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CORRECTION PROCEDURES ERROR OF IMPEDANCE MEASUREMENT

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Abstract: In the paper, a voltage comparison circuit and a bridge circuit for impedance measurement by phase shift conversion (IMPSC) is presented. Use of microprocessor has enabled this kind of measurement, as well as error correction of impedance measurement. Error correction is possible thanks to by use of the adaptation procedures, calibration, zeroing, and minimization of influence of the phase shift converter input impedance. Using such impedance measurement a method, as well as mentioned error correction procedures make it possible to measure an impedance of any character, and with values varying within a broad range, without changing the structure of the measuring circuit. This allows co-operation between such circuit and different kinds of impedance sensors constituting the equipment of intelligent measurement nodes in distributed measurement systems.
Keywords: impedance measurement, error correction procedures

1 INTRODUCTION

Measuring circuits in which the impedance components are determined by measuring of current and voltage constitute a large group of an impedance measuring circuits. Measuring the phase shift between two appropriately selected voltages of the measuring circuit [1] can also carry out evaluation of the impedance components. Reference [2] presents different ways of impedance measuring by phase shift conversion (IMPSC) with the voltage comparison circuit (Fig. 1) and bridge circuit (Fig. 2).

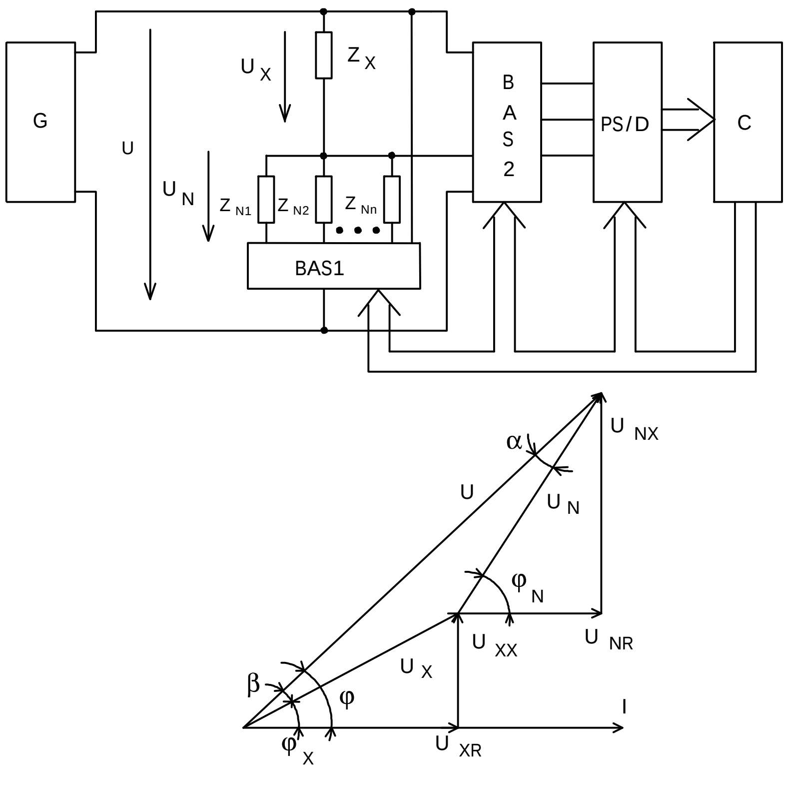

Figure 1. Block diagram of the IMPSC circuit with the voltage comparison circuit.

