How to read EIS accuracy contour plots

I – INTRODUCTION

The impedance measurement accuracy of an impedance analyser depends on the impe-dance magnitude and on the measure-ment frequency. Potentiostats/galvanostats/ EIS (Electrochemical Impedance Spectroscopy) specifications are given in graphs called accu-racy contour plots[1]. The aim of this note is to help the user understand and use the EIS accuracy contour plots.
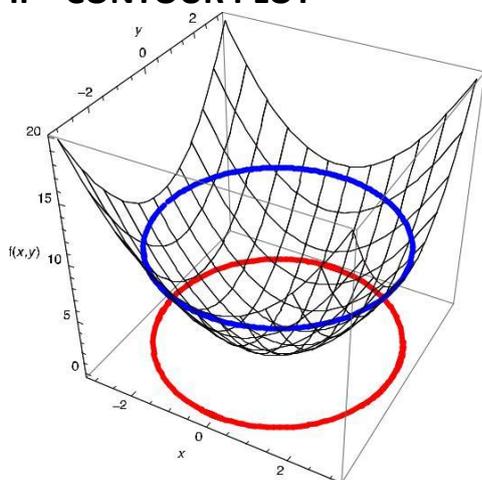
II – CONTOUR PLOT

Figure 1: 3D graph of a two-variable function, level curve (blue curve) and projection in the x, y **plan (red curve).**

Contour plots are isovalue curves of a function depending on two variables. As an example 3D graph of a two variables function $f(x, y) = x^2 + y^2$ and a level curve of this function for $f(x, y) = 10$ are shown in Fig. 1. The level curve is a cross-section of the 3D graph parallel to the (x, y) plan at $f(x, y) = 10$. The projection of this curve on the x, y plan is a contour plot. For any point (x, y) inside of this contour, we have $f(x, y) < 10$ and for any point outside of this contour we have $f(x, y) \geq 10$.

III – EIS ACCURACY CONTOUR PLOT
III - 1 SP-300 EIS ACCURACY CONTOUR PLOT
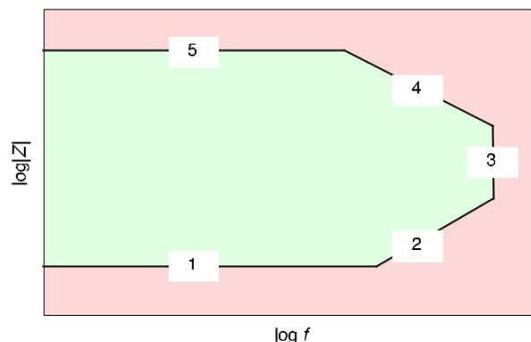The scheme of an EIS accuracy contour plot is shown in Fig. 2.

Figure 2: Scheme of an EIS accuracy contour plot.

The two horizontal limits (high (5) and low (1) Z) are related to the ability of the instrument to measure/control accurately the current. To increase the high Z portion of accuracy contour plot, the instrument has to be able to measure low current (often related to the electrometer impedance in the specifi-cations).

To increase the low portion of the accuracy contour plot, the instrument has to be able to manage high current. Current booster may be added to improve the measurement in this area. The vertical limit (3) depends on the regulation speed of the instrument. This is the maximum frequency that can be reached by the instrument with an acceptable error. It is related to the bandwidth of the instrument. The two other limits (4) and (2) are related to stray capacitor and stray inductor, respect-ively. Inductive effects are very sensitive to the current level and the cell connection.

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[1] Considering the definitions given in [1] and recalled in Appendix A, the word accuracy is a time-honored mis-nomer. Uncertainty should preferably be used.

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The contour plot of an SP-300 potentiostat is shown in Fig. 3. The shaded areas show different ranges of impedances that can be measured at various frequencies within a specified error in magnitude and in phase. These errors refer to the borders and not to the areas as is explained below.
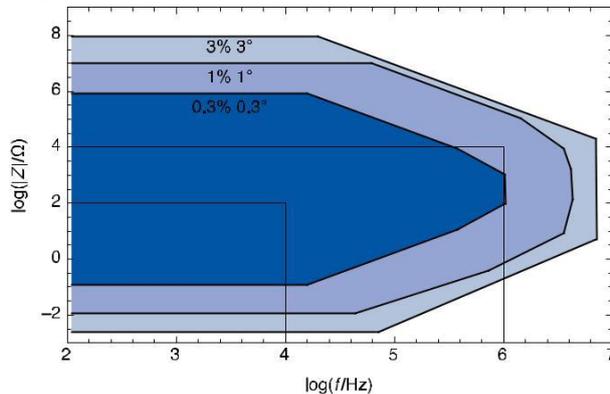

Figure 3: SP300 EIS accuracy contour plot. Black dot: f = 10^6 Hz, $|Z|$ = 10^4 Ω, white dot: f = 10^4 Hz, $|Z|$ = 10^2 Ω.

