

## Automated quasi-balancing in virtual quasi-balanced circuit designed to capacitance measurements

Adam Cichy<sup>1</sup>, Artur Skórkowski<sup>2</sup>, Sebastian Barwinek<sup>3</sup>

<sup>1</sup> Institute of Measurement Science, Electronics and Control, Silesian University of Technology, Akademicka 10 Street, 44-100 Gliwice, Poland, +48322371241, fax +48322372034, adam.cichy@polsl.pl

<sup>2</sup> Institute of Measurement Science, Electronics and Control, Silesian University of Technology, Akademicka 10 Street, 44-100 Gliwice, Poland, +48322371241, fax +48322372034, artur.skorkowski@polsl.pl

<sup>3</sup> Institute of Measurement Science, Electronics and Control, Silesian University of Technology, Akademicka 10 Street, 44-100 Gliwice, Poland, +48322371241, fax +48322372034, sebastian.barwinek@polsl.pl

**Abstract-** A basic purpose of this research was to verify a possibility of automatic balancing in the virtual realization of a quasi-balanced circuit for capacitance measurements. The diagrams of a virtual quasi-balanced instrument are presented in this paper. The tested circuit was built using a PC computer and the DAQ card NI-6009. The DAQ card and the calculation were controlled by the application developed in the graphical development platform LabVIEW.

### I. Introduction

Quasi-balanced circuits are AC circuits destined for measuring impedance components. They have a special selected state, the so-called quasi-equilibrium state, which is usually a predetermined phase shift between the selected signals. The advantage of quasi-balanced circuits is the use of only one control element. The quasi-equilibrium state is an a priori assumed non-zero state – generally meant as the achieving of the determined phase shift between the selected signals of the circuit. The maximum convergence is the advantage of the circuits under consideration, whereas the lack of possibility of simultaneous measurement of both immittance components is the disadvantage, although the measurement of the second component is usually possible after uncomplicated reconfiguration of the circuit.

### II. A virtual quasi-balanced circuit designed for capacitance measurements

There are many solutions of quasi-balanced circuits for measuring impedance components, e.g. those presented in [1], [2]. Figure 1 shows an example of realization of the circuit used for measuring the capacitance modeled by a series combination of RC [3].

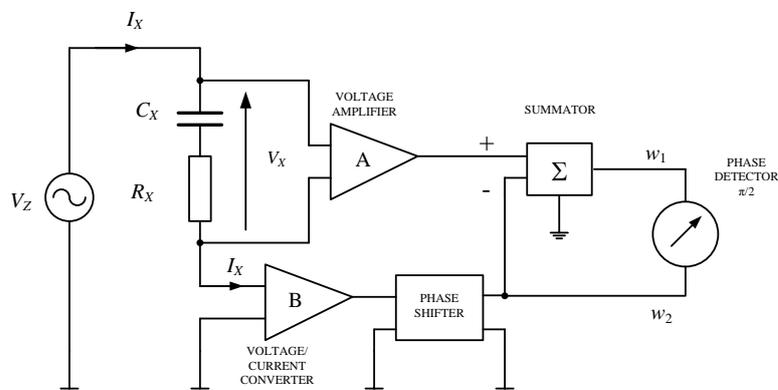


Figure 1. Block diagram of the quasi-balanced circuit for capacitance measurements

Modern measuring instruments are more and more often built as virtual instruments. In analog technique operations realized on measurement signals are performed on sampled and quantized signals by software. The block diagram of the circuit (Fig. 1) describing analog processing becomes then a measurement algorithm (virtual instrument). Quasi-balanced circuits can very easily be virtualized, since there are only operations of summing, amplifying or shifting signals by  $\pm\pi/2$  in the discussed circuits. Phase-sensitive detection can also be realized with algorithmic methods.

The equations describing the selected output signals  $w_1, w_2$  in the system shown in Figure 1 have the form:

$$\begin{cases} w_1 = AV_x - BI_x e^{j\frac{\pi}{2}} \\ w_2 = BI_x e^{j\frac{\pi}{2}} \end{cases} \quad (1)$$

where  $A$  is the voltage amplifier gain,  $B$  is the conversion rate of the current /voltage converter;  $V_x$  and  $I_x$  is the voltage and current of the RC object under test, respectively.

