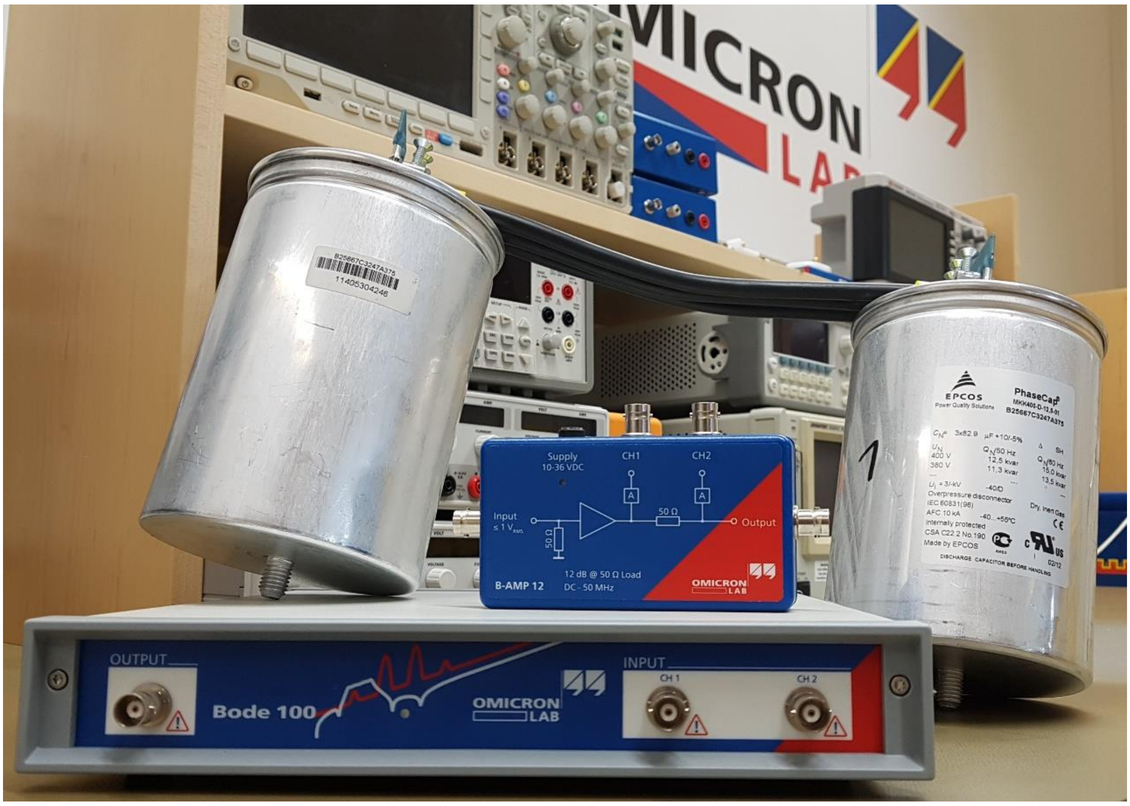
Bode 100 - Application Note

PFC Capacitor ESR Measurement



This application note was written with the support of Mr. Malte Keil from Fraunhofer IVI.

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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. You can download the Bode 100 user manual at https://www.omicron-lab.com/downloads/vector-network-analysis/bode-100/

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.20. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at https://www.omicron-lab.com/downloads/vector-network-analysis/bode-100/

1 Executive Summary

This application note describes how to measure the impedance of PFC[1] or DC Link capacitors using the Bode 100 vector network analyzer in conjunction with the B-AMP12 amplifier.
A MTFC[2] PFC capacitor is used as device under test (DUT).

Due to their favorable characteristics, MTFCs have become very popular in modern electronics and electrics. They provide high capacity, are self-healing and can withstand the industrial temperature range. The MTFC's ESR is at least one magnitude lower than that of an otherwise comparable electrolytic capacitor, allowing for applications with much higher energy density, e.g. inverters. Moreover, MTFCs are not polarized, making them the perfect choice for power factor correction in industrial applications. Also, large scale manufacturing and readily available base materials ensure competitive prices.

Stressful applications like the ones mentioned above take their toll on a capacitor's lifetime. Most age gracefully: their capacity slowly diminishes until an application-specific threshold is reached and the unit must be replaced. Though capacity is easy to measure, research suggests ESR might be a much better indicator of ageing in MTFCs (Flicker et al, 2013). In applications where availability and/or accuracy are crucial, the knowledge of ESR might provide a valuable additional alarm signal that helps to prevent damage and loss.

2 Measurement Task

Obtaining the ESR is a challenging task since it is very low (few milliohms in this case) and masked by capacity in most situations. A widely used equivalent circuit for capacitors consists of four elements, of which R_P can be neglected for MTFCs unless extremely low frequencies must be considered.

