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Virtual quasi-balanced circuits and method of automated quasi-balancing

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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.

Section: RESEARCH PAPER

Keywords: automatic balancing; virtual instrument; quasi-balanced circuit; LabVIEW development

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1. 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 achievement of the determined phase shift between the selected signals of the circuit. Maximum convergence is the advantage of the circuits under consideration, whereas the lack of possibility of simultaneous measurement of both immitance components is the disadvantage, although the measurement of the second component is usually possible after uncomplicated reconfiguration of the circuit.

2. QUASI-BALANCED CIRCUIT FOR IMPEDANCE COMPONENTS MEASUREMENTS

There are many solutions of quasi-balanced circuits for measuring impedance components, e.g. those presented in [1...7]. Figure 1 shows an example of the circuit used for measuring a capacitance modelled by a series combination of RC [8].

Modern measuring instruments are more and more often built as virtual instruments. In analog techniques, operations on measurement signals are performed on sampled and quantized signals by software. The block diagram of the circuit (Figure 1) describing analog processing becomes then a measurement algorithm (virtual instrument). Quasi-balanced circuits can be virtualized very easily, 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:

$$\begin{cases} w_1 = AV_X - BI_X e^{j\frac{\pi}{2}} \\ w_2 = BI_X e^{j\frac{\pi}{2}} \end{cases} \tag{1}$$

where A is the voltage amplifier gain, B is the conversion factor of the current /voltage converter; V_X and I_X are the voltage and current of the RC object under test, respectively.

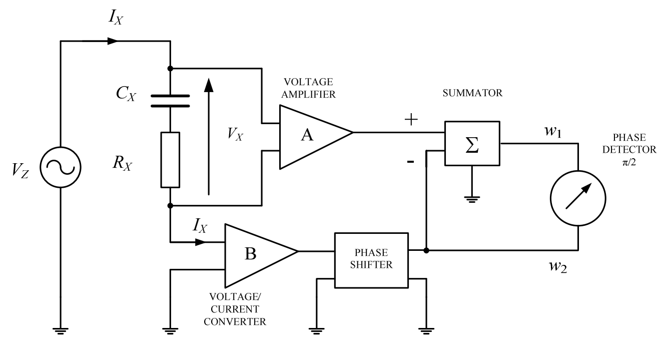

Figure 1. Block diagram of the quasi-balanced circuit for capacitance measurements.

The complex numbers in Eq. 1 can be expressed in polar from 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: $|w_1|, |w_2|$ - modules of the selected signals of the circuit; Φ_1, Φ_2 – phases of the selected signals of the circuit; $|V_X|, |I_X|$ - modules of the voltage and current of the tested RC two-port; Ψ_1, Ψ_2 - phases 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: Φ_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 Eq. (5) by each other and trigonometric transformation, one obtains the equation describing the signal Φ_W being detected as a function of the circuit parameters A and B as well as the tested impedance components:

$$\Phi_W = \operatorname{arccotan}\left(\frac{1-\frac{A}{B}|Z_X|\sin\varphi_X}{\frac{A}{B}|Z_X|\cos\varphi_X}\right) = \operatorname{arccotan}\left[\frac{B - A\,\mathrm{Im}(Z_X)}{A\,\mathrm{Re}(Z_X)}\right] \quad (6)$$

if $A \neq 0$ and $\mathrm{Re}(Z_X) \neq 0$.

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

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

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

$$\mathrm{Im}(Z_X) = \frac{B_0}{A_0} \quad (8)$$

where A_0 is the voltage amplifier gain in the quasi-equilibrium state, B_0 is the conversion factor 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 Eq. (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:

$$C_X = \frac{1}{\omega\,\mathrm{Im}(Z_X)} = \frac{A_0}{\omega B_0} \quad (9)$$

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:

$$\Phi_W = \operatorname{arccotan}\left(\frac{B - A\frac{1}{\omega C_X}}{AR_X}\right) \quad (11)$$

The detected signal Φ_W is a phase shift between the selected signals w_1 and w_2. The equation describes the Φ_W signal as a function of the parameters A, B and the measured impedance component. Eq. 11 is a conversion equation of the circuit of Figure 1.

The