The complex numbers in Equation 1 can be expressed in the polar form as follows:

$$\begin{cases} |w_1| e^{j\Phi_1} = A|V_x| e^{j\Psi_1} - B|I_x| e^{j\Psi_2} e^{j\frac{\pi}{2}} \\ |w_2| e^{j\Phi_2} = B|I_x| e^{j\Psi_2} e^{j\frac{\pi}{2}} \end{cases} \quad (2)$$

where:  $|w_1|, |w_2|$  - modulus of the selected signals of the circuit;  $\Phi_1, \Phi_2$  - phase of the selected signals of the circuit;  $|V_x|, |I_x|$  - modulus of the voltage and current of the tested RC two-port;  $\Psi_1, \Psi_2$  - phase of the tested RC two-port.

After dividing both sides of the system of equations (2) by each other one obtains the expression:

$$\frac{|w_1|}{|w_2|} e^{j(\Phi_1 - \Phi_2)} = \frac{A|V_x| e^{j\Psi_1} - B|I_x| e^{j\Psi_2} e^{j\frac{\pi}{2}}}{B|I_x| e^{j\Psi_2} e^{j\frac{\pi}{2}}} \quad (3)$$

which can be brought to the form:

$$\left| \frac{w_1}{w_2} \right| e^{j\Phi_w} = \frac{A}{B} |Z_x| e^{j\left(\Psi_1 - \Psi_2 - \frac{\pi}{2}\right)} - 1 \quad (4)$$

where:  $\Phi_w$  - angle of the phase shift between the selected signals of the circuit,  $|Z_x|$  - modulus of the impedance of the tested RC two-port.

The dependence (4) is a complex number equation and can be written as a system of two real number equations in the trigonometric form:

$$\begin{cases} \left| \frac{w_1}{w_2} \right| \cos \Phi_w = \frac{A}{B} |Z_x| \sin \varphi_x - 1 \\ \left| \frac{w_1}{w_2} \right| \sin \Phi_w = -\frac{A}{B} |Z_x| \cos \varphi_x \end{cases} \quad (5)$$

After dividing both sides of the system of equations (5) by each other and trigonometric transformation, one obtains the equation describing the signal  $\Phi_w$  being detected as a function of the circuit parameters  $A$  and  $B$  as well as the tested impedance components:

$$\Phi_w = \operatorname{arccotan} \left( \frac{1 - \frac{A}{B} |Z_x| \sin \varphi_x}{\frac{A}{B} |Z_x| \cos \varphi_x} \right) = \operatorname{arccotan} \left[ \frac{B - A \operatorname{Im}(Z_x)}{A \operatorname{Re}(Z_x)} \right] \quad (6)$$

if  $A \neq 0$  and  $\operatorname{Re}(Z_x) \neq 0$ .

In the quasi-equilibrium state the conversion equation (6) is reduced to the form:

$$B_0 - A_0 \operatorname{Im}(Z_x) = \cotan \frac{\pi}{2} = 0 \quad (7)$$

from which it is possible to calculate the passive component of the measured impedance

$$\operatorname{Im}(Z_x) = \frac{B_0}{A_0} \quad (8)$$

where  $A_0$  is the voltage amplifier gain in the quasi-equilibrium state,  $B_0$  is the conversion rate of the current/voltage converter in the quasi-equilibrium state.

Since the discussed circuit is destined for capacitance measurements, the capacitance of the capacitor is calculated from Equation (8). In the quasi-equilibrium state the phase angle is set to  $\pi/2$ . Then the capacitance of the capacitor can be determined from the relationship:

$$C_x = \frac{1}{\omega \operatorname{Im}(Z_x)} = \frac{A_0}{\omega B_0} \quad (9)$$

where  $A_0$  and  $B_0$  as in Equation (8).

In the case of using a circuit for capacitance measurements and taking into account that

$$Z_x = R_x + \frac{1}{j\omega C_x} \quad (10)$$

Equation (6) can be rewritten as:

$$\Phi_w = \operatorname{arccotan} \left( \frac{B - A \frac{1}{\omega C_x}}{A R_x} \right) \quad (11)$$

The detected signal  $\Phi_w$  is a phase shift between the selected signals  $w_1$  and  $w_2$ . The equation describing  $\Phi_w$  signal as a function of the parameters  $A$ ,  $B$  and the measured impedance component. The above equation is a conversion equation of the circuit of Figure 1.

