The Influence of Parameters of Input Probe
on the Error of High Impedance Measurement

Jerzy Hoja[1], Grzegorz Lentka[2]

Department of Metrology and Electronic Systems, Faculty of Electronics, Telecommunication and Informatics, Gdansk University of Technology, Narutowicza 11/12, 80-952 Gdansk, POLAND,
[1] *+48583471487,* hoja@eti.pg.gda.pl   [2] *+48583471457,* lentka@eti.pg.gda.pl

***Abstract*-**The paper presents the probe for measuring high impedance in range of 1 k$\Omega \leq |Z_x| \leq$ 100 GΩ. The probe can cooperate with gain-phase analysers. The influence of the probe parameters (parasitic capacitance, tolerance of resistors determining amplifier gain) on the accuracy of the determination of modulus and argument of the complex ratio of signals extracted in the probe has been analysed. The results of simulations and measurements have been included, which allow entering corrections in order to increase the accuracy of the impedance measurement.

I. Introduction

For many years the impedance spectroscopy is one of the common research methods for technical objects modelled by equivalent electrical circuit. One of the examples of the spectroscopy usage is the diagnostics of the anticorrosion coatings either performed in the laboratory on the samples or in the field directly on the objects. Continuous technology advances in the protecting coating performance extort the need of measurement of the very high impedance exceeding the level of 100GΩ.

The analysis of the input circuitry of the typical impedance analysers [1, 2] excluded the possibility of connecting the impedance of the tested anticorrosion coating using shielded cables to the input of the analyser when measuring $|Z_x| \geq$ 10 MΩ. Due to this fact, the authors developed the measurement probe, which makes possible direct connection of the object under measurement to the input circuitry, thus eliminating the influence of the parasitic capacitance on the measured impedance of the coating. Additionally, the developed probe is designed for the diagnostics of the anticorrosion coatings on the objects in the field, which are usually grounded (e.g. steel bridge) determining the conditions of the impedance measurement of the coating [3, 4].

The paper is aimed to show the limitations appearing due to real parameters of the probe (taking into an account the parasitic capacitance, differential Z_d and common-mode Z_c input impedance of the operational amplifier and accuracy of resistors determining the gain of the differential amplifier) and to analyse their influence on the accuracy of the impedance measurement.

II. The construction of the measurement probe

The developed probe is used to extract two measurement signals proportional to current (u_i) and voltage (u_u) on the measured impedance Z_x. Measured signals u_i and u_u are used to determine
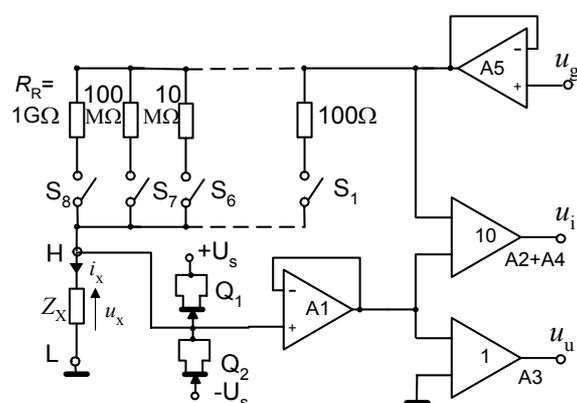

Figure 1. The diagram of probe designed for grounded impedance measurement

impedance according to the definition. The probe has two terminals and is designed for measurement of the anticorrosion coatings on the grounded objects. Range resistor R_R connected in series with measured impedance allows measuring of the current flowing through the impedance under measurement Z_x (Fig. 1). In order to assure the wide range of the measured impedance Z_x (i_x changes from 10pA to 1mA) range resistors are switched decadely (100Ω,...,100MΩ,1GΩ) with the aid of miniature reed relays. The value of the range resistor is selected to meet the criterion: 0.01 $|Z_x|<R_R\leq$0.1 $|Z_x|$, so the signal from the R_R resistor is additionally amplified by 10. This way the amplitude of the signal u_i is comparable to signal u_u, which
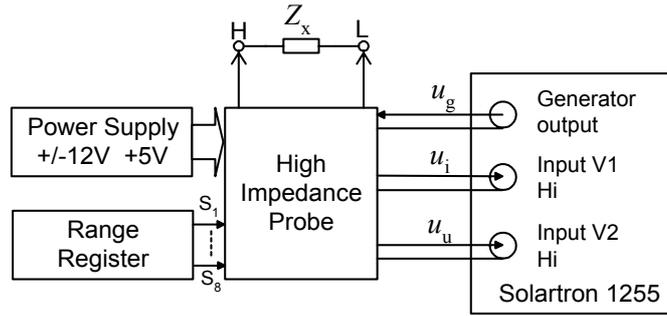
Figure 2. The high impedance measuring with the probe connected to Solartron gain-phase analyser