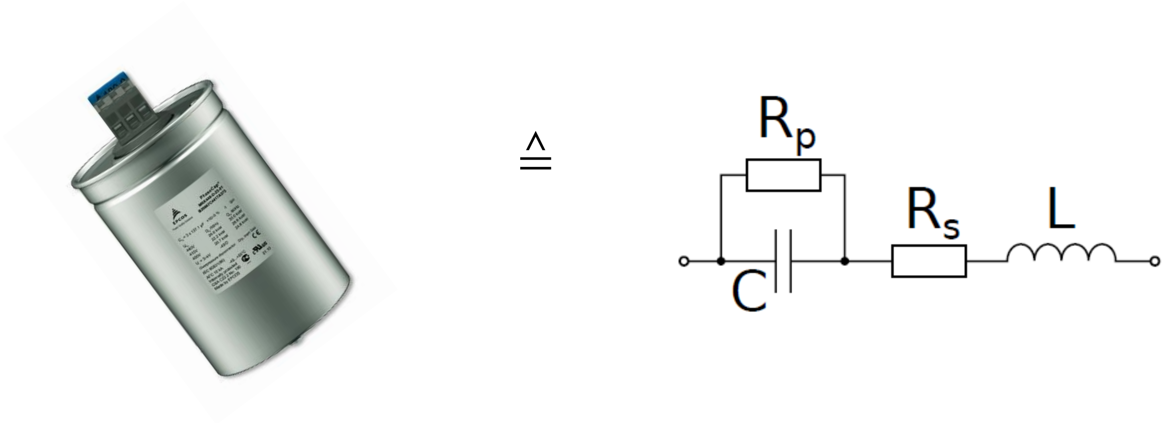

Figure 1: Capacitor equivalent circuit model

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[1] Power Factor Correction
[2] Metallized Thin Film Capacitor

This equivalent circuit proves insufficient to explain frequency response of more complex units like the ones examined in this application note, which feature a delta structure between their three poles. Nonetheless, it explains that we see three characteristically distinct zones with impedance at low frequencies being dominated by capacitance, impedance at resonance being dominated by ESR, and impedance at high frequencies being dominated by inductance. Thus, a high-quality measurement of impedance over frequency allows us to learn a lot about a specific capacitor, including an estimation of the capacitors ESR.

3 Measurement Setup & Results

3.1 Measurement Equipment

- Bode 100 Vector Network Analyzer
- B-AMP 12 amplifier
- DUT (in this case a MTFC)
- Self-made calibration board

3.2 Measurement Setup and Calibration

3.2.1 Measurement Setup

Since the ESR is expected to be very low, the Shunt-Thru measurement method is chosen. To achieve optimum signal/noise ratio, the B-AMP 12 is used to boost the measurement signal up to 25 dbm. Furthermore, the B-AMP helps to reduce the ground-loop error of the Shunt-Thru measurement setup. The output of the B-AMP 12 as well as Channel 2 of the Bode 100 are connected to the DUT as shown in the picture below. It is important to isolate at least one of the BNC connectors next to the DUT, to do not short the grounds, bypassing the 4-wire connection.

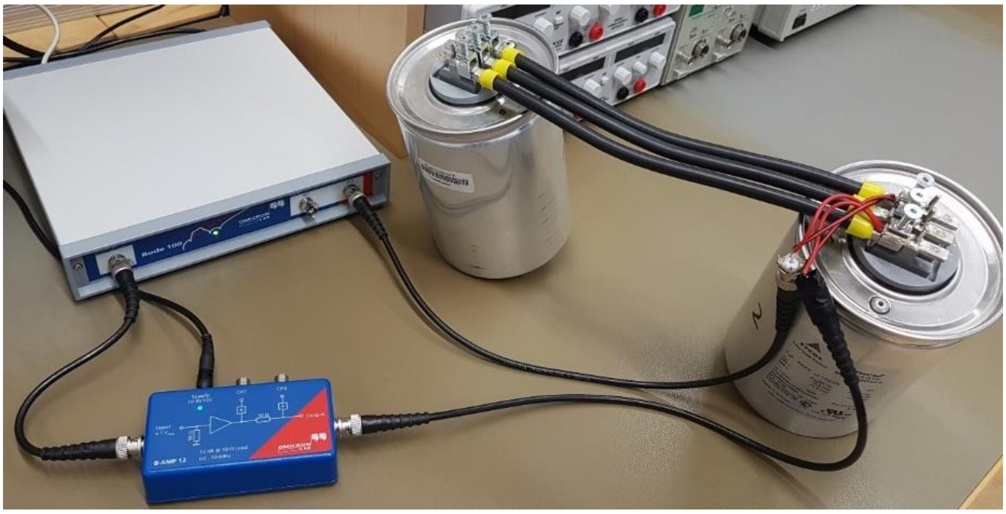
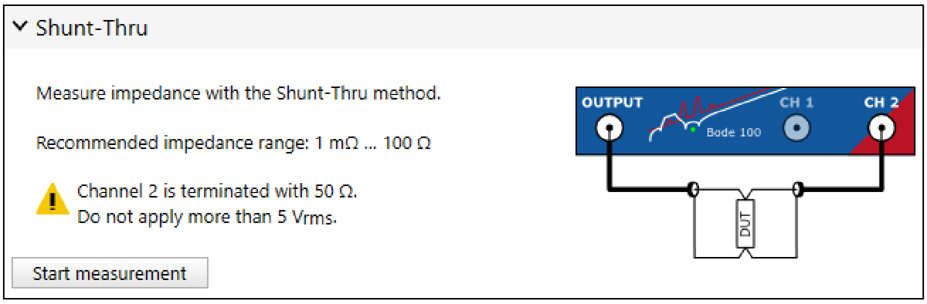