III - 2 EXAMPLE

Let us consider the black dot in Fig. 3. This dot corresponds to the measurement of an impedance $|Z|$ = 10^4 Ω measured at a frequency f = 10^6 Hz. As this measurement is located between the 0.3 %, 0.3° and 1 %, 1° contour plots, the accuracy is 0.3 % < $|Z|/|Z|$ < 1 %, for the modulus (relative error) and 0.3° < ϕ_Z < 1° for the phase (absolute error). The phase is given in absolute error because the relative error could be indeterminate in the case where ϕ = 0. An impedance whose modulus is 100 Ω at 10^4 Hz is measured with a relative uncertainty lower than 0.3 % for the modulus and lower than 0.3° for the phase (Fig. 3, white dot).

IV – HOW TO USE AN EIS CONTOUR PLOT

IV - 1 IMPEDANCE OF THE R1+R2/C2 CIRCUIT
The impedance for the R_1+R_2/C_2 is given by

$$Z(f) = R_1 + \frac{R_2}{1 + R_2 C_2 j2\pi f}$$

(1)

The modulus of the impedance as a function of the frequency is shown in Fig. 4 for R_1 = 0.1 Ω, R_2 = 3 Ω and C_2 = 10^{-6} F.
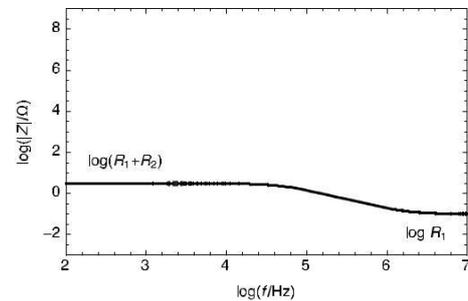

Figure 4: Modulus Bode diagram of the impedance for the R_1+R_2 /C_2 circuit. R_1 = 0.1 Ω, R_2 = 3 Ω and C_2 = 10^{-6} F.

IV - 2 EXAMPLE #1
The modulus Bode impedance diagram of this electrical circuit R_1+R_2/C_2 and the SP-300 contour plot are superimposed in Fig. 5. This figure allows to predict the precision of the impedance measurements as a function of the frequency. One has to determine the frequency values where the modulus diagram moves into a different precision domain. For instance, the modulus diagram moves from the high precision domain ($|Z|/|Z|$ < 0.3 % and ϕ_Z < 0.3°) to the mid-range precision domain (0.3 < $|Z|/|Z|$ <1 % and 0.3 < ϕ_Z < 1°) for a frequency moving from $f_1 \approx$ 10 kHz to $f_2 \approx$ 60 kHz (Fig. 5).
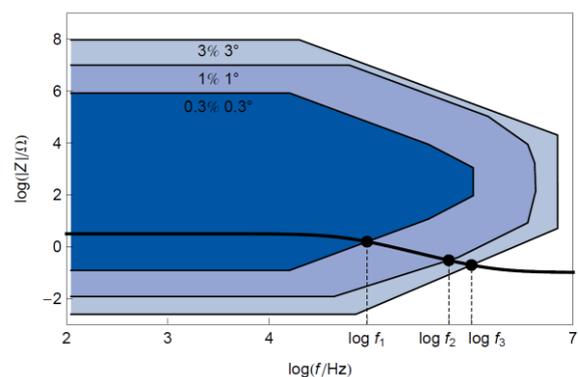

Figure 5: Superimposition of the modulus Bode impedance diagram of the electrical circuit R_1+R_2/C_2 and the SP-300 contour plot.

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The Nyquist impedance diagram of the R_1+R_2/C_2 circuit is show in Fig. 6 with the impedances measured at f_1, f_2 and f_3.
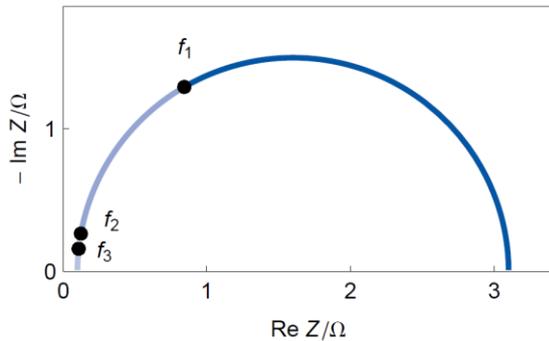

Figure 6: Nyquist diagram of the impedance for the R_1+R_2 /C_2 circuit, $f_1 \approx$ 10 kHz, $f_2 \approx$ 60 kHz, $f_3 \approx$ 100 kHz.