is taken from the impedance Z_x by the voltage follower A1. Due to maximum value of measured impedance $|Z_x|$=100GΩ, the amplifier A1 has to have low input current (on the level of pA) and high Z_d and Z_c input impedance, while achieving wide frequency bandwidth. In the realised probe the OPA627 amplifier has been used, which has input current not exceeding 1-2pA (at 20°C temperature) and impedance Z_d and Z_c are determined by resistance $R_d=R_c$=10TΩ and capacitance C_d=8pF and C_c=7pF.

In order to protect amplifier A1 against the overvoltages, which can appear on the object under test, the FET transistors (2N4117A) have been used acting as diodes with very low leakage current ($\leq$1pA).

The proposed probe should be connected to gain-phase analyser as shown in Fig. 2 in order to measure impedance. The analyser allows measuring the modulus and argument of the complex ratio of signals u_u and u_i extracted in the probe. The admittance (or impedance) of the measured coating can be calculated according to (1).

$$Y_x = \frac{1}{10 \cdot R_R} \cdot \left| \frac{u_i}{u_u} \right| \cdot e^{j\varphi}, \quad \text{where } \varphi = \arg\left(\frac{u_i}{u_u} \right) \tag{1}$$

III. Analysis and evaluation of the probe

The equivalent circuit shown in Fig. 3 has been proposed to analyse the influence of real parameters of used operational amplifiers, parasitic capacitance and tolerance of the resistors $R_1 \div R_6$ on extracted signals u_u and u_i.
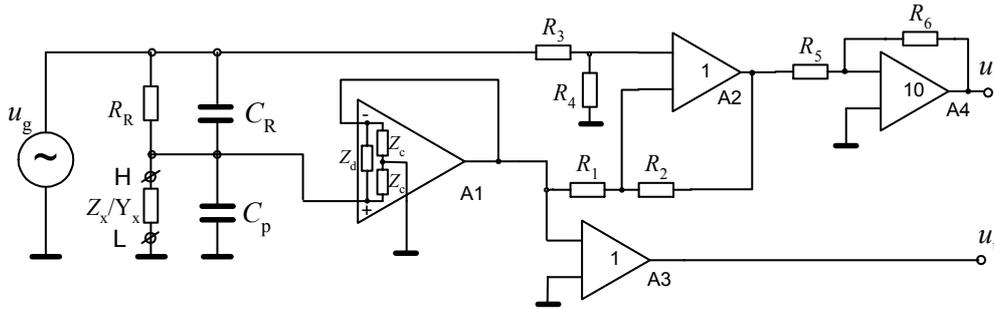

Figure 3. Equivalent circuit of input probe

The following parameters have been taken into an account:

$Z_R = \dfrac{1}{\dfrac{1}{R_R} + j\omega C_R}$ - impedance describing the parallel connection of range resistor R_R and the capacitance C_R caused by reed relays performing range selection and montage capacitance,

C_p – the resulting capacitance entered by transistors Q1 and Q2 protecting amplifier A1, cables connecting the object under test and montage capacitance,

$$Z_d = \frac{1}{\frac{1}{R_d} + j\omega C_d} \; , \; Z_c = \frac{1}{\frac{1}{R_c} + j\omega C_c}$$ - differential and common input impedance of A1 opamp, which are connected in parallel for the voltage follower configuration of the operational amplifier,