Figure 2: Measurement setup

The Bode Analyzer Suite (BAS) is started in the “Shunt-Thru” measurement mode.



Shunt-Thru

Measure impedance with the Shunt-Thru method.

Recommended impedance range: 1 mΩ ... 100 Ω

Channel 2 is terminated with 50 Ω.
Do not apply more than 5 Vrms.

Start measurement

Figure 3: Start menu

Within the BAS, a frequency sweep from 100 Hz to 1 MHz is set. Furthermore, the number of points is set to 801 for best resolution at the different resonances.

3.2.2 Calibrating the Measurement Setup

User-Range Impedance calibration (Open/Short/Load) must be performed prior to the measurement. For Open/Short/Load, a calibration board like the one below was constructed. It consists of a 10 Ω resistor for the Load calibration and a low-impedance Short with 4 connection points. The resistance of the short is around 30 µΩ.

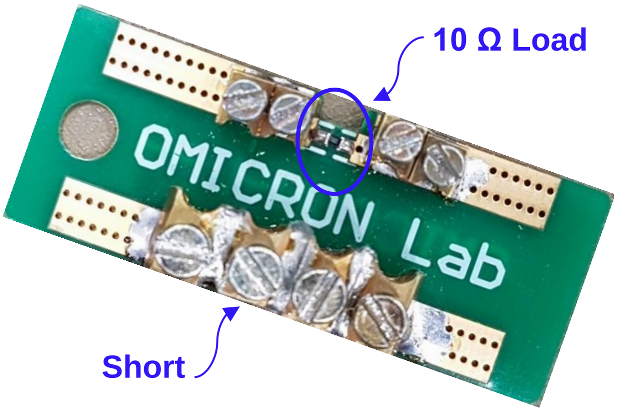
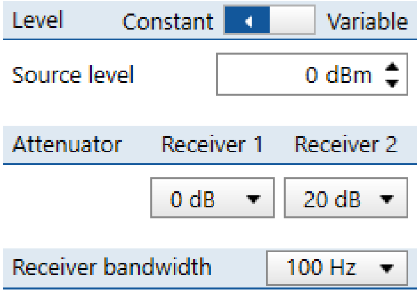


Figure 4: calibration board

Prior calibration, the settings are:



Level: Constant / Variable
Source level: 0 dBm

Attenuator	Receiver 1	Receiver 2
	0 dB	20 dB

Receiver bandwidth: 100 Hz

Figure 5: settings for calibration

To get the best possible results, a **User-Range** impedance calibration is performed as follows:

Open-Calibration:

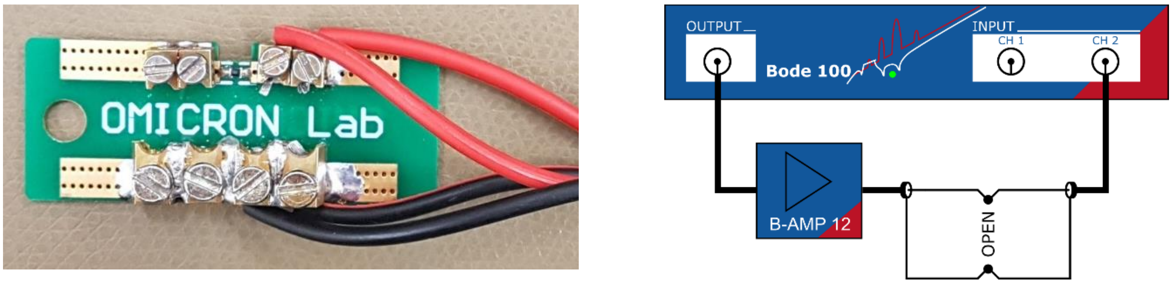


Figure 6: Open calibration

Short-Calibration:

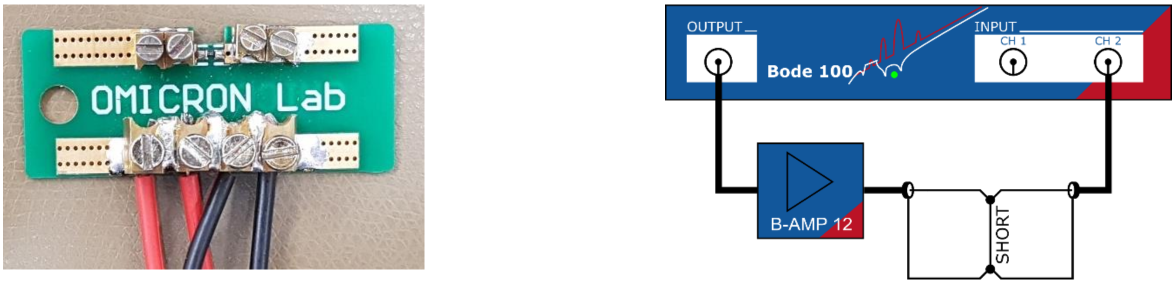


Figure 7: Short calibration

Load-Calibration:

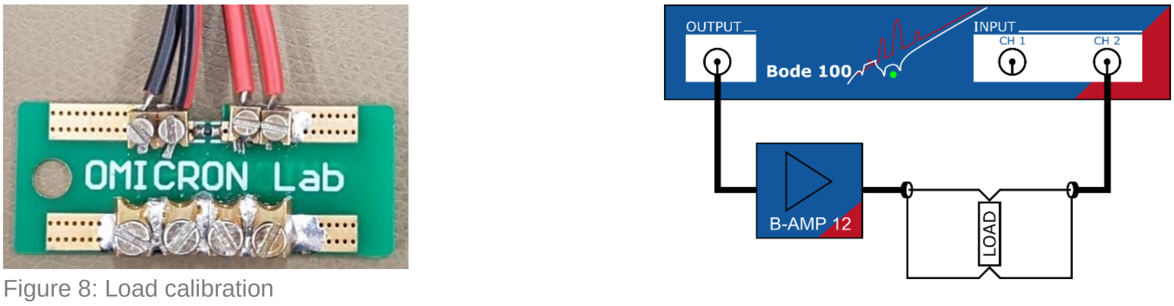
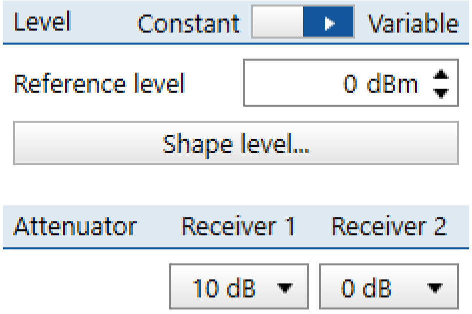


Figure 8: Load calibration

3.2.3 Performing the Measurement

Configuring the source level and attenuators:

To get the best signal-to-noise ratio, the attenuator of Receiver 2 is set to 0 dB. To avoid overloading the receiver at high impedance values (low frequencies), shaped level is used in addition.