Tab. I shows how the precision of the impedance modulus and phase evolves with the frequency for the R_1+R_2/C_2 electrical circuit with intermediate Rs and C values.

Table I: Impedance measurement accuracy as a function of the frequency. R_1 = 0.1 Ω, R_2 = 3 Ω and C_2 = 10^{-6} F.

Frequency	Impedance modulus	Impedance phase
$f < f_1$	$\Delta|Z|/|Z| < 0.3\,\%$	$\phi_Z < 0.3°$
$f_1 < f < f_2$	$0.3\,\% < \Delta|Z|/|Z| < 1\,\%$	$0.3° < \Delta\phi_Z < 1°$
$f_2 < f < f_3$	$1\,\% < \Delta|Z|/|Z| < 3\,\%$	$1° < \Delta\phi_Z/° < 3°$
$f > f_4$	$\Delta|Z|/|Z| > 3\,\%$	$\phi_Z > 3°$

IV - 3 EXAMPLE #2

Another situation can be observed for high values of R_2 and low values of C_2, for instance R_1 = 10^4 Ω, R_2 = 0.2 × 10^7 Ω and C_2 = 5 × 10^{-9} F (Figs. 7 and 8).
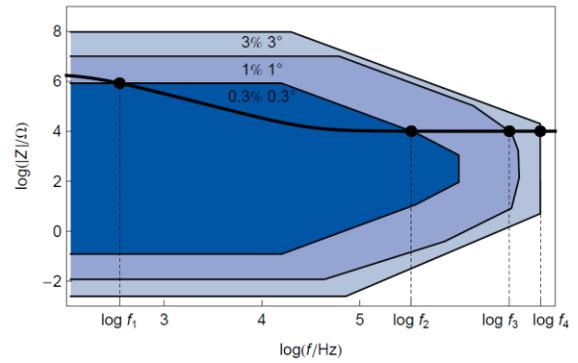

Figure 7: Superimposition of the modulus Bode impedance diagram of the electrical circuit R_1+R_2/C_2 (high Rs values and low C value) and the SP-300 contour plot.
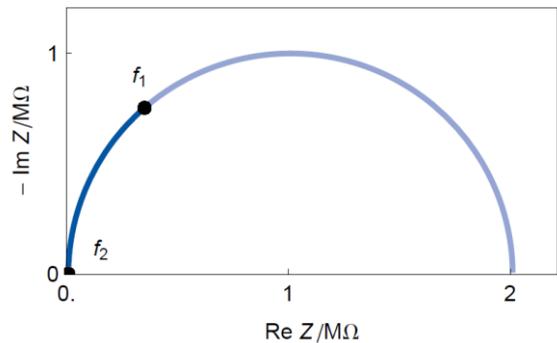

Figure 8: Nyquist diagram of the R1+R2/C2 circuit. R1= R_1 = 10^4 Ω, R_2 = 0.2.10^7 Ω and C_2 = 5.10^{-10} F.

As the frequency reaches lower values, the measurement precision moves outside of the best precision domain. Tab. II shows how the precision of the impedance modulus and phase evolves with the frequency for an R+R/C electrical circuit with high R values and low C values.

Tab. II: Change of impedance measurement accuracy with frequency. R_1 = 10^4 Ω, R_2 = 0.2 × 10^7 Ω and C_2 = 5 × 10^{-10} F.

Frequency	Impedance modulus	Impedance phase
$f < f_1$	$0.3\,\% < \Delta|Z|/|Z| < 1\,\%$	$0.3° < \Delta\phi_Z < 1°$
$f_1 < f < f_2$	$\Delta|Z|/|Z| < 0.3\,\%$	$\Delta\phi_Z < 0.3°$
$f_2 < f < f_3$	$1\,\% < \Delta|Z|/|Z| < 3\,\%$	$1° < \Delta\phi_Z < 3°$
$f > f_4$	$\Delta|Z|/|Z| > 3\,\%$	$\Delta\phi_Z > 3°$

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V – CONCLUSION

This note aims at explaining how to read and understand EIS contour plots, which are provided with each of our instrument. Contour plots must be used to interpret errors made during an EIS measurement and to find the best frequencies to be used for a given impedance range.

APPENDIX

A - DEFINITIONS [1]

Measurand:
Quantity intended to be measured, quantity subject to measurement.

Measurement accuracy:
Closeness of agreement between a measured quantity value and a true quantity value of a measurand. The concept `measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

Measurement uncertainty, uncertainty:
Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand.

Measurement precision, precision:
Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

REFERENCES

1) International vocabulary of metrology. Basic and general concepts an associated terms. JCGM (2008).

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