$R_1 \div R_5$ - resistors with value of 1kΩ and R_6=10kΩ and the tolerance different than zero.
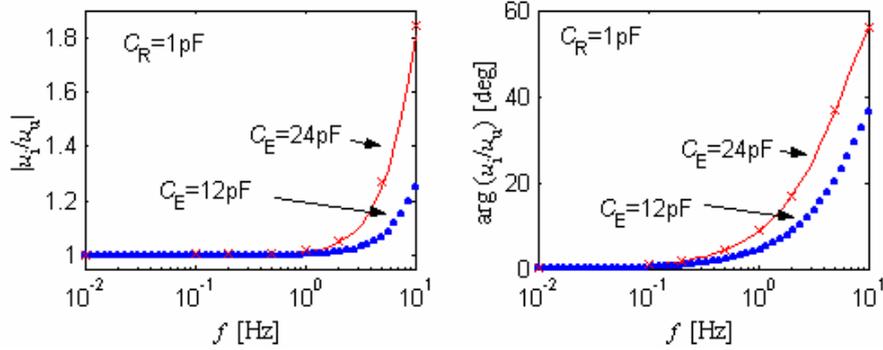

Figure 4. Results of simulations and measurements of u_i/u_u ratio

The analysis of the probe has been performed in two phases. In the first one, the influence of real parameters of operational amplifier A1 (Z_d, Z_c) and parasitic capacitances C_R and C_p has been analysed. The second stage contains the analysis of the influence of tolerances of resistors $R_1 \div R_6$. At both stages the complex ratio of signals u_i/u_u, which is used for determining of modulus and phase of admittance Y_x (for two terminal network Z_x in parallel equivalent circuit). This way, the factors influencing both signals identically are eliminated (like amplitude of signal u_g) and the measured parameters are not affected.

At the first stage, on the basis of assumed equivalent circuit of the probe (Fig. 3), the relation determining the ratio of u_i and u_u has been derived.

$$\frac{u_i}{u_u} = 10 \cdot Z_R \cdot \left(\frac{1}{Z_x} + \cdot \frac{1}{Z_d} + \frac{1}{Z_c} + j\omega \cdot C_p \right) \tag{2}$$

It was assumed that the amplifiers A1 and A3 gain is equal to 1 and for A4 is equal to 10 in analysed frequency range and the resistors $R_1 \div R_6$ have zero tolerance. The analysis of the equation (2) has been performed using Matlab. The parameters of OPA627 operational amplifier has been taken for calculations. The results shown in Fig. 4 were obtained for difficult measurement conditions, e.g. $Z_x = R_x = 1$GΩ, when the influence of the parasitic capacitance can be noticeable. For the simulation, the value of parasitic capacitance C_R was assumed to be 1pF. This value is fully realistic in situation, when the range selection is done with miniature reed-relay.

When analysing graphs, one can notice that the influence of sum of capacitances $C_E = C_p + C_d + C_c$ exists for measurement frequencies higher than 1Hz. The curve drawn with continuous line takes into an account the capacitance of the OPA627 and transistors 2N4117A. The measurement points (marked with x) were measured as shown in Fig. 2 for the probe realised with above-mentioned elements. They prove that the assumed equivalent circuit is correct. The curves for C_E=12pF are obtained when only input capacitances of amplifier A1 has been taken into an account.

In order to determine the influence of the capacitance C_E on the measurement accuracy of ratio of signals u_i and u_u the relative error of modulus and absolute error of phase measurement of ratio u_i/u_u has been presented in Fig. 5.

