

IMPEDANCE COMPENSATION

I – INTRODUCTION

Impedance spectroscopy is a powerful analytical tool for the characterization of the electrical properties of materials. This characterization needs cables and/or sample holder to interface the Device Under Test (DUT) to the measuring instrument (Impedance analyzer, LCR, potentiostat, etc). The cables and/or the sample holder introduce additional impedances termed as “residual impedances”. These additional impedances impact the measurement accuracy by an overestimation of the measured electrical properties of the DUT and so an overestimation of the relative contribution of individual processes (bulk, grain boundaries, interface, or electrode capacitances/resistances) involved in the electrical response of the DUT.

The residual impedances can be “eliminated” or compensated using a compensation procedure.

The aim of this note is to introduce impedance users to the capabilities of compensation for obtaining reliable and accurate measurements. It also explains why the compensation is needed and how to perform it. An example of compensation on a low capacitance capacitor that “mimics” a bulk capacitance is given here to illustrate the effect of compensation on the accuracy and reliability of impedance measurement.

II – THEORITICAL BACKGROUND

As mentioned above, cables and sample holder are sources of “stray” impedance affecting the accuracy of the measured impedance of the DUT. In order to “remove” these residual impedances a compensation procedure is needed [1]. This procedure is sometimes named “nulling” [2-3]. The compensation consists in performing at least one of the three processes below:

- 1- Open-circuit (OC) compensation to compensate for the Open-circuit residual impedance Z_{OC} . It consists in measuring the residual impedance Z_{OC} in parallel with the actual impedance Z_{DUT} of the DUT (Fig. 1)
- 2- Short-circuit (SC) compensation to compensate for the Short-circuit residual impedance Z_{SC} . It consists in measuring the residual impedance Z_{SC} in series with the actual impedance of the DUT (Fig. 1).
- 3- Load compensation compensates for complex effects within the cables and/or the sample holder mainly observed at high frequencies. It consists in measuring the impedance of a load Z_{Load} (Fig. 1).

Figure.1 shows a scheme of the residual impedances Z_{OC} , Z_{SC} and Z_{Load} .

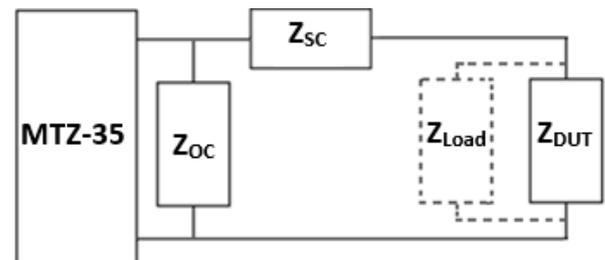


Figure 1: Sketch of the residual impedances measured during impedance compensation.

II-1 OPEN & SHORT CIRCUIT COMPENSATION

In general, the residual impedance can be seen as the sum of the two main residuals impedances: an OC residual impedance Z_{OC} and a short circuit residual impedance Z_{SC} . Z_{OC} corresponds mainly to the capacitance of the cables and/or the sample holder whereas Z_{SC} is mainly due to the inductance and the resistance of the cables. More details on the open-circuit and short-circuit compensation can be found in the technical note TN#1 [4].

Once Z_{OC} and Z_{SC} have been measured, the actual impedance of the sample Z_{DUT} is calculated as follows:

$$Z_{DUT} = \frac{Z_M - Z_{SC}}{1 - (Z_M - Z_{SC})/Z_{OC}} \quad (1)$$

Where

- Z_{DUT} the compensated (actual) impedance of DUT.
- Z_{OC} the impedance measured at open-circuit.
- Z_{SC} the impedance measured at short-circuit.
- Z_M the measured “raw” impedance of DUT.

II-2 LOAD COMPENSATION

Load compensation is performed by replacing the DUT by a load which is an electronic component (high precision resistor or capacitor) with a known impedance value, preferably close to DUT’s impedance [5]. This compensation is recommended for measurement performed at high frequencies. It is carried-out once the open-circuit and short-circuit compensations have been performed.

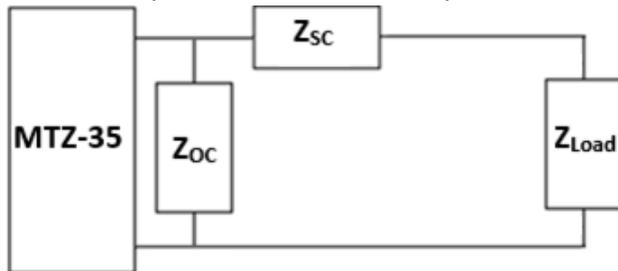


Figure 2: Load impedance Z_{Load} .