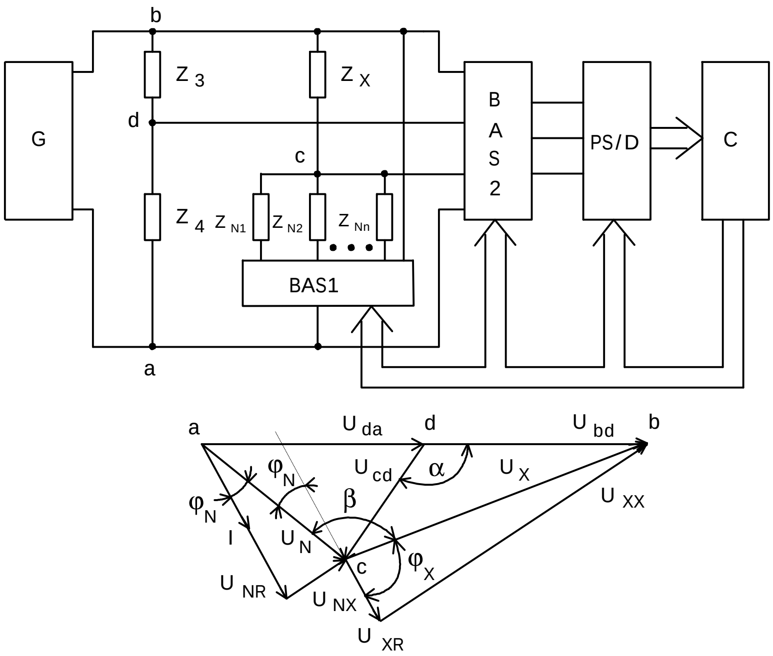

Figure 2. Block diagram of the IMPSC circuit with the bridge circuit.

In these circuits, the impedance components are determined by measuring the **a** and **b** angles or two different values of the **a** angle (**a**$_1$ and **a**$_2$). A digital phase shift converter (PS/D) carries out the measurement of the selected phase shifts. The accuracy analyses of IMPSC, carried out by the author show that the best results are achieved for measurement of **a** and **b** angles. Impedance components are then calculated by the microcomputer (C) according to the following formulae:

- with the voltage comparison circuit:

$$|Z_X| = |Z_N| \frac{\sin a}{\sin b} \qquad j_X = j_N - (a+b) \qquad (1)$$

- with the bridge circuit:

$$|Z_X| = |Z_N| \left\{ \frac{\sin(b)}{\tan(a)} + \sqrt{\left[\frac{\sin(b)}{\tan(a)}\right]^2 + 1} \right\} \qquad j_X = 180^0 + j_N - b \qquad (2)$$

where:

$|Z_X|$, $|Z_N|$ - magnitudes of the measured, Z_X, and standard, Z_N, impedances, respectively,
f$_X$, **f**$_N$ - arguments of the measured, Z_X, and standard, Z_N, impedances, respectively.

The calculated values $|Z_X|$ and φ_X allow to evaluate of the impedance components R_X and X_X. The direct determination of the R_X and X_X impedance components in the presented circuits is not advisable because of far lower measuring accuracy are achieved.

2 IMPEDANCE MEASURING ERROR

In the voltage comparison (Fig. 1) and bridge (Fig. 2) circuits the accuracy of impedance components measurement is influenced by:

a). errors of the voltage comparison or bridge circuit depend on:

- accuracy of Z_N (R_N or C_N) manufacturing; the stability of Z_N parameters for different values of the temperature, frequency, etc.; the value of the standard R_N time-constant (**t**), or the standard C_N tan **d**,
- balance of the U_{da} and U_{bd} voltages (in the bridge circuit),
- content of a harmonics in the voltages of measuring circuit,

- occurrence of a parasitic impedances due to earth couplings (capacitance couplings and leakage conductance); the impedance of the switches in the circuits BAS1 and BAS2, and the impedance of the input circuits of the PS/D converter,
- sensitivity of the measuring circuit,

b). errors **a** and **b** of the phase shift measuring channel dependent on:

- the accuracy of the phase shift measuring by the PS/D converter,
- the additional phase shift introduced by the input circuit of the PS/D converter.

On figs. 3 and 4 are presented the results of the calculations of the $|Z_X|$ measuring error for the assumed accuracy of the phase shift measurement, the accuracy of manufacturing of the standard impedance $|Z_N|$, and with taken into account the discrimination error. From these characteristics it follows that:

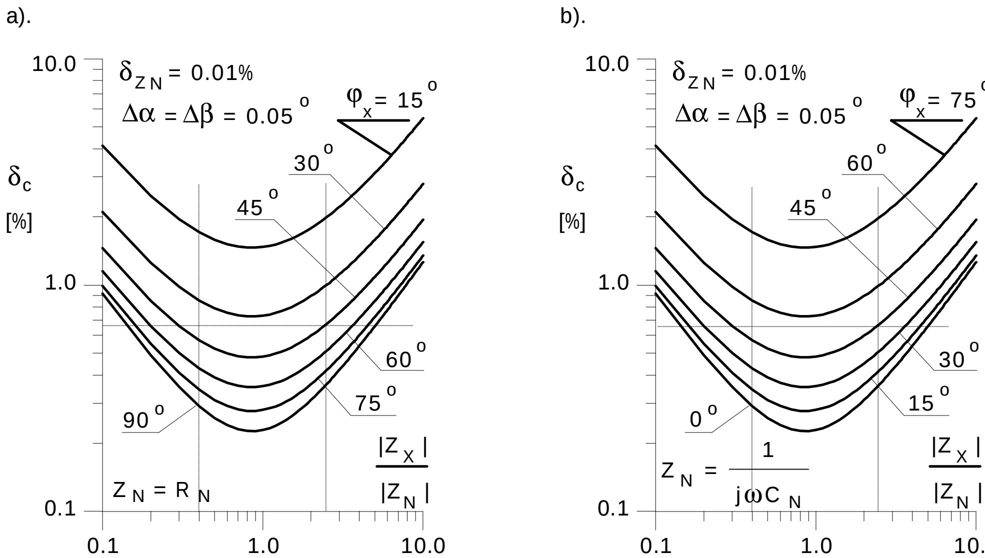

Figure 3. Total error of Z_X measurement with the voltage comparison circuit for: a) $Z_N = R_N$, b) $Z_N = \dfrac{1}{jwC_N}$.

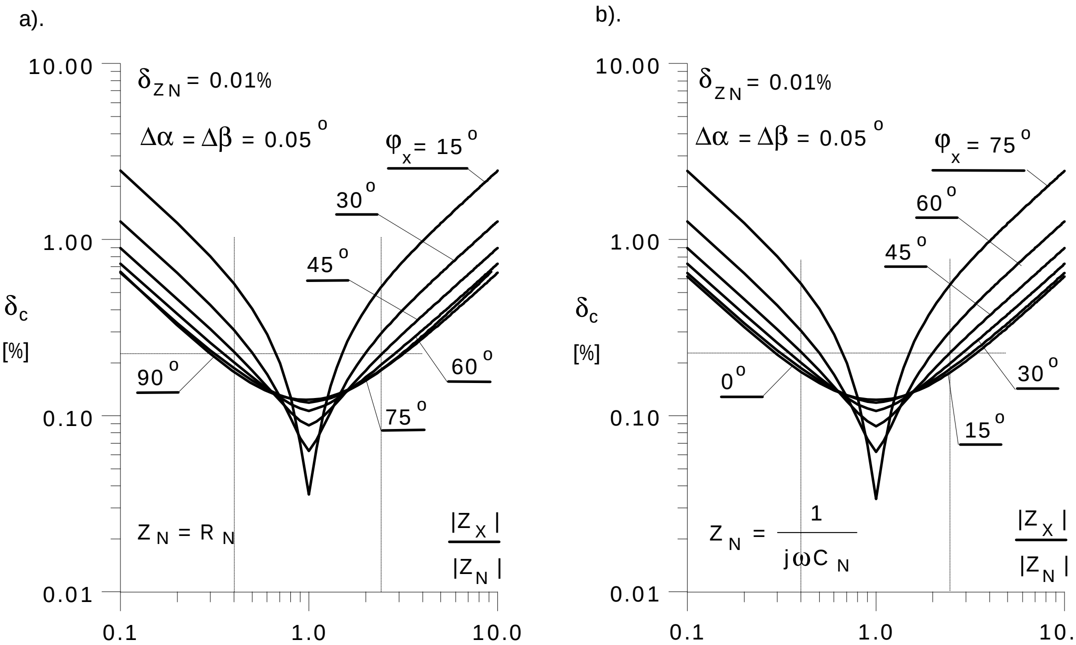

Figure 4. Total error of Z_X measurement with the bridge circuit for: a) $Z_N = R_N$, b) $Z_N = \dfrac{1}{jwC_N}$.