The graphs confirm that errors increase fast when C_E capacitance or measurement frequency increase. To minimize the influence of capacitance C_E and resistances R_d and R_c on parameters of measured impedance Z_x (parallel equivalent circuit R_x and C_x was assumed) the relations (3) have been derived, which are taking into an account the corrections connected with:

$$C_x = \frac{1}{10} \cdot \left(\frac{\sin\varphi}{\omega \cdot R_R} + C_R \cdot \left| \frac{u_i}{u_u} \right| \cdot \cos\varphi \right) - C_E ; \quad G_x = \frac{1}{10} \cdot \left(\left| \frac{u_i}{u_u} \right| \cdot \frac{\cos\varphi}{R_R} - \omega \cdot C_R \cdot \sin\varphi \right) - \left(\frac{1}{R_d} + \frac{1}{R_c} \right) \tag{3}$$
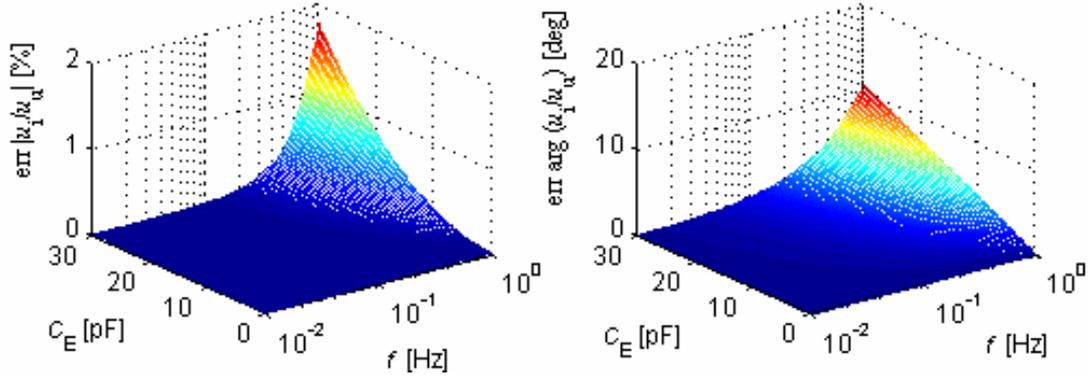
Figure. 5. Relative error of magnitude and absolute error of phase measurement of complex ratio of signals u_i and u_u in relation to C_E capacitance and frequency.

Using (3), it is possible to increase accuracy of identification of components of measured impedance Z_x in comparison to (1) and increase maximum frequency limit for each measurement range.

At the second stage, in the analysis of the signals u_i/u_u ratio, the only influence of tolerance of resistors $R_1 \div R_6$ was considered. The following relation has been obtained:

$$\frac{u_i}{u_u} = \frac{R_6}{R_5} \cdot \left(\left(\frac{Z_R}{Z_x} + 1 \right) \cdot \frac{\left(\frac{R_2}{R_1} + 1 \right)}{\left(\frac{R_3}{R_4} + 1 \right)} - \frac{R_2}{R_1} \right) \tag{4}$$

The calculations performed for measurement range $R_R = 100M\Omega$ (the following values for $R_x = 1G\Omega$, $C_x = 100pF$ were assumed) were presented in Fig. 6.
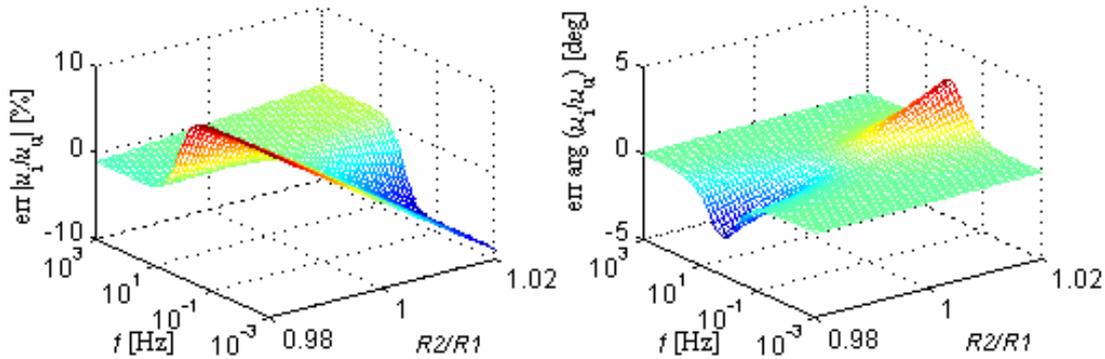

Figure. 6. Relative error of magnitude and absolute error of phase measurement of complex ratio of signals u_i and u_u in relation to R_2/R_1 (or R_3/R_4) ratio and frequency ($R_x = 1G\Omega$, $C_x = 100pF$)

