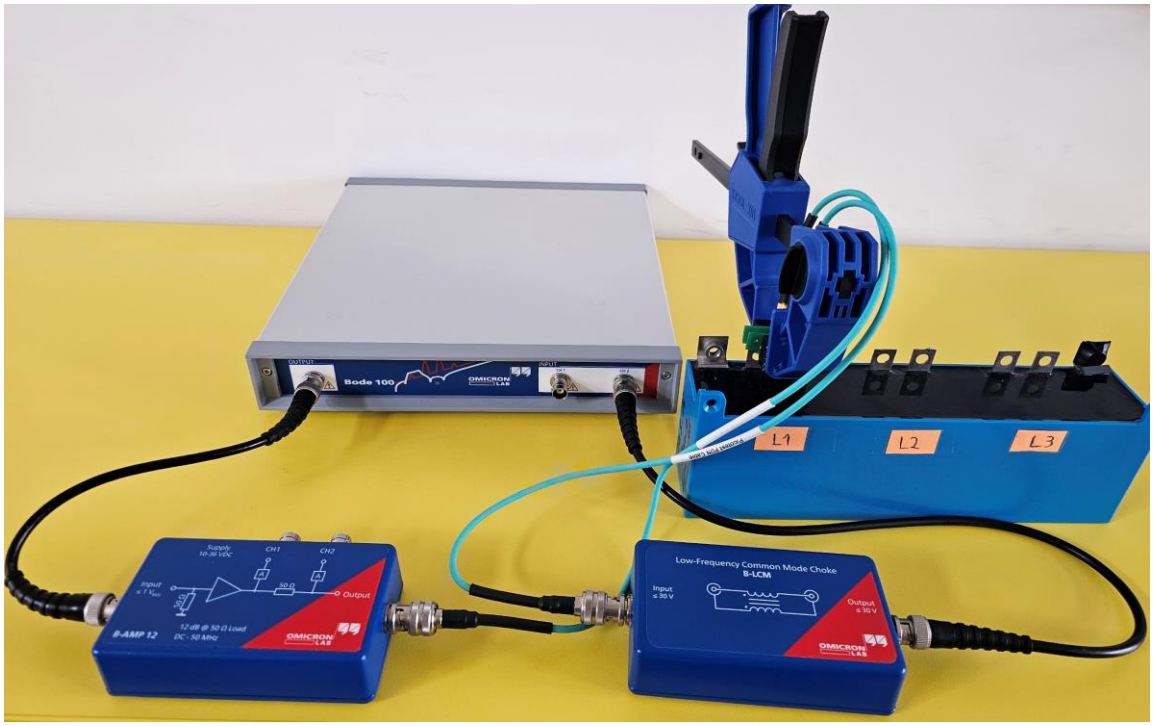
Bode 100 - Application Note

Impedance Measurement and ESR Analysis of a DC-Link Capacitor



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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 V3.50 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

A three-phase DC-Link capacitor is a critical element in power electronics, especially within three-phase inverter systems. The DC-link capacitor is commonly used as a filter at the output of the rectifier, and its central role is to suppress voltage ripples arising from the switching behavior of the inverter. Understanding the equivalent series resistance (ESR) of the DC-Link capacitor is crucial, as an increased ESR can lead to higher voltage ripple on the DC link, reducing the effectiveness of the capacitor's filtering capabilities. Excessive ESR can even cause significant power loss and temperature rise within the capacitor.

This application note outlines comprehensive procedures for configuring connections and adjusting device parameters of the Bode 100, essential for conducting accurate and reproducible impedance measurements on a DC-Link capacitor.

2 Measurement Task

The goal of this document is to show how the Bode 100 can be used to measure the impedance and ESR of a DC-Link capacitor.

Device Under Test (DUT)

Figure 1 shows the three-phase DC-Link capacitor used for the measurements shown in this document. The labels shown describe the terminal pairs for each phase.