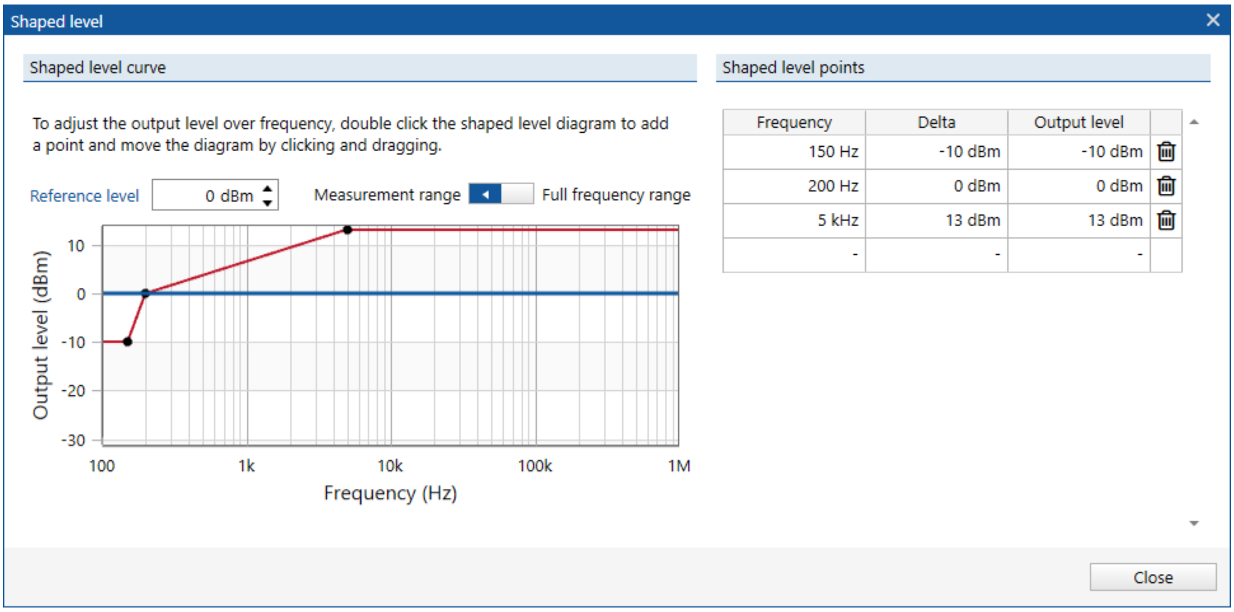
Level Constant ▶ Variable

Reference level 0 dBm

Attenuator	Receiver 1	Receiver 2
	10 dB	0 dB

Figure 9: Output level and attenuator settings

As shown in the following figure, the signal source level is shaped for low signal at low frequencies (where the DUT represents a high impedance) and maximum signal level (13 dBm + 12 dB = 25 dBm) at higher frequencies (self-resonance of DUT).



To adjust the output level over frequency, double click the shaped level diagram to add a point and move the diagram by clicking and dragging.

Reference level 0 dBm

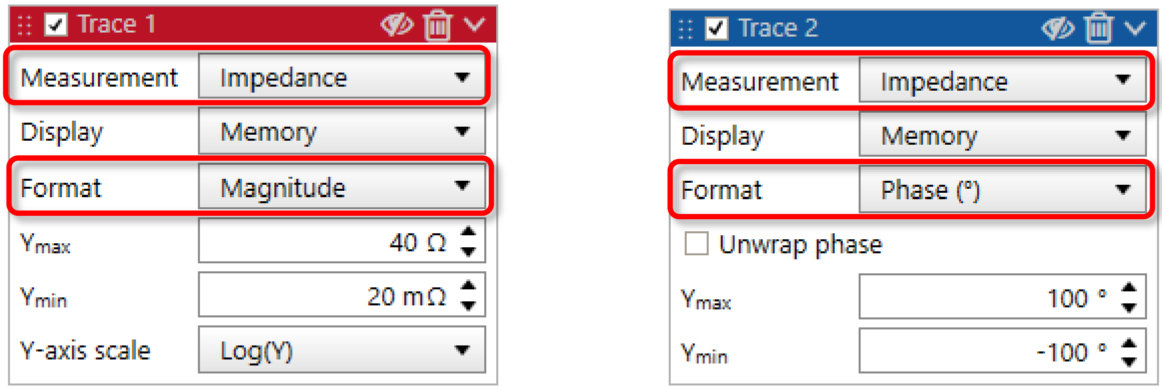
Measurement range ◀ Full frequency range

Frequency	Delta	Output level
150 Hz	-10 dBm	-10 dBm
200 Hz	0 dBm	0 dBm
5 kHz	13 dBm	13 dBm
-	-	-

Figure 10: Shaped level curve

Configuring the measurement traces:

First, the impedance magnitude and phase are measured to see the frequency response of the capacitor impedance. To conduct the measurement of the impedance magnitude and phase the following trace settings are required.



☑ Trace 1

Measurement	Impedance
Display	Memory
Format	Magnitude
Y_{max}	40 Ω
Y_{min}	20 mΩ
Y-axis scale	Log(Y)

☑ Trace 2

Measurement	Impedance
Display	Memory
Format	Phase (°)

☐ Unwrap phase

Y_{max}	100 °
Y_{min}	-100 °

Figure 9: Trace settings

Connecting the DUT:

In this specific case, the application of the capacitors requires them to be connected in parallel. During the measurement we therefore use the same configuration. The two 3-phase MTFCs (C1 and C2) have 3 connectors each, which are marked with a, b & c.

For the following measurement, the two capacitors are connected as can be seen in the following:

Connector	Capacitor	to	Connector	Capacitor
a	C1	-	c	C2
b	C1	-	b	C2
c	C1	-	a	C2

Table 1: MTFC parallel connection

Figure 11: MTFC parallel connection

3.3 Measurement Results

The following graph shows the magnitude of the capacitor impedance and phase from 100 Hz to 1 MHz. The three curves show the measurement results of the three capacitors. The measurement connection point was made at capacitor C2.