When analysing graphs, the unwanted increase of modulus and phase errors can be seen at frequencies near 1Hz. The tendency is increasing when tolerance of resistor increases. The ratio $R_2/R_1 = 1.02$ corresponds to tolerance of both resistors equal to +1% and 0.98 means –1% respectively. The measurement frequency, at which maximum error is observed, depends on time constant of the impedance under measurement ($R_x C_x$) and range resistance R_R in the measurement probe. Similar nature of errors (like in Fig. 6) was obtained as a function of changes of ratio R_3/R_4.

The conclusion appearing in simulations made necessary the use of at least 0.1% tolerance resistors in the differential amplifier A2. For tolerance 0.1%, the limits of ratio R_2/R_1 are determined as 1.002 and 0.998 respectively. Figure 7 presents the errors of modulus and phase of ration u_i/u_u for two limits of R_2/R_1 ratio. When analysing graphs, one can notice meaningful decrease of errors. The changing relation between errors and measurement frequency and capacitance C_x shorting R_x is caused by changes of amplitude and phase of signal u_i extracted by differential amplifier A2. The highest errors

appear when the amplitude of differential signal is smaller (by two orders) then common signal for amplifier A2. This requires usage of operational amplifier with very high CMRR and precise resistors $R_1 \div R_4$. To analyse the influence of tolerance of those resistors on errors of modulus and phase of signals ratio u_i/u_u the simulation has been performed (Fig. 8) for the specified measurement frequency (100Hz) and capacitance $C_x=100pF$. In these conditions, the errors of phase are the greatest while modulus errors are also important.

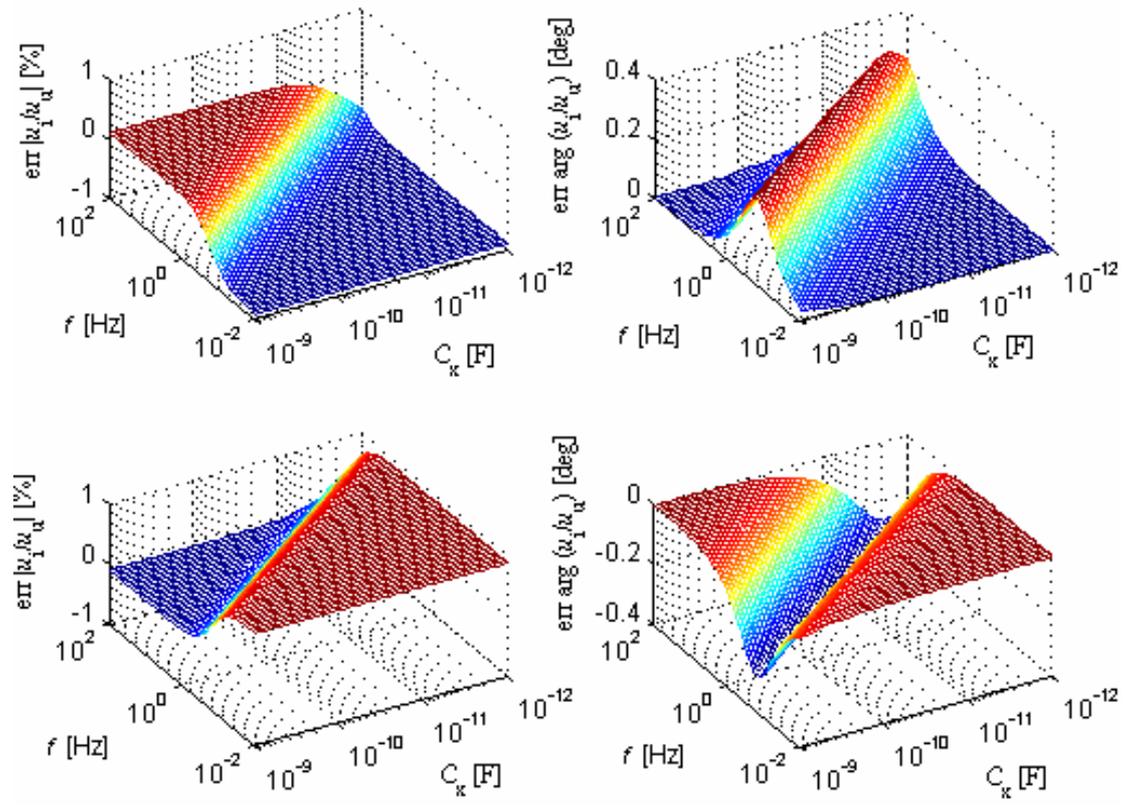Figure. 7. Relative error of magnitude and absolute error of phase measurement
of complex ratio of signals u_i and u_u in relation to C_x capacitance and frequency
(for $R_2/R_1 =1.002$ – upper 2 graphs and for $R_2/R_1 =0.998$ – lower 2 graphs)