Figure 1: Device under test (DUT) - DC-Link Capacitor

The capacitor is a metalized film capacitor with a nominal total capacitance of 500 µF. Typically, these capacitors have a very low ESR value, which can easily reach below 1 mΩ.

3 Measurement Method

Figure 2 illustrates the Shunt-Thru method, which is the preferred technique for measuring the very low impedance of DC-Link capacitors. In this document, the impedance of the DC-Link capacitor is measured within the frequency range of 100 Hz to 1 MHz.

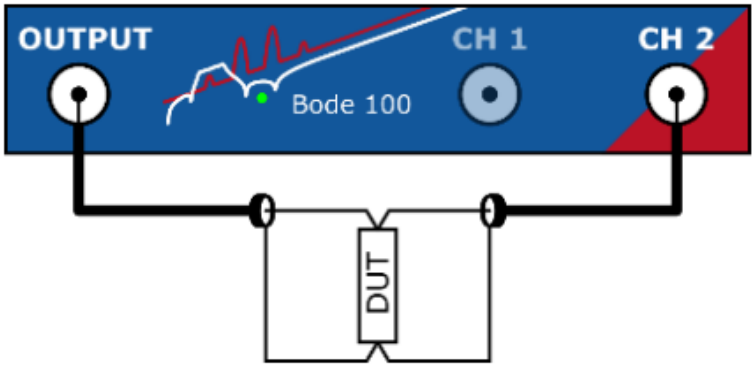


Figure 2: Shunt-Thru Method

To further improve the accuracy of the Shunt-Thru method, the Bode 100 is utilized in conjunction with the Low-Frequency Common Mode Choke (B-LCM) and the Power Amplifier B-AMP 12. The B-LCM is employed to mitigate the effects of currents flowing in the cable shield (ground-loop error) while the B-AMP 12 is a power amplifier designed to increase the Bode 100 output signal and improve the Signal-to-Noise Ratio (SNR). Furthermore, the B-AMP 12 improves the measurement by reducing the loading of the Bode 100 signal source and therefore reducing device-internal crosstalk. Coaxial cables and specifically PDN cables from Picotest are incorporated in the setup. PDN cables from Picotest are flexible, facilitating connection and routing in setups with space constraints. Finally, a specific clamp connection has been designed to ensure a repeatable measurement by offering low and stable contact resistance.

3.1 Making Contact with the DUT

The Shunt-Thru setup emulates a four-wire Kelvin measurement. Therefore, four connections should be made directly to the DUT. On the signal source side (output of the B-AMP 12 amplifier), the signal is provided at the center pin of the coaxial connection and returns over the shield of the coaxial connection. On the second side, the voltage across the DUT is measured over the 50 Ω coaxial connection going to CH2 of the Bode 100.

To ensure reproducible results of the Shunt-Thru method, a low and repeatable contact resistance between the measurement setup and the DUT is important.

In this document, a Shunt-Thru clamp was designed to enhance measurement accuracy. The PCB of the “Shunt-Thru crocodile clamp” can be equipped with solid, gold-coated contact pins that establish contact during the shunt-thru impedance measurement. Additionally, it features an SMA connector for interfacing with the Picotest PDN cables, as can be seen in Figure 3.





Figure 3: “Shunt-Through crocodile clamp”

The PCB was mounted on a one-handed bar clamp using a 3D printed adapter piece.

3.2 Measurement Setup

The complete setup for measuring the impedance of the DC-Link capacitor is shown in Figure 4 below. It consists of the Bode 100, the B-AMP 12 power amplifier, the B-LCM common mode choke, and the special clamps that connect to the DUT via the PDN cables.