- the $|Z_X|$ measuring error depends also on the measured impedance Z_X in relation to the standard impedance Z_N and reaches its minimum value for $|Z_X| = |Z_N|$,
- the error value depends on the value of the measured impedance argument $\mathbf{f}_X$ and on the character of the standard impedance, for $Z_N = R_N$ the total error of impedance measurement decreases with the increase in the $\mathbf{f}_X$ value, and for $Z_N = \frac{1}{jwC_N}$ the dependence of the total impedance measuring error is reverse.

The presented sets of errors determine the final value of the impedance measuring error. This error can be minimized in two ways. The first way is associated with an appropriate selection of the measuring circuit's elements, such as: the bridge supply voltage with a low distortion ratio; an inductive voltage divider or precision resistors ensuring equality of the U_{da} and U_{bd} voltages in the bridge circuit; precision resistors and capacitors constituting the standard impedance Z_N; a PS/D converter with the highest possible accuracy of the **a** and **b** angles measurement and an infinitely large input impedance.

The second way based-on in introducing appropriate measuring procedures implemented by means of hardware and software.

3 ERROR CORRECTION PROCEDURES OF IMPEDANCE MEASUREMENT

3.1 Adaptation Procedure

The error characteristics presented on Figs. 3 and 4 show that the measuring circuit adaptation procedure can be used, and makes the minimization of the impedance Z_X measuring error possible. This procedure consists on switching the specific switch (BAS1) making possible the choice of the standard impedance in terms of its character (R_N or C_N) and magnitude. The algorithm of this procedure is presented on Fig. 5. The selection of the standard impedance Z_N magnitude value in relation to the measured impedance Z_X magnitude value results from the following condition:

$$0.4 \le \frac{|Z_X|}{|Z_N|} \le 2.5 \qquad (3)$$

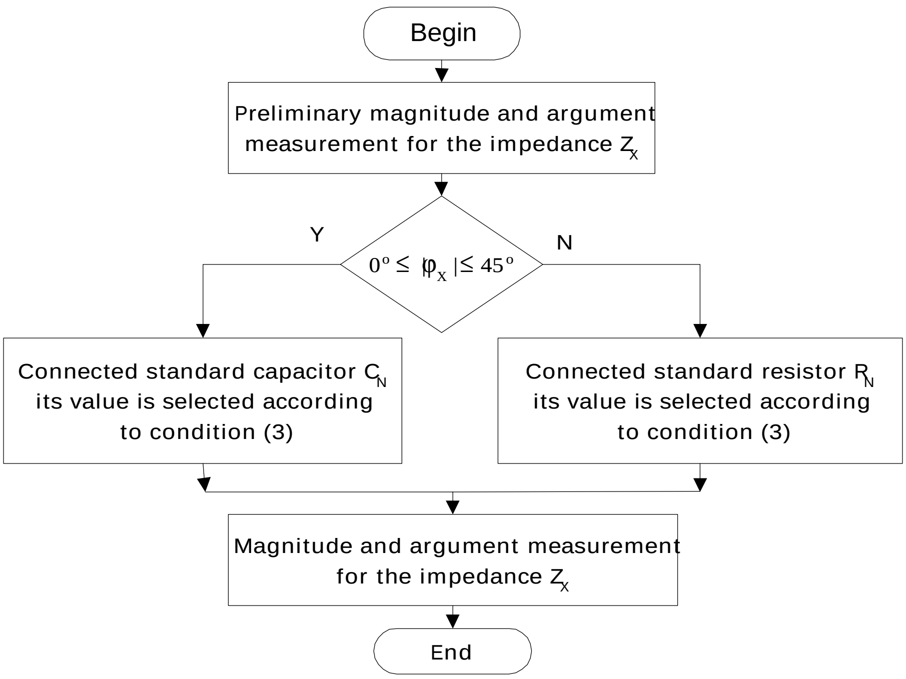

Figure 5. Algorithm of the adaptation procedure.