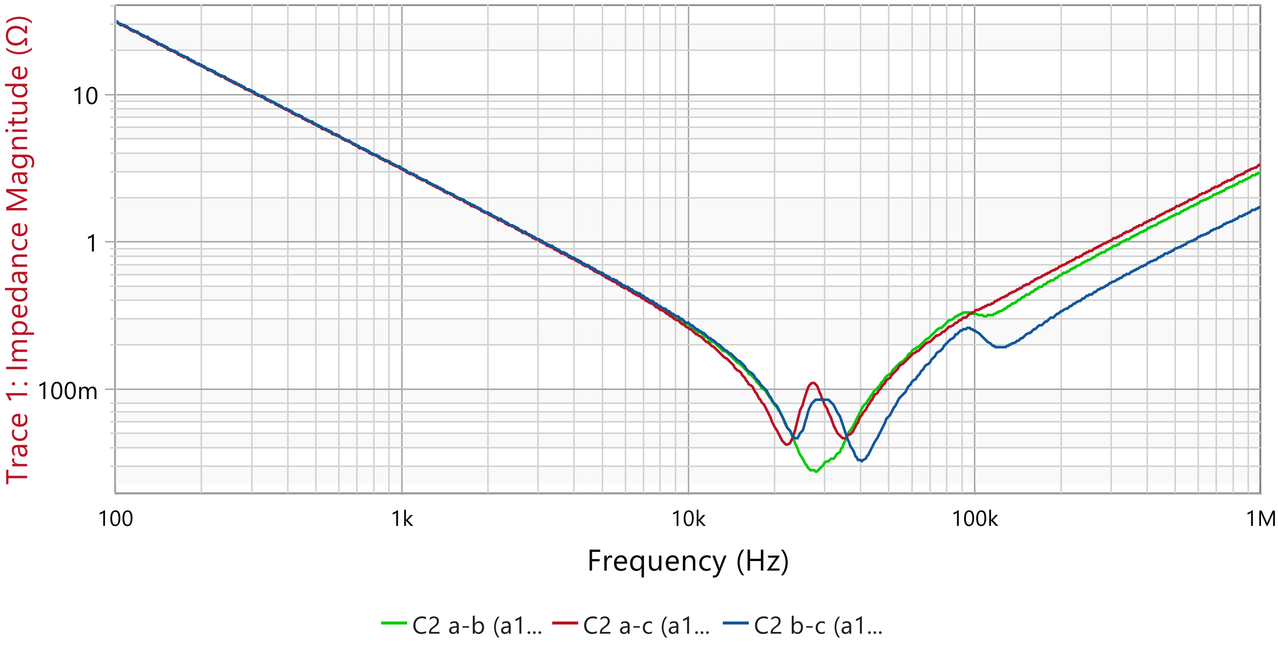


Figure 12: Impedance Magnitude

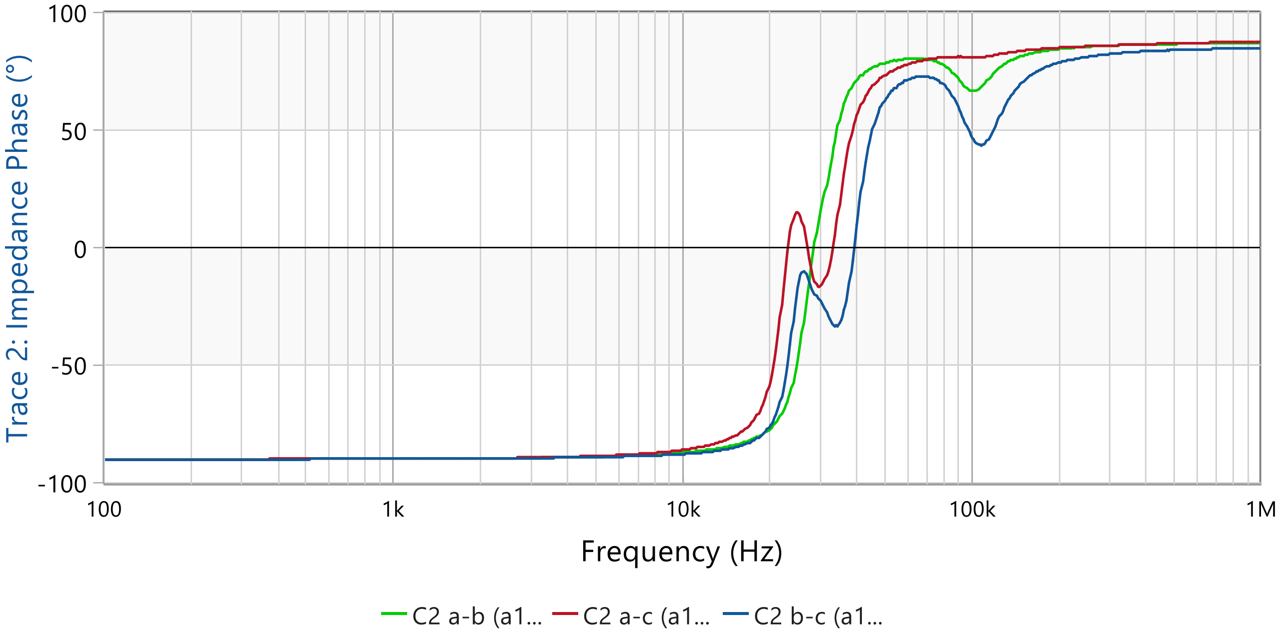


Figure 13: Phase of the impedance

Looking at the impedance magnitude, a straight line with -20 dB per decade from the start frequency to approximately 10 kHz can be seen. This nearly pure capacitive behavior can also be seen in the impedance phase curve, where the phase is at -90°.