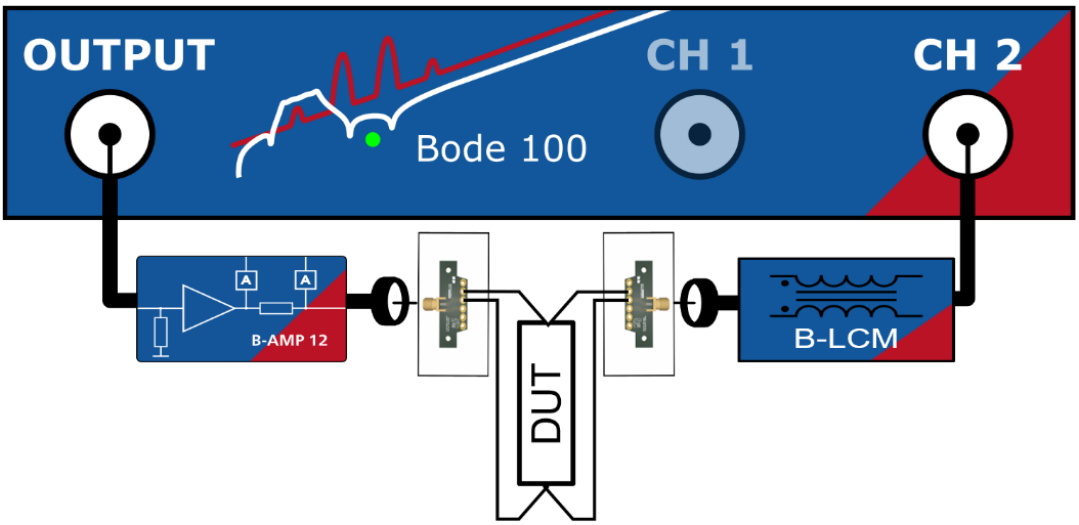


Figure 4: DC-Link Capacitor measurement setup

Short coaxial cables are recommended. Also, it is advisable to arrange the coaxial cables between the devices and the clamp in a manner that prevents any movement of the clamp. The PDN cables provide great flexibility, which can simplify the measurement.

3.3 Bode Analyzer Suite Configuration

The DC-Link capacitor measurement can be performed directly with the Bode 100 using the Shunt-Thru impedance method. The following settings presented in Figure 5 are applied to the Bode 100 using the Bode Analyzer Suite (BAS).