The assumed range of changes $\frac{|Z_X|}{|Z_N|}$ is a compromise between the accuracy of the impedance Z_X measurement and the number of elements of the standard impedance Z_N. For the assumed conditions of impedance determination, with the above adaptation procedure employed, the maximum error of the impedance Z_X measurement within a broad range of changes of the magnitude and argument amounts to 0.67% for the voltage comparison circuit (Fig. 3), and 0.23% for the bridge circuit (Fig. 4).

3.2 Calibration Procedure

From relationships (1) and (2) it follows that the accuracy of the standard Z_N directly influences the accuracy of the impedance Z_X measurement. However, as it follows from the presented voltage comparison and bridge methods it is necessary that standard capacitors (characterized by lower accuracy than that of the employed standard resistors) are used as the elements of the standard impedance Z_N. The error of the capacitance standard ($\mathbf{d}_{ZN}$) depends on:

- accuracy of the standard capacitor ($\mathbf{d}_{CN}$),
- stability of its parameters, e.g. for different temperatures, ($\mathbf{d}_{Ct}$),
- value of tan $\mathbf{d}$ ($\mathbf{d}_{tan\mathbf{d}}$),
- stability of the bridge supply voltage frequency ($\mathbf{d}_{f}$).

Errors $\mathbf{d}_{Ct}$, $\mathbf{d}_{tan}$, $\mathbf{d}_{f}$ cause an additional change in the standard impedance Z_N magnitude value. The greatest changes in the value of $|Z_N|$ are caused by changes in the temperature and frequency. They may be up to anywhere between ten and twenty times greater than the basic error ($\mathbf{d}_{CN}$) of the capacitor C_N. However, the dielectric loss angle $\mathbf{d}$ causes a change in the value of phase shift measurement by values significantly greater than the recommended accuracy of phase shift measurement. In the bridge circuit, the measuring of the angle $\mathbf{b}$ takes into account the influence of the angle $\mathbf{d}$ on the result of the $|Z_X|$ calculation. However, changes in the $|Z_N|$ value of the standard capacitor influencing the accuracy of $|Z_X|$ determination can be minimized by the use of the calibration procedure. In the voltage comparison circuit, the influence of the angle $\mathbf{d}$ and changes in $|Z_N|$ of the standard capacitor on the accuracy of the impedance Z_X measurement may also be minimized by employing the calibration procedure. In this procedure, the current magnitude and argument values are determined by comparing the capacitor with the standard resistance. The algorithm of this procedure is presented in Fig. 6. The block of analog switches BAS1 makes it possible to connect the selected capacitor C_N in place of the impedance Z_X. It follows from Figs. 3 and 4 that for the assumed conditions of impedance measurement, the accuracy of the determination of the standard capacitor impedance Z_N magnitude value is 0.1% and 0.2% for the bridge and voltage comparison circuits, respectively. Such accuracy value of the standard Z_N does not cause any significant deterioration in the final accuracy of the impedance Z_X measurement. To give an example, for the assumed conditions of impedance determination in the bridge circuit, with the procedures of adaptation and calibration employed, the maximum error of the impedance Z_X measurement, within a broad range of changes in the magnitude and argument values, will not exceed 0.26% (Fig. 7).

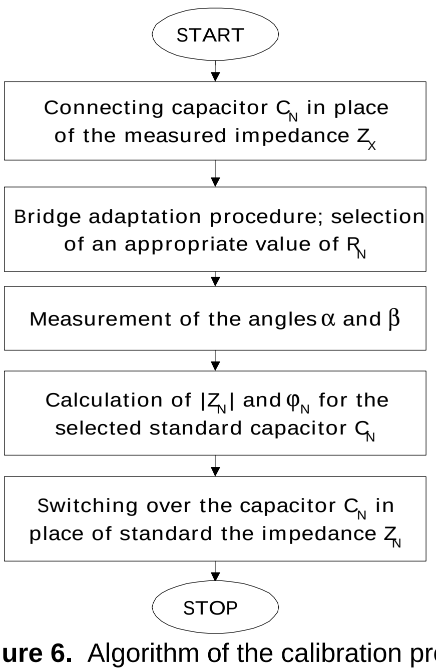

Figure 6. Algorithm of the calibration procedure.