Once the impedance of the load has been measured, the actual impedance of the DUT can be computed using the following formula:

$$Z_{DUT} = \frac{Z_{ref}(Z_M - Z_{SC})(Z_{OC} - Z_{Load})}{(Z_{OC} - Z_M)(Z_{Load} - Z_{SC})} \quad (2)$$

Where:

- Z_{OC} the impedance measured at open-circuit.
- Z_{SC} the impedance measured at short-circuit.
- Z_M the measured “raw” impedance of DUT.
- Z_{Load} the measured impedance of the load.
- Z_{ref} the nominal impedance (resistance or capacitance) of the load. This value is given by the load’s manufacturer or measured by a high precision instrument.

The three compensations (Open, Short & Load) are used to compensate for the residual

impedances. However only the open-circuit compensation is necessary. The short-circuit compensation (in addition to open-circuit compensation) is needed for DUTs with low impedance. For high frequencies measurements, the load compensation is also recommended.

III – EXPERIMENT

In order to illustrate the effect of the compensation on the accuracy of the impedance measurement, a capacitor with a low capacitance of 100 pF was chosen as a DUT. A second test was performed on a second capacitor with a high capacitance of 10 nF. Its results are provided upon request.



Figure 3: 100 pF capacitor.

The capacitor was connected to MTZ-35 impedance analyzer using a real two terminal connection and two alligator clips [6]. This connection mode was chosen in order to perform the measurement at very high frequencies. The capacitor was installed in a Faraday cage in order to protect it from electromagnetic noise. The Faraday cage was then connected to the earth connector of the MTZ-35 (Fig. 4).



Figure 4: Experimental setup.

The impedance measurements were performed in the frequency range of 30 MHz to 100 Hz by applying an AC voltage of $V_{pp} = 100$ mV.

Figure 5 shows the experimental settings used for measuring the impedance of the capacitor.

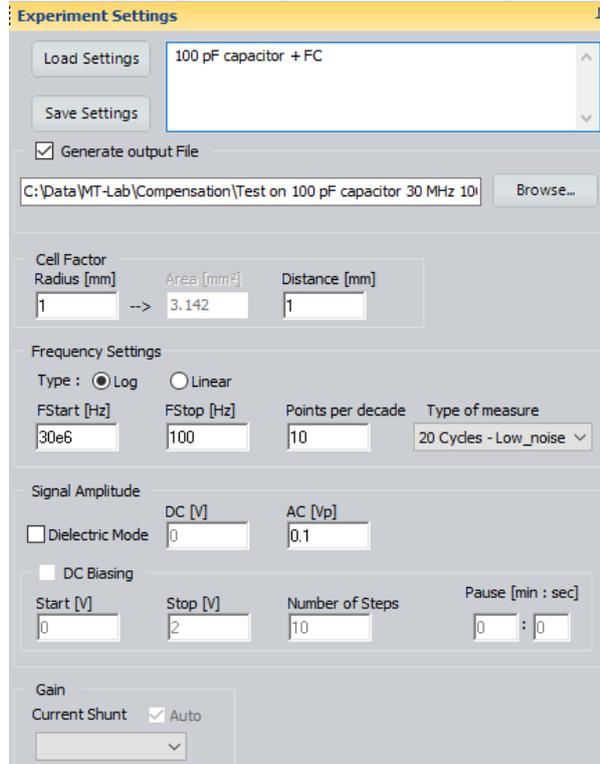


Figure 5: Experimental setting.

During the open-circuit compensation where no sample holder is used, the positive and the negative terminals of the cable have been separated before measuring the impedance at open-circuit.

In the case where a sample holder is used, open-circuit impedance is measured after separating the electrodes of the sample holder (after removing the DUT). The separation distance between the electrodes of the sample holder should be equal to the DUT thickness.

The short-circuit compensation consists in measuring the impedance when the positive and the negative terminals of the cable are shorted. In the case where a sample holder is used the electrodes of the sample holder have to be shorted.

The Load compensation consists in measuring the impedance of a load (high precision capacitor or resistor). In our case (high frequencies measurement) a load compensation was performed. It consisted in measuring the impedance of a 10 nF capacitor (load). The three compensations were repeated to check the reproducibility of measurement.