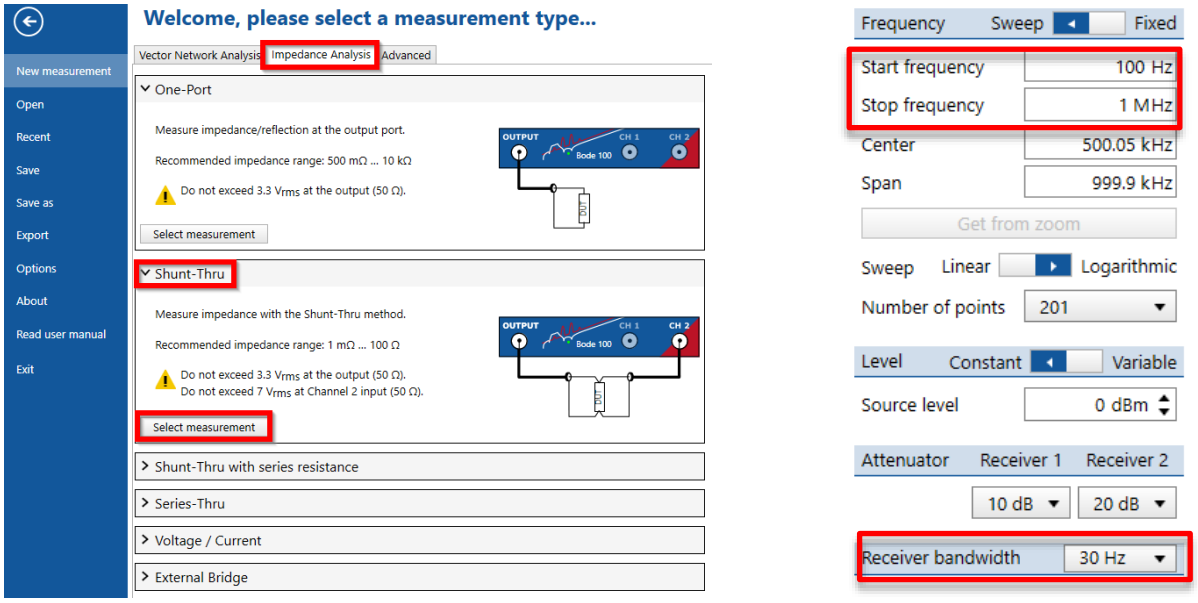


Figure 5: Bode 100 measurement type and settings setup

3.4 Calibration

It is recommended to perform a Thru calibration as shown in Figure 6. The setup for the measurement consists of Bode 100, B-AMP, B-LCM, and the custom Shunt-Thru crocodile clamp designed for the DUT. The B-AMP is connected to the Bode 100 output, and the B-LCM is connected to CH2. Both accessories are then connected to the crocodile clamp (Figure 6).

User-range calibration is recommended for this measurement. For more details about User-Range calibration, please take a look at the following link: [Bode 500 Vector Network Analyzer User Manual].

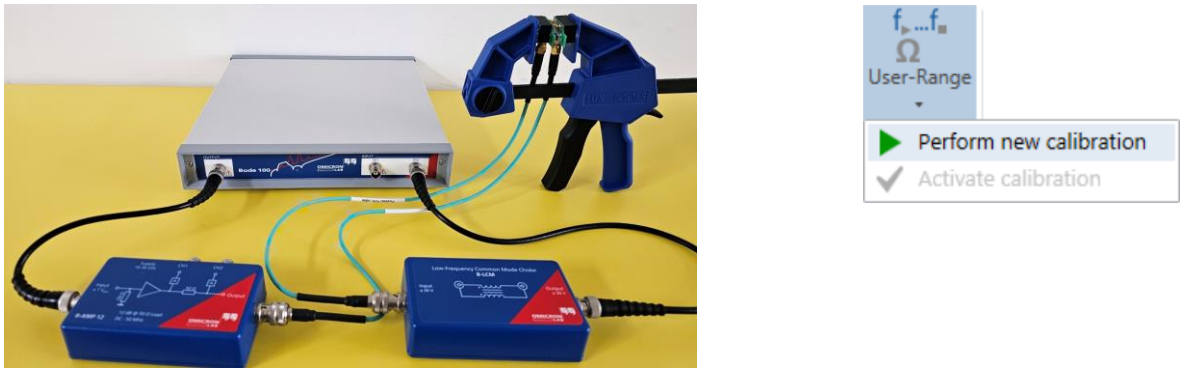


Figure 6: User-Range calibration setup

Before executing the Thru calibration, ensure that the contacts between the pins of the clamp are secure and make good contact. Figure 7 below shows the details of the connection. Both signal pins are connected, and both ground pins are connected during Thru calibration.

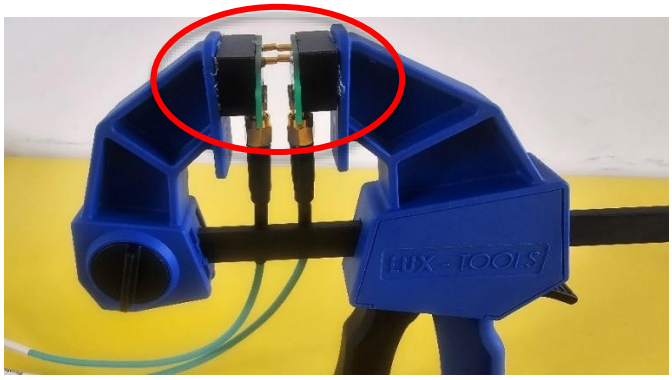


Figure 7: Shunt-Through Crocodile Clamp contact between pins

The clamp applies pressure to the pins. This pressure ensures firm contact between the pins, maintaining reliable connections during both calibration and measurement.