The special arrangement of the two capacitors results in two separated resonance frequencies. C2 is closer to the measurement connection, resulting in lower inductance. C1 is connected in parallel via cables, resulting in a higher inductance and therefore lower self-resonance frequency.

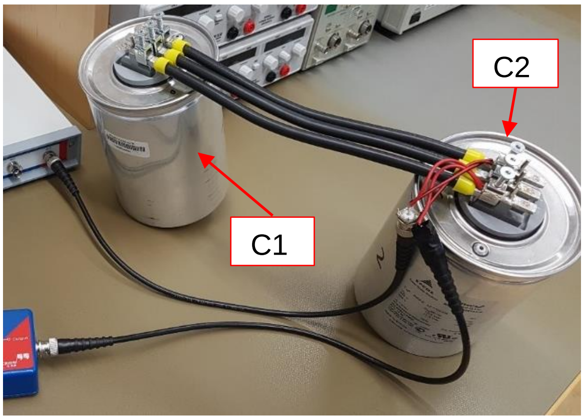


Figure 14: C1 and C2 with paralleling wires

At each resonance, the capacitive part of the impedance is cancelled out by the parasitic inductance. As a result, only the resistive behavior caused by the ESR can be seen. The ESR does damp the resonance peak. In this case we have quite low ESR and therefore a spiky resonance.

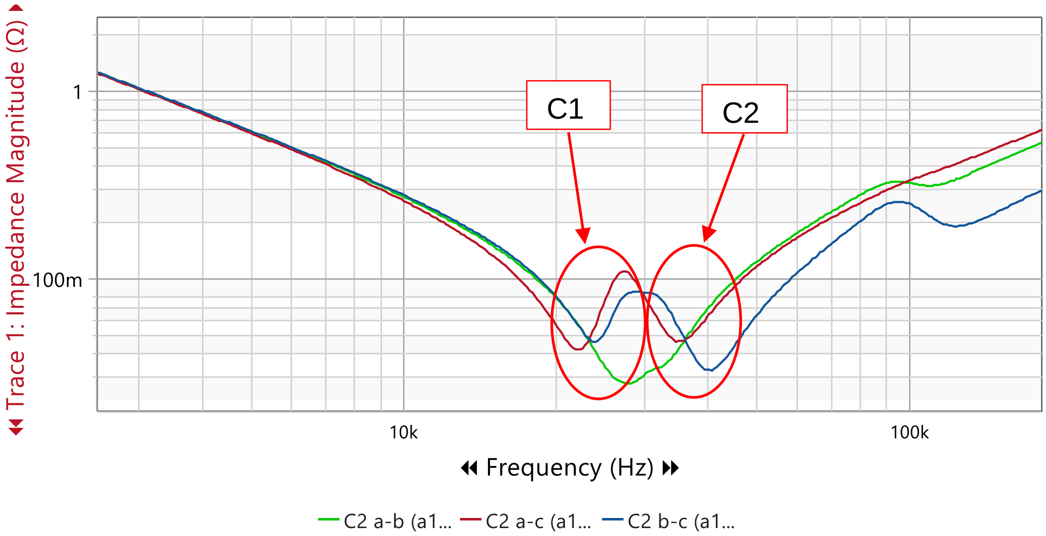
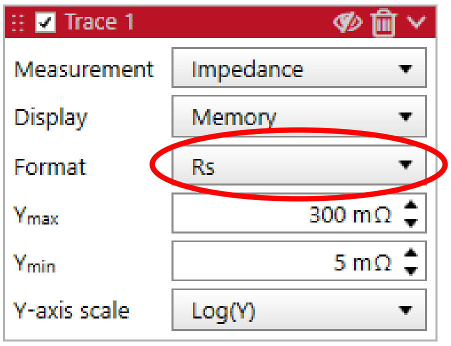


Figure 15: Double-resonance caused by two capacitors in parallel and connecting wires

In addition to that, additional resonances can be seen around 100 kHz, where the inductive part is dominant. (+20 dB per decade in the magnitude and +90° phase)

The Bode Analyzer Suite allows to directly display the series equivalent circuit values. To do so, the format is changed to R_S. The picture below shows the trace setting:



Measurement	Impedance
Display	Memory
Format	Rs
Y_{max}	300 mΩ
Y_{min}	5 mΩ
Y-axis scale	Log(Y)

Figure 16: Trace setting for ESR

This results in the following curve. The ESR is around 10 mΩ in a wide frequency range from 100 Hz to 10 kHz. At higher frequencies, the ESR starts to rise and shows peaking near the self-resonance frequencies.