IV – RESULTS

IV-1 IMPEDANCE OF THE DUT

The impedance of the 100 pF capacitor was measured using 2-point setup.

Figure 6 shows the obtained impedance data (without compensation). The Bode diagram shows an impedance plot typical to a pure capacitor.

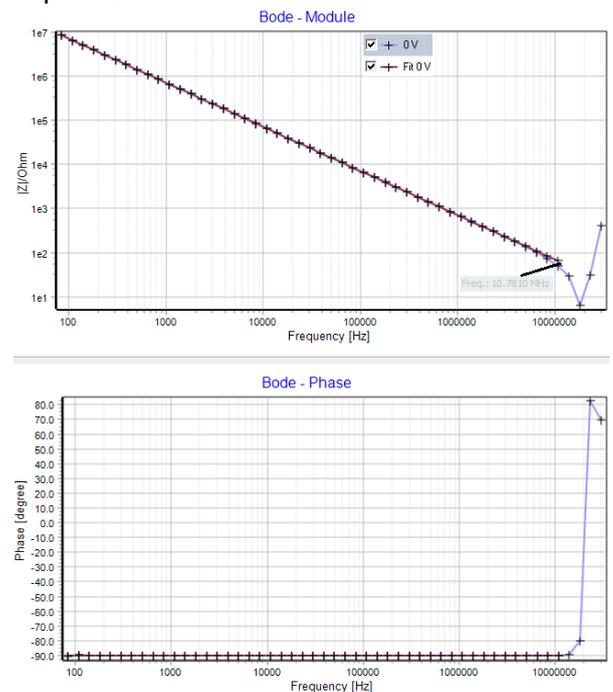


Figure 6: Bode diagram of 100 pF capacitor impedance.

The impedance plot was fitted to a pure capacitor with a capacitance of 223 pF (Fig. 7).

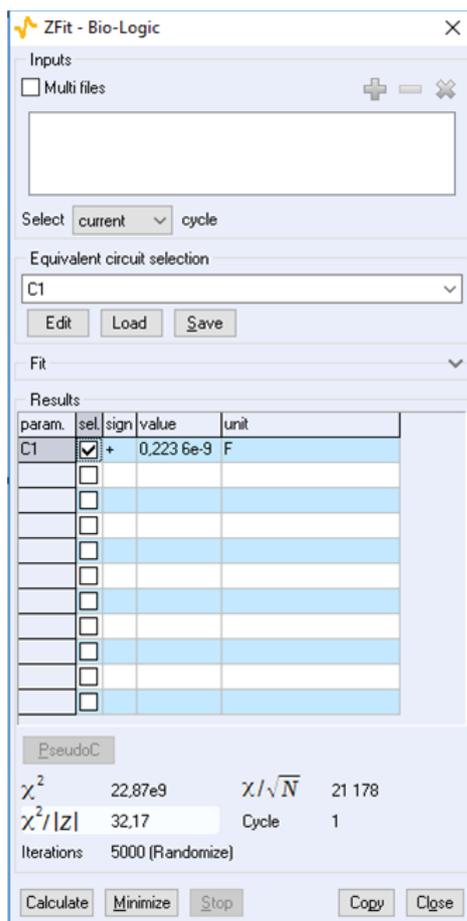


Figure 7: ZFit window of uncompensated measurement.

The measured capacitance is higher than the nominal value (100 pF) provided by the manufacturer. The “offset capacitance” (123 pF) corresponds to the residual capacitance due to cables. Indeed, the MTZ-35 impedance analyzer is calibrated up to the BNC connectors (front panel) of the MTZ-35. The cables used to connect the capacitor generate a residual impedance (capacitance). In order to eliminate this residual impedance due to the cables a compensation is needed.

IV-2 COMPENSATION

The compensation described in this note is complementary to that performed with MT-Lab software which was detailed in the technical note TN#1 [4]. This compensation, available in EC-Lab software, is compatible with data provided by EC-Lab and MT-Lab

software. It is a fast post-process method where the actual impedance of the DUT is computed using the equation (1) or (2). In this example, the open-circuit, short-circuit and load impedance data were acquired separately by MT-Lab software connected to MTZ-35. The load compensation was performed using a capacitor with a nominal capacitance of 10 nF. In the compensation window of EC-Lab software, a 10 nF value was set in Z_{ref} box (Fig. 9)

For computing the actual impedance of the DUT, the user has to open EC-Lab software, select “Analysis” menu, impedance spectroscopy and “Compensation” tool (Fig. 8).