Note: After having performed a User-Range calibration, be aware that changing the start frequency, stop frequency, sweep, or number of points will invalidate the calibration data.

3.5 Performing the Measurement

To perform the measurement, connect the DC-Link capacitor as shown in Figure 8. It is crucial to avoid moving the clamp once measurements have commenced, as any alteration in the clamp's position during the test may result in variations in the measurement outcomes.



Figure 8: Complete DC-Link capacitor measurement setup

4 Measurement Results

4.1 Importance of Calibration

Figure 9 and Figure 10 show the measurement result with calibration (blue) and without calibration (green). Without calibration, the measurement results are off due to the amplification of the B-AMP 12 that is not considered. Also, the ESR curve between 100 Hz to approximately 5 kHz is not plausible. This highlights the importance of a correct Thru calibration that must be performed prior to conducting the measurements.

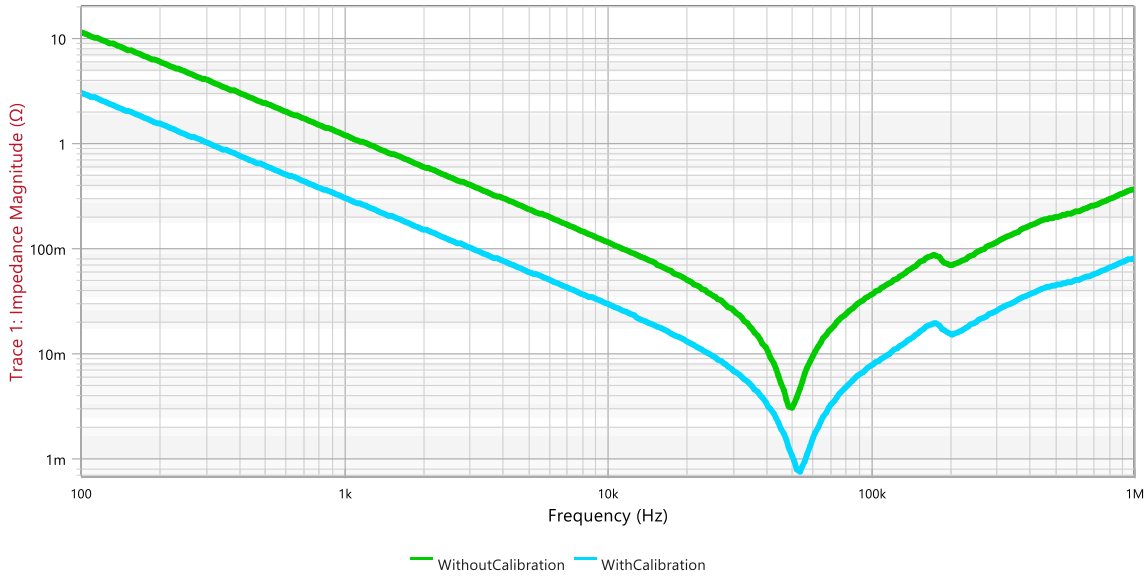


Figure 9: DC-Link Capacitor Impedance Magnitude (Ω)