The amplifier voltage gain  $A$  or the conversion rate of the current/voltage converter  $B$  can be the adjusted parameter in the circuit of Figure 1. The circuit is brought to the quasi-equilibrium state by changing the value of one selected, adjustable parameter  $A$  or  $B$ . Such a process is called the process of quasi-balancing the circuit. If the measuring circuit of Figure 1 is destined for measuring the reactance of capacitors, then it is more advantageous to change the setting of the parameter  $B$ . Change of the parameter  $A$  will be more advantageous in the circuits for measuring the capacitance. In both above mentioned cases there is obtained a simple dependence between the adjustable parameter and the quantity being measured in the quasi-equilibrium state. Such a feature is not of great importance in modern measuring instruments containing microprocessors, but in some cases (for instance in order to decrease the energy consumption in portable instruments) one still tends to simplify calculations and to reduce the balancing time of the circuit.

In the case of the adjustable parameter  $A$ , the parameter  $B$  remains constant. During the whole measuring process and after achieving the quasi-equilibrium state

$$B = B_0 = \text{const} \quad (12)$$

After substituting Equation (12) in Equation (6) and dividing the numerator and denominator of the argument of the arccotan function in this equation by  $A_0$  one obtains

$$\Phi_{wA} = \operatorname{arccotan} \left[ \frac{\frac{B_0}{A_0} - \frac{A}{A_0} \operatorname{Im}(Z_x)}{\frac{A}{A_0} \operatorname{Re}(Z_x)} \right] = \operatorname{arccotan} \left[ \frac{\left(1 - \frac{A}{A_0}\right) \operatorname{Im}(Z_x)}{\frac{A}{A_0} \operatorname{Re}(Z_x)} \right] \quad (13)$$

where  $\Phi_{wA}$  is the signal being detected in the case of the adjustable parameter  $A$ .

The relation between the active and passive component of the series RC impedance  $Z_X$  is the dielectric loss factor  $\text{tg } \delta_X$  of this impedance

$$\frac{\text{Re}(Z_X)}{\text{Im}(Z_X)} = \text{tg } \delta_X \quad (14)$$

hence Equation (13) can be written as follows:

$$\Phi_{WA} = \text{arccotan} \left( \frac{1}{\text{tg } \delta_X} \cdot \frac{1 - \frac{A}{A_0}}{\frac{A}{A_0}} \right) \quad (15)$$

Figure 2 shows the dependence of the signal being detected  $\Phi_{WA}$  on the adjustable parameter  $A$  relative to the value of  $A_0$  for different typical values of  $\text{tg } \delta_X$ .

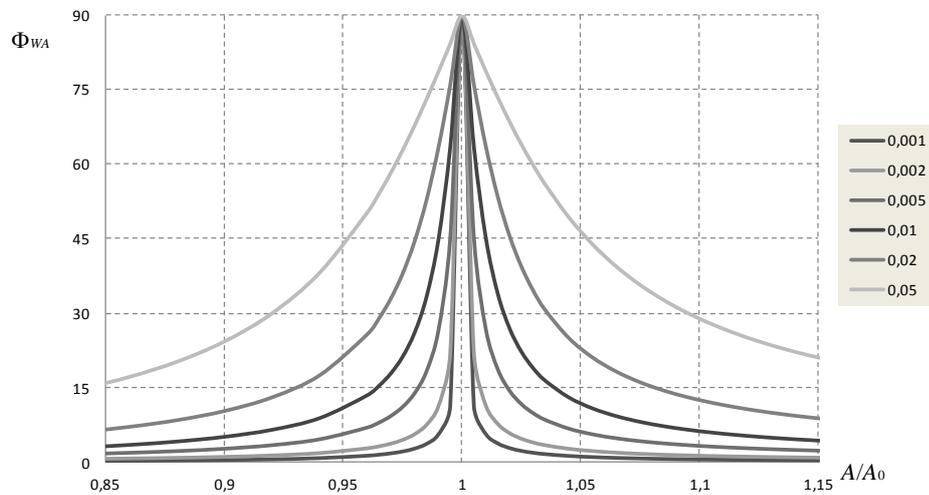


Figure 2.  $\Phi_{WA}$  signal vs. relative parameter  $A/A_0$  for different loss factor  $\text{tg } \delta_X$  values

### III. Automated quasi-balancing

Figure 3 shows a simplified structure of the virtual instrument executed in the LabVIEW graphical programming environment, according to the approach presented in [3].