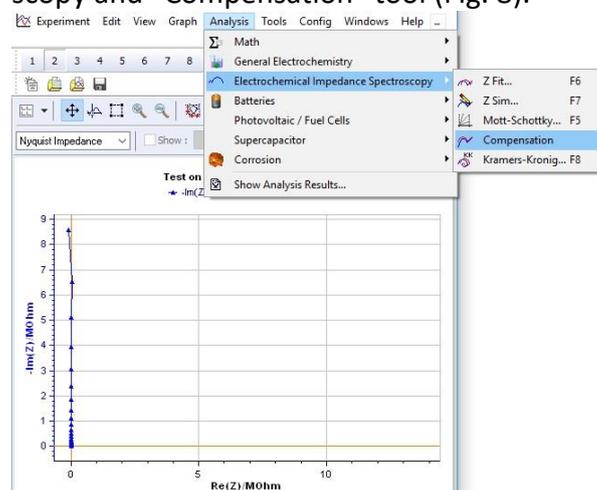


Figure 8: Compensation tool in EC-Lab software.

The impedance of DUT, the open-circuit, short-circuit and load impedance files are loaded in the compensation window (Fig. 9). The user has to select “fra” extension in the open window in order to be able to load the four files in the compensation window.

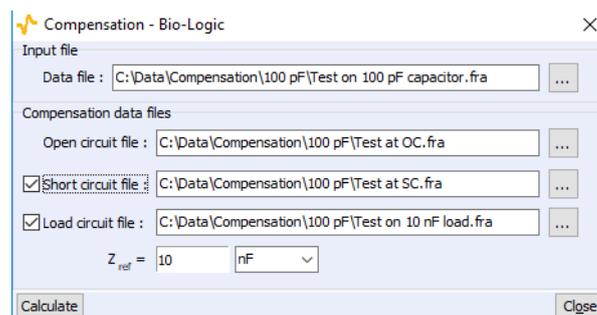


Figure 9: OC & SC and load compensation window.

Once we click on “Calculate” button the computed data file is generated. This file has the same filename as the uncompensated data file with a “_comp” suffix and a mpp extension. Figure 10 shows the Bode diagram of the compensated data.

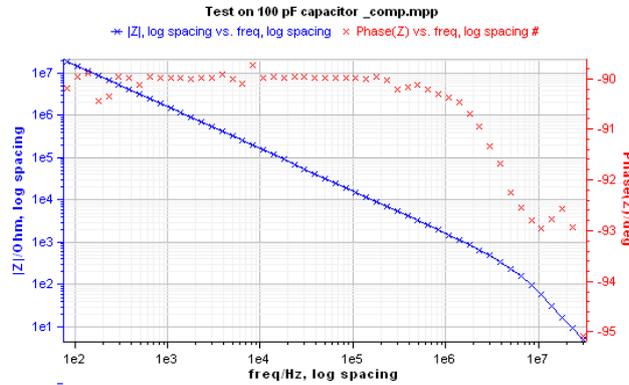


Figure 10: Bode plot of the impedance of 100 pF capacitor after compensation.

The compensated data was fitted to a pure capacitor with a capacitance value of **98.9 pF** (Fig. 11 & 12).

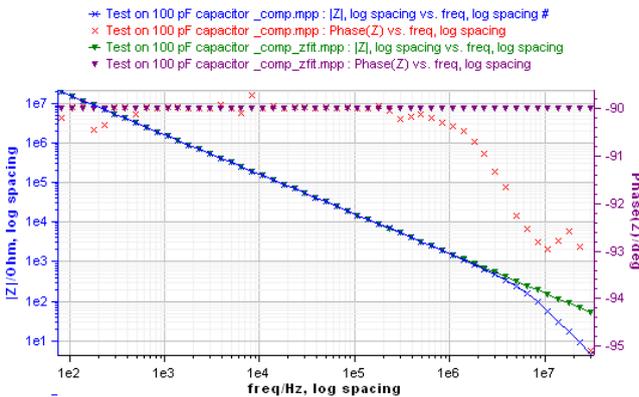


Figure 11: Fit of the impedance of 100 pF capacitor after compensation.