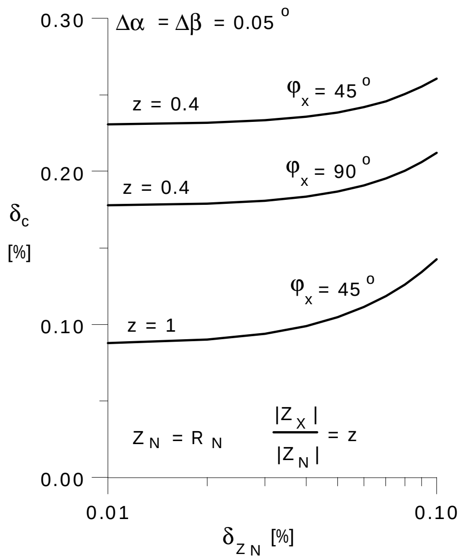

Figure 7. Influence of the accuracy of the standard impedance Z_N on the total error of impedance Z_X measurement in the bridge circuit.

Use of the calibration procedure results in the fact that the changes in C and tan **d** of the standard capacitor due to time, temperature, etc. fluctuations are taken into account. This procedure makes it possible to use capacitors of any type and values as the standard impedance.

3.3 Zeroing Procedure

IMPSC requires use of a phase shift converter measuring the phase shift angles **a** and **b**. In this converter there are two measuring channels introducing their own phase shifts chiefly due to dynamic properties of the employed followers, amplifiers, voltage limiters, and comparators. The difference in the phase shift between the two channels causes an additional phase shift measuring error. The minimization of the influence of this error on the total impedance measuring error is connected with the employment of the zeroing procedure. This procedure consists in simultaneous connection of the reference voltage by the block of analog switches BAS2 to both inputs of the phase converter, and the measurement of the phase shift angle between the two channels. The measured value of this angle is taken into account in all the calculations connected with the impedance Z_X determination.

3.4. Procedure of minimization of influence of PS/D input impedance

The PS/D employed in the impedance Z_X measuring circuit is characterized by specific metrological properties. One of them is the input impedances of the converter PS/D, which are appropriately connected by the block of analog switches (BAS2) to selected points of the measuring circuit. This causes a change in the values of the measured phase shift angles **a** and **b**, and consequently an erroneous calculation of the measured impedance Z_X magnitude and argument. For example, for the bridge circuit, when $|Z_X| = 0.1|Z_{in}|$, and with the assumption that the input circuits' impedances of the converter PS/D are equal ($Z_{in1}=Z_{in2}=Z_{in}$) and $|Z_X| = 2.5|Z_N|$ (according to the employed adaptation procedure), the greatest value of the angle **a** amounts to $+2^0$, and the angle **b**, -4.5^0. Such large changes in the values of the angles **a** and **b** cause an additional impedance measuring error equal to +10%. The necessity to limit the influence of the PS/D input impedance on the accuracy of the impedance Z_X components determination in the voltage comparison and bridge circuits requires the employment of an appropriate calculating procedure. In this procedure on the grounds of the relationships taking into account the PS/D input impedances, the impedance Z_X magnitude and argument are calculated iteratively.

4 SUMMARY

The employment of the phase shift conversion method in impedance measurement along with error correction procedures makes it possible to measure impedance of any character and values varying within a broad range with no necessity to change the structure of the measuring circuit. This is a significant feature of the presented measuring circuits, which may be allocated to the interaction between different types of impedance sensors constituting the equipment of intelligent measurement nodes in distributed measurement systems.

From the presented analyses it follows that the bridge circuit is characterized by a lower impedance measuring error than the voltage comparison circuit. Within a broad range of changes in the impedance values, for the assumed phase shift measurement accuracy (0.05^0 – 0.1^0), the impedance magnitude measurement error in a bridge circuit amounts to 0.2% – 0.5%.

An additional feature of IMPSC circuits is the conversion of the measured impedance Z_X directly into a digital signal omitting its intermediate conversion into voltage or current. Besides that, the direct measurement of the impedance Z_X argument **f**$_X$ makes it possible to determine tg **d** of a capacitor or the magnification factor (Q) of a coil directly for the investigated object with no necessity to measure its capacitance or inductance.

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