Although graphs show the possibility of error compensation, when using resistor with the same tolerance but with different signs, the better guarantee of small errors is usage of 0.01% tolerance resistors allowing to achieve the maximum modulus error on the level of 0.1% and phase error on the level of 0.05°.
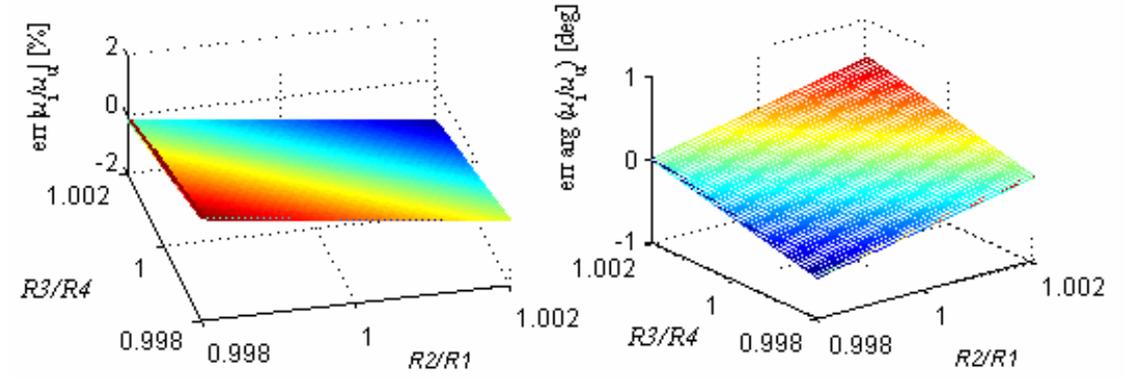

Figure. 8. Relative error of magnitude and absolute error of phase measurement of complex ratio of signals u_i and u_u in relation to R_2/R_1 ratio and R_3/R_4 ratio ($C_x=100pF$, f=1Hz)

IV. Conclusions

The paper presents the measurement probe designed for high impedance spectroscopy (up to 100GΩ) in a wide frequency range 10μHz÷100kHz. The results of simulation have been given. The results are pointing on high sensitivity of the ratio of the extracted in the probe measurements signals u_i and u_u on parasitic capacitance existing on the input of the probe and on the tolerances of resistor of differential amplifier extracting current signal.

The influence of parasitic capacitance can be significantly decreased by entering its approximate value to the equations for calculating impedance parameters of the objects under measurement. In the computer measurement system for impedance spectroscopy (ATLAS-0441) [5-7] which uses the presented probe, the table with parasitic capacitances and conductances for each range of 8 ranges is placed. It allows to increase the accuracy of parameters measurement of the object and to increase (by an order) maximum measurement frequency for each range. The realised probe (Fig. 9) is designed for testing objects directly in the field.

Figure. 9. View of the realised high impedance probe

To minimize the influence of resistors of differential amplifier on the ratio of extracted in the probe signals, the precise resistors with temperature coefficient 5ppm/K and tolerance 0.01% have been used. This way, the errors of modulus and phase do not exceed 0.1%.

The conclusions appearing from presented analysis of the high impedance probe allow to design final version of the probe with taking into an account rules formulated in the paper.

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