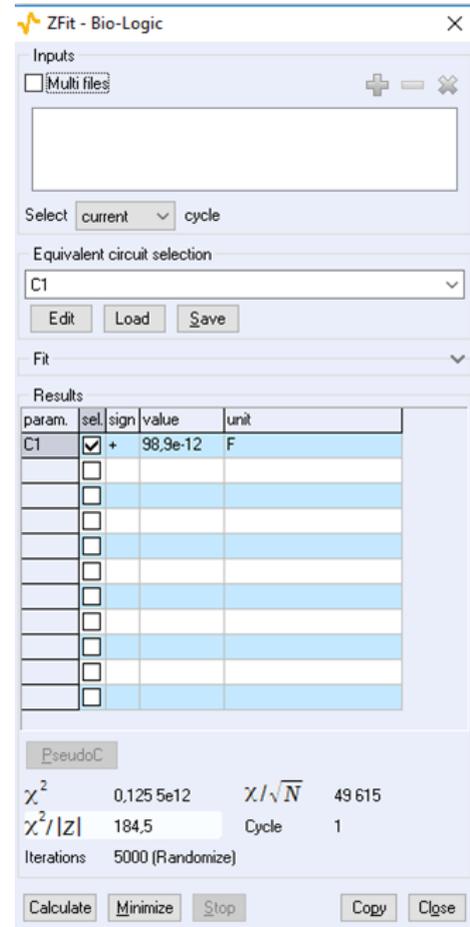


Figure 12: Z Fit window of impedance after compensation.

After compensation, the measured capacitance value matches the nominal capacitance given by the manufacturer.

IV-3 DISCUSSION

It was shown that when the DUT capacitance is smaller than, or comparable in magnitude to, the cables or/and sample holder capacitance (100 pF capacitor) the impedance measurements are not reliable and a compensation is needed. This compensation is also needed even for relatively high capacitance DUT especially when a high accuracy is requested. Indeed, a second test was performed on a 10.00 nF capacitor (around 100 time higher than the cables capacitance) to check the effect of compensation on relatively high capacitance. A 10.18 nF capacitance value was measured without compensation. After compensation a

capacitance of 10.05 nF was obtained. So, even for high capacitance values, the compensation is recommended for optimum accuracy. The compensation could be ignored for very high capacitances when a high accuracy is not requested.

For accurate and repeatable measurements, the open circuit, short circuit and probably load compensation have to be performed exactly in the same conditions as that on the DUT.

Table 1 below summarizes the measured capacitances of two capacitors (with nominal capacitance of 100 pF and 10 nF) with and without compensation.

Table 1: Measured capacitances obtained with and without compensation.

DUT	100 pF	10 nF
Nominal capacitance	100 pF	10.00 nF
Capacitance without compensation	223 pF	10.18 nF
Capacitance with compensation	99 pF	10.05 pF

Note: Compensation vs. Calibration

The accuracy of a measuring instrument (LCR, impedance analyzer, etc) is specified by the manufacturer in the Impedance contour plot [7]. The accuracy is given at the BNC connectors which define the "Calibration Plane" or the reference plane. The instrument is calibrated up to BNC connectors. The use of cables and or a sample holder alters the accuracy of the instrument and a compensation procedure is needed to compensate for residual impedances introduced by the cables and or the sample holder.

A potentiostat can also be used for measuring electrical properties of a DUT. A potentiostat is mainly calibrated up to the end of the cables so a compensation is needed when a sample holder is used.

V- CONCLUSION

Impedance measurement performed on 100 pF and 10 nF capacitors showed residual

capacitances induced by cables. The compensation has eliminated these residual impedances. This compensation is almost always necessary to compensate for residual impedances due to cables and/or sample holder. After compensation, the measured capacitances match the nominal capacitances given by the manufacturer.

REFERENCES

- 1) Agilent Impedance Measurement Handbook, a guide to measurement technology and techniques, 4th edition.
- 2) B. J. Christensen, R.T Coverdale, R. A. Olsen, S.J. Ford, E.J. Garboczi, H. M. Jennings, T. O. Mason, J. Am. Ceram. Soc, 77 (1994), 2789.
- 3) S.J. Ford, T.O. Mason, B.J. Christensen, R.T. Coverdale, H.M. Jennings and E.J. Garboczi, J. Mater. Sci. 30(5), (1995) 1217.
- 4) [Technical note #1](#) Cell cable and sample holder compensation.
- 5) E. Barsoukov, J. Ross Macdonald, John Wiley & Sons, (2005), chap 3, 184.
- 6) [Technical note #5](#) Which connection to use with MTZ-35.
- 7) [Application note #54](#) How to read EIS accuracy contour plots.