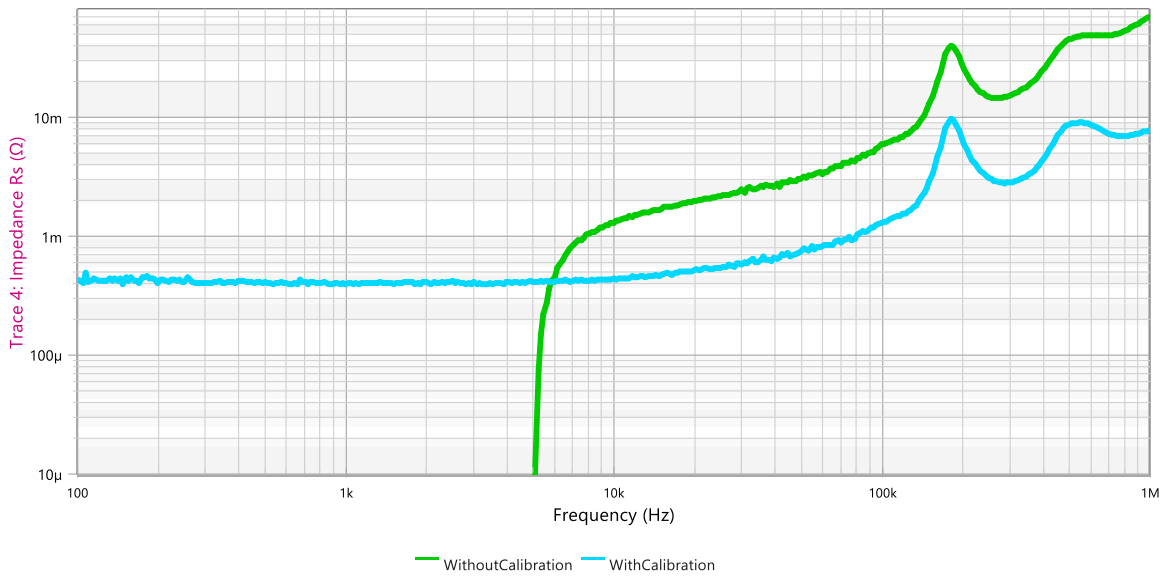


Figure 10: DC-Link Capacitor ESR (Ω)

4.2 Results and Analysis

In Figure 11 illustrates the results of the impedance magnitude measurements for the three different phase connection points of the DC-Link capacitor: L1, L2, and L3. Since all phases are connected in parallel, the impedance is the same at all connection points up to roughly 10 kHz.

At 100 Hz, 1 kHz, and 5 kHz, the impedance at all three phase connection points is nearly identical. Only around the self-resonance of the capacitor and at higher frequencies above self-resonance, the impedance starts to depend more on the point of connection. The self-resonance frequency of the DC-Link capacitor is around 50 kHz. The impedance at self-resonance drops below 1 mΩ, indicating a very low ESR of this capacitor. At frequencies above self-resonance, the impedance starts to rise from parasitic inductance.

