC Impedance Adapter](image)

The measured capacitance is

\[ C_H = 10.215 \text{ pF} \] (7)
The intra-winding capacitance $C_D$ is now calculated with the following formula. (Inter-winding capacitance $C=3.35 \, pF$, measured in 4.2.5).

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

$$\Rightarrow C_D = \frac{1}{4 \cdot \pi^2 \cdot f_{DR}^2 \cdot L_D} - 2 \cdot C - 2 \cdot C_H =$$

$$= \frac{1}{4 \cdot \pi^2 \cdot (25.517 MHz)^2 \cdot 0.975 \mu H} - 2 \cdot (3.4 \, pF + 10.215 \, pF) =$$

$$C_D = 12.7 \, pF$$

4.2.4 Open Mode Measurement and Calculations

To perform the open mode measurement we switch back to the B-WIC Impedance Adapter and connect the DUT as in the following picture.

![Figure 23: Open mode impedance measurement, DUT configuration and corresponding equivalent circuit.](image)

We now set the star frequency to 100 Hz and the stop frequency to 40 MHz. Trace 1 measures the impedance and displays the series capacitance “Cs”.
The here seen capacitance is the inter-winding capacitance of the choke.

\[ C = 3.4 \, \text{pF} \] (10)

4.2.5 Coupling Factor Measurement and Calculation

To get the coupling factor \( k \) we need to perform three inductance measurements. In the first and second measurement we measure the inductance of each winding \( L_1 \) and \( L_2 \). In the third measurement we measure the inductance of both windings in series \( L_S \), as it can be seen in the following picture.
A single measurement is performed.

![Graph showing coupling factor measurement, L1](image)

Figure 26: Coupling factor measurement, L1

The following results were measured:

\[ L_1 = 1.03 \, mH \]  \hspace{1cm} (11)
\[ L_2 = 1.03 \, mH \]  \hspace{1cm} (12)

For the series inductance we use the measured inductance from 4.2.3 3

\[ L_S = 3.9 \, \mu H \]  \hspace{1cm} (13)

With these values we now can calculate the mutual inductance:

\[ L_S = L_1 + L_2 - 2 \cdot M_S \]  \hspace{1cm} (14)
\[ M_S = \frac{L_1 + L_2 - L_S}{2} = \frac{1.03 \, mH + 1.03 \, mH - 3.9 \, \mu H}{2} = 1.028 \, mH \]

Now the coupling factor is calculated with the following formula:

\[ k_D = -\frac{M_S}{\sqrt{L_1 \cdot L_2}} = -\frac{1.028 \, mH}{\sqrt{1.03 \, mH \cdot 1.03 \, mH}} = -0.998 \]  \hspace{1cm} (15)
\[ k_C = -k_D = 0.998 \]
4.3 Y Capacitor Measurement

To measure the Y capacitor we set the start frequency to 100 Hz and the stop frequency to 40 MHz. Trace 1 displays the magnitude and Trace 2 the phase of the impedance.

Figure 27: Y capacitor measurement with B-WIC Impedance Adapter

We now start a single measurement. This leads us to the following chart.

![Figure 28: Y capacitor impedance measurement](image)

As we can see the Y capacitors start to get inductive close to 40 MHz. Therefore we ignore the effects of the parasitic inductance in the simulation model.
When we set the trace format to Cs, we can see the curve of the capacitance:

![Capacitance Curve](image)

Figure 29: Y Capacitor measurement

The capacitance of the Y capacitor is:

\[ C_Y = 3.0 \, nF \]  

(16)

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

![Resistance Curve](image)

Figure 30: Y Capacitor measurement

This curve shows how frequency depended the equivalent series resistance is. For the simulation we use the value which reproduces the measurement the most.

\[ R_Y = 200 \, m\Omega \]  

(17)
4.4 X Capacitor Measurement and Calculation

We measure and model the X Capacitor together with the power inlet. Furthermore we use the same connection leads as used in the insertion loss measurement.

To measure the impedance of this input circuit we set the Bode 100 to the *Frequency Sweep* mode:

![Sweep Settings](image)

The sweep settings are set to:

- Start Frequency: 100,000 kHz
- Stop Frequency: 40,000 MHz
- Center Frequency: 20,050 MHz
- Span: 39,900 MHz

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

![Measurement Setup](image)
Before we perform the measurement we have to calibrate the Bode 100.

(a) Open calibration
(b) Short calibration
(c) Load calibration

Figure 34: Probe calibration with BNC connectors

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

Figure 35: X capacitor measurement trace settings
A single measurement shows the following impedance spectrum.

![Impedance Spectrum](image)

Figure 36: X capacitor with input circuit, impedance measurement

We now set the cursor to the resonance frequency.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>TR1: Mag</th>
<th>TR2: Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,297211 MHz</td>
<td>89,952 mΩ</td>
<td>-8,188 °</td>
</tr>
</tbody>
</table>

As we can see the resonance of this input circuit is roughly at 2.4 MHz. This is the frequency where also the insertion loss measurement shows a peak (see [1] (OMICRON Lab, 2016)). This leads us to the assumption that the measured peak in the insertion loss measurement is caused by the parasitic effects of the input circuit.

To derive the values for the equivalent circuit components we measure the impedance below and above the resonance. The ESR is the resistance at resonance.

\[
R = 89,9 \text{ mΩ} \tag{18}
\]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>TR1: Mag</th>
<th>TR2: Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>395,831 kHz</td>
<td>3,987 Ω</td>
<td>-89,043 °</td>
</tr>
</tbody>
</table>

Because of the phase shift of nearly -90° we see that the impedance below the resonance is capacitive.

\[
C = \frac{1}{|Z(f)| \cdot 2 \cdot \pi \cdot f} = \frac{1}{3,987 \Omega \cdot 2 \cdot \pi \cdot 395,831 \text{ Hz}} = 100,8 \text{ pF} \tag{19}
\]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>TR1: Mag</th>
<th>TR2: Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>23,934606 MHz</td>
<td>6,948 Ω</td>
<td>88,327 °</td>
</tr>
</tbody>
</table>

If we set the cursor above the resonance the impedance is inductive.

\[
L = \frac{|Z(f)|}{2 \cdot \pi \cdot f} = \frac{6,948 \Omega}{2 \cdot \pi \cdot 23,934 \text{ MHz}} = 46,2 \text{ nH} \tag{20}
\]
5 Simulation

With the gathered parameters from the measurement, we can now simulate the insertion loss of the filter. We perform a common mode and a differential mode simulation. To use the common mode choke model in both simulations we put it into a separate file and use sub circuits for the simulations. All the simulations are performed with Qucs. We simulate the $S[2,1]$ parameter and calculate the insertion loss according the following formula.

$$IL = -20 \cdot \log_{10}(|S[2,1]|)$$  \hspace{1cm} (21)

The simulations are referenced to 50 Ω.

5.1 Common Mode Choke Model

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

Figure 38: Common mode choke model

\footnote{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 we use the following circuit.

![Common Mode Insertion Loss Simulation Circuit](image)

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

![Common Mode Insertion Loss Chart](image)

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 we use the following circuit.

![Differential Mode Insertion Loss Simulation Circuit](image)

Figure 41: Differential mode insertion loss simulation circuit

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

![Differential Mode Insertion Loss Chart](image)

Figure 42: Differential mode insertion loss simulation

When we compare the measured and the simulated data, we can clearly see that the peak at 2.4MHz occurs also in the simulation. It is caused by a resonance at the input of the filter. At frequencies above this peak the simulation does not fit exactly to the measured data, but shows the same trend.
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


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