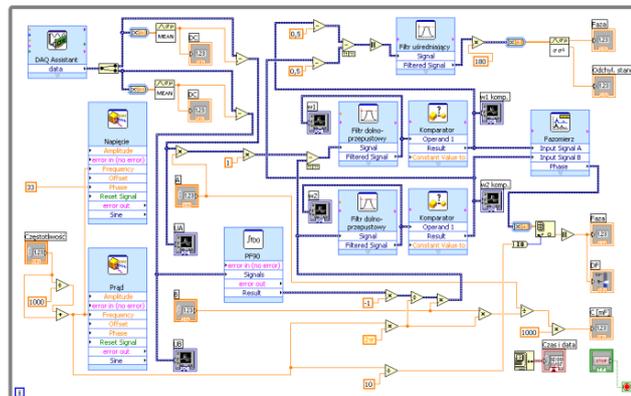


Figure 3. The LabVIEW realization of the virtual capacitance meter

The quasi-balanced circuit for capacitance measurements shown in Figure 1 was executed as a virtual instrument (Figure 3). Measurement signals, such as a voltage drop across the measured impedance and a current converted into a voltage, were applied to the data acquisition card USB NI 6009. Further conversion of the signals in measuring channels was carried out by a program executed in the LabVIEW graphical programming environment.

The amplifier voltage gain or the conversion rate of a current/voltage converter may be the adjustable parameter in this system [4]. By amending the value of one selected adjustable parameter  $A$  or  $B$ , the system is automatically set into the quasi-equilibrium state. In the circuit for capacity measurement it is better to adjust the parameter  $A$  at a constant value of the parameter  $B = B_0$ .

The process of the automated quasi-balancing of the circuit shown in Figure 1 aiming at determining the capacitance  $C_X$  given by Equation (9) consists in changing the setting of  $A$  at the constant setting of  $B$  ( $B = B_0$ ) until the value of the signal being detected achieves  $\pi/2$ .

The automated quasi-balancing of the circuit is performed in three steps according to the conversion characteristic presented in Figure 4:

- for the optional setting  $A = A_1$  there is determined the indication of a phase-sensitive detector  $\Phi_{WA_1}$  (point 1 in Figure 4),
- the setting of  $A$  is changed and for  $A_2 \neq A_1$  there is again determined the indication of a phase-sensitive detector  $\Phi_{WA_2}$  (point 2 in Figure 4),
- according to the relationships presented in the system of equations (16) there is determined the setting  $A_0$  corresponding to the selected quasi-equilibrium state  $\Phi_{WA} = \pi/2$  (point 0 in Figure 4).

$$\left\{ \begin{array}{l} \Phi_{WA_1} = \operatorname{arccotan} \left( \frac{1}{\operatorname{tg} \delta_X} \cdot \frac{1 - \frac{A_1}{A_0}}{\frac{A_1}{A_0}} \right) \\ \Phi_{WA_2} = \operatorname{arccotan} \left( \frac{1}{\operatorname{tg} \delta_X} \cdot \frac{1 - \frac{A_2}{A_0}}{\frac{A_2}{A_0}} \right) \end{array} \right. \quad (16)$$

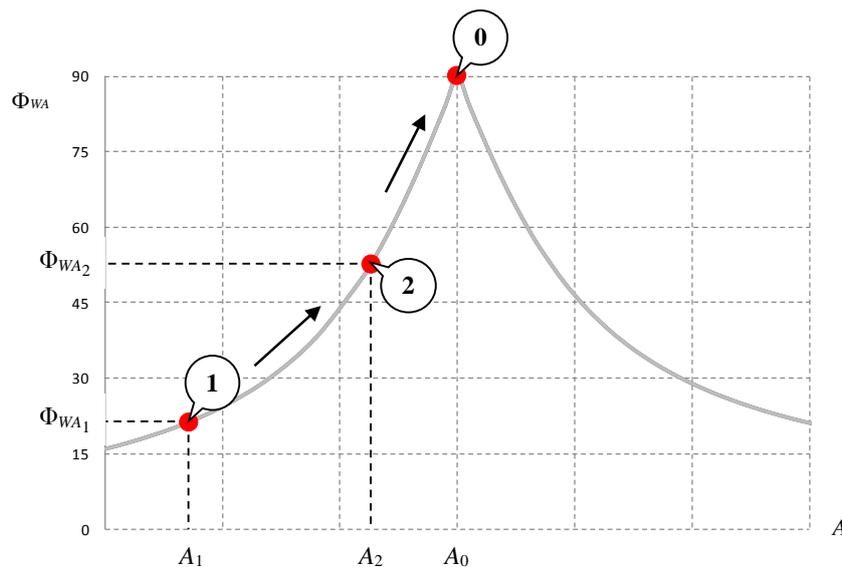


Figure 4.  $\Phi_{WA}$  signal vs. parameter  $A$  for unknown loss factor  $\operatorname{tg} \delta_X$  values (conversion characteristic)