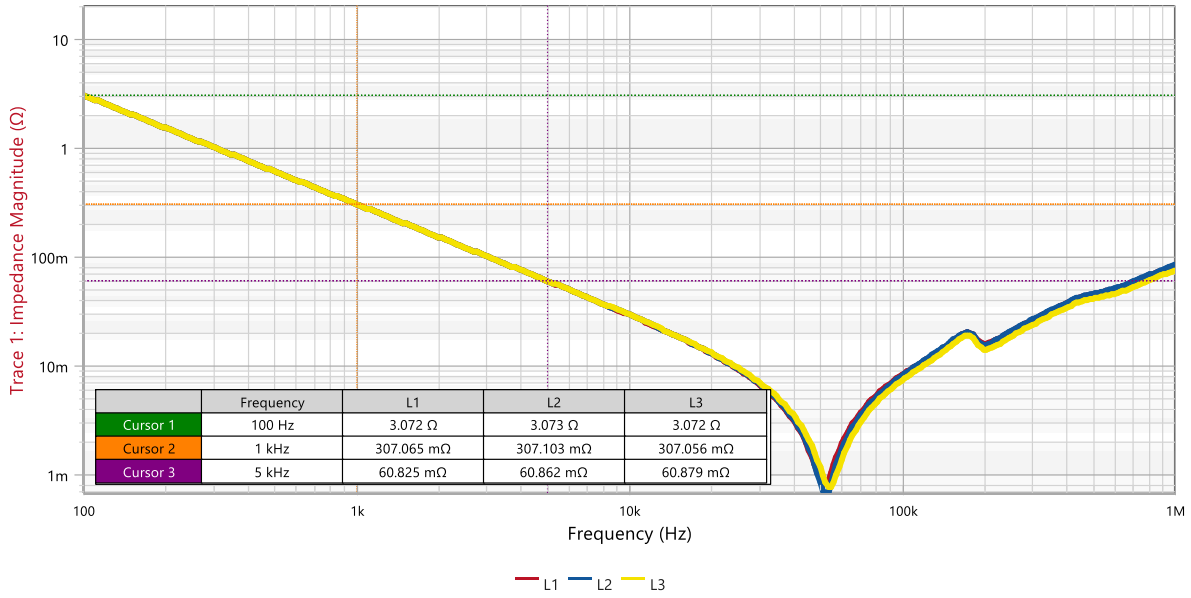


Figure 11: Impedance Magnitude Plot

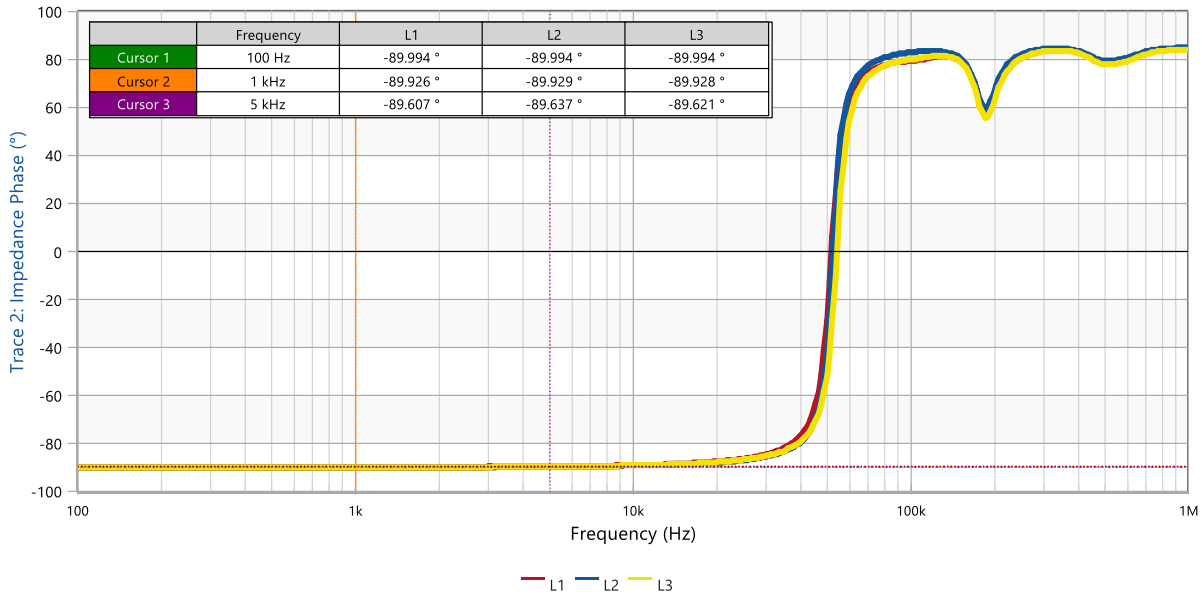


Figure 12: Impedance Phase Plot

Figure 13 shows the impedance phase over frequency confirming that the results at all phase connection points are similar up to frequencies close to the self-resonance frequency. Above the self-resonance frequency, the impedance phase turns from -90° to +90° indicating inductive behavior from the parasitic inductance. The parasitic inductance can be estimated, using the following equation:

$$\text{At 1 MHz: } |Z| \approx X_L = \omega \cdot L \rightarrow L \approx \frac{|Z|}{\omega} \approx \frac{80\ \text{m}\Omega}{2 \cdot \pi \cdot 1\ \text{MHz}} = 12.7\ \text{nH} \quad (1)$$

Figure 13 below shows the measured ESR over frequency. At low frequencies between 100 Hz and 1 kHz, the ESR is almost constant around 310 to 350 µΩ. However, as the frequency increases, the resistance (ESR) also increases due to factors like skin effect in the bus bars and other conducting parts. The ESR starts to rise significantly starting at 5 kHz and further. Around 180 kHz, the ESR value reaches a maximum of nearly 10 mΩ due to a resonance effect. This maximum is about 30 times higher than the low-frequency ESR.