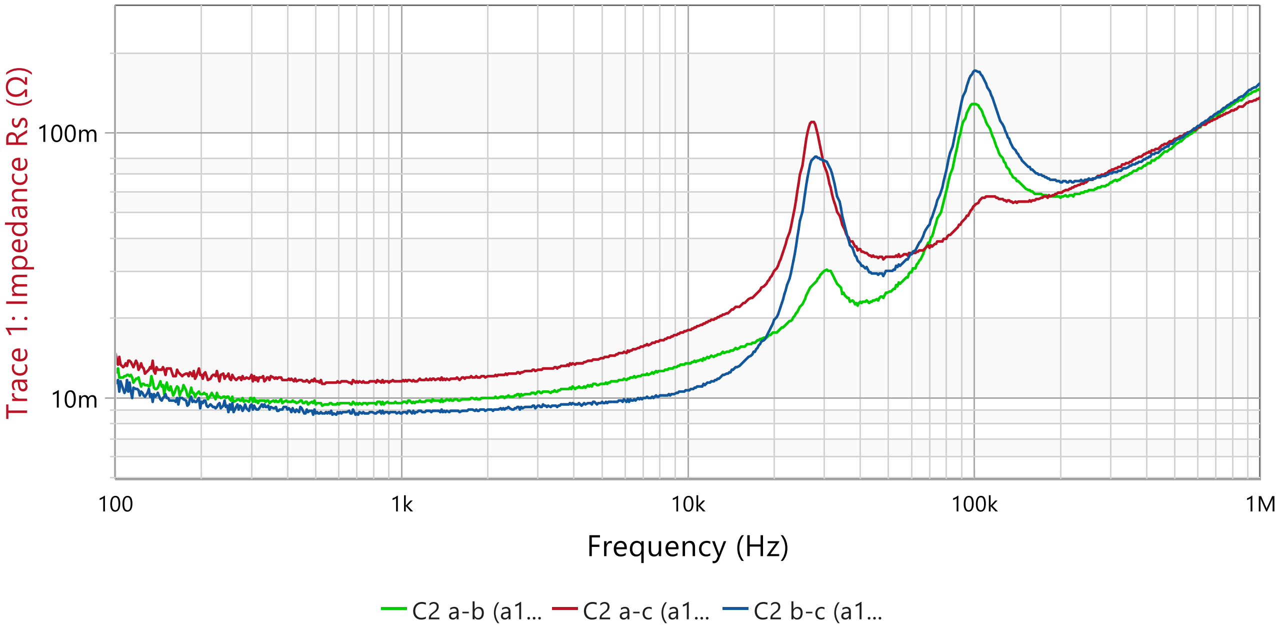
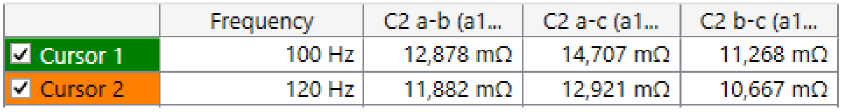


Figure 17: Frequency depending resistance (ESR)

The exact series resistance value can easily be measured by activating the cursors.
In accordance to the IEC60384-1:2008 capacitors with a rated C of > 10 µF should be measured at 100 Hz or 120 Hz. Therefore, the Cursors are set to these frequencies.



	Frequency	C2 a-b (a1...	C2 a-c (a1...	C2 b-c (a1...
☑ Cursor 1	100 Hz	12,878 mΩ	14,707 mΩ	11,268 mΩ
☑ Cursor 2	120 Hz	11,882 mΩ	12,921 mΩ	10,667 mΩ

Figure 18: Cursor table

An additional requirement of IEC60384-1 is that the measuring voltage shall not exceed 3 % of V_R or 5 V, whichever is smaller. In this case, 5 V since 3 % of the rated 400 V are 12 V. The maximum power with the B-AMP 12 amplifier is 25 dBm at 50 Ω load. 25 dBm equals a power of:

$$P = 1\,\mathrm{mW} \cdot 10^{\frac{25\,\mathrm{dBm}}{10}} = 316\,\mathrm{mW}$$

At 50 Ω this results in a voltage of roughly 4 V_{RMS}. Since the capacitor impedance at 100 Hz is around 12 Ω and lower at higher frequencies, this limit cannot be exceeded with this test setup.

4 Conclusion

This application note shows how to measure PFC capacitors using the Bode 100 in conjunction with the B-AMP 12 amplifier.
To get the complete results, every possible variation of the parallel connection between the two MTFCs as well as every combination of the connections to C1 and C2 should be measured.

Provided proper reference values and experience, the measurement results can be used to provide a gauge of the expected remaining lifetime. Combined with further measurement results characterizing the capacitor’s environment, the causes for ageing processes can be isolated and quantified.
Such services have been developed for all types of batteries by the Fraunhofer IVI in Dresden, Germany. The Institute for applied science now transfers its expertise to provide similar services around capacitors.

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