For determining the setting  $A_0$  it is not necessary to know the loss factor  $\text{tg } \delta_x$ , since it has the constant value in the system of equations (16) and does not appear in the solution of this system which can be presented as follows:

$$A_0 = \frac{A_1 A_2 (\cotan \Phi_{WA_2} - \cotan \Phi_{WA_1})}{A_2 \cotan \Phi_{WA_2} - A_1 \cotan \Phi_{WA_1}} \quad (17)$$

Having finished the automated quasi-balancing of the circuit of Figure 1, one can determine the capacitance of the tested capacitor from the dependence (9) based on the known settings  $B_0$  and  $A_0$ .

The exemplary results of the tests made for the virtual circuit for capacitance measurements during classical (by changes of the adjustable parameter by a given constant value) and automated quasi-balancing are given in Table 1.

Table 1. Comparison of selected measurement results obtained during classical and automated quasi-balancing of the circuit for capacitance measurement

| The classical quasi-balance method |               |        |               |        |               |                    |
|------------------------------------|---------------|--------|---------------|--------|---------------|--------------------|
|                                    |               |        |               | $A_0$  | $\Phi_{WA_0}$ | $C_x, \mu\text{F}$ |
|                                    |               |        |               | 1.0357 | 90.00         | 0.3294             |
| The automated quasi-balance method |               |        |               |        |               |                    |
| $A_1$                              | $\Phi_{WA_1}$ | $A_2$  | $\Phi_{WA_2}$ | $A_0$  | $\Phi_{WA_0}$ | $C_x, \mu\text{F}$ |
| 100.0000                           | 15.14         | 1.0404 | 89.01         | 1.0356 | 90.00         | 0.3294             |
| 3.9401                             | 20.00         | 1.0875 | 80.00         | 1.0360 | 90.00         | 0.3295             |
| 1.9393                             | 30.09         | 1.1482 | 70.09         | 1.0359 | 90.00         | 0.3295             |
| 1.5238                             | 40.00         | 1.2272 | 60.00         | 1.0374 | 89.82         | 0.3299             |

#### IV. Conclusions

The tests of the presented way of quasi-balancing the circuit for capacitance measurements proved the worked out procedure to be correct and showed the possibility of significantly faster achieving the quasi-equilibrium state than in the case of classical balance methods by changes of the adjustable parameter by a given constant value.

The presented automated quasi-balance method does not reduce the accuracy of the phase detector operation and does not increase the uncertainty of determining the tested capacitor capacitance significantly. During investigations there was observed an insignificant influence of the circuit conversion characteristic shape (Figure 4) and the selection of the points on this characteristic during realization of the automated quasi-balancing procedure on the accuracy of achieving the the quasi-equilibrium state.

Further investigations will aim at the detailed determination of the selection of points 1 and 2 during realization of the procedure of quasi-balancing the circuit on the accuracy of assessing the setting  $A_0$  in the quasi-equilibrium state. There is also planned the examination of possibilities of using the presented measuring circuit and the automated quasi-balancing procedure for determining the dielectric loss factor  $\text{tg } \delta_x$  of an RC impedance.

#### References

- [1] Skórkowski A. and Cichy A.: "Virtual Capacitance Meter Based on Impedance Modulus Measurement". Proceedings of the XIX IMEKO World Congress, Lisbon, Portugal, September 2009.
- [2] Marcuța C., Fosalau C. and Petrescu C.: "A virtual impedance measuring instrument based a quasi balanced bridge". Proceedings of the 14th Int. Symposium IMEKO TC4, Sept. 2005, pp. 517–523.
- [3] Skórkowski A., Cichy A.: "Testing of the virtual realization of the quasi-balanced circuit for the capacitance measurement. *Measurement Automation and Monitoring*, vol. 53, no. 12, 2007, pp. 91-93.
- [4] Cichy A., Skórkowski A.: "Virtual realization of a quasi-balanced circuit for measuring the dielectric condition index of capacitance type". *Measurement Automation and Monitoring*, vol. 55, no. 1, 2009, pp. 34-37.