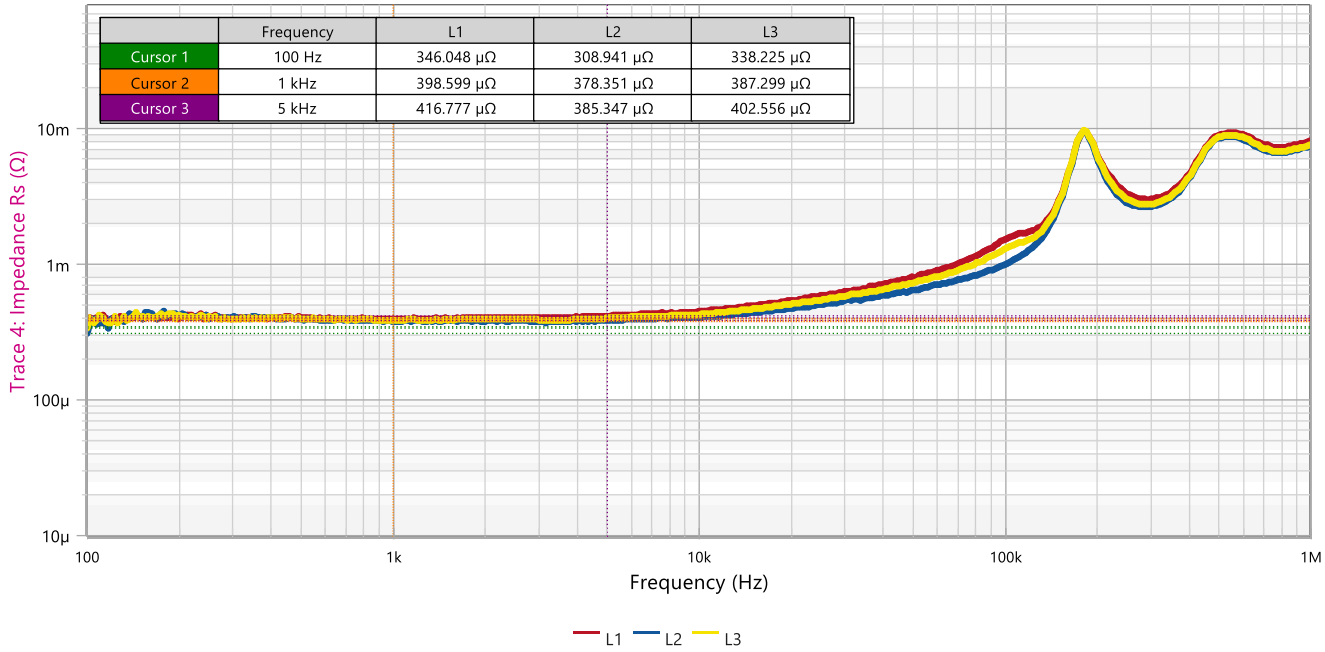


Figure 13: Impedance Rs(Ω)

5 Conclusion

Measuring the ESR of a DC-Link film capacitor is a challenging task due to the high quality-factor and low ESR values typical of such a construction. This document demonstrates that the Bode 100 can be used to solve this challenging task by employing the B-AMP 12 amplifier in combination with the B-LCM common mode choke, Picotest PDN cables, and a specifically constructed contact clamp made from a one-handed bar clamp available from a hardware store, extended with a 3D printed holder and a simple PCB.

The ESR of a three-phase DC-link capacitor can have resonance effects, particularly at frequencies around and above 100 kHz. If switching frequencies or harmonic content of ripple currents meet the increasing ESR value from a resonance, excessive heat and power loss could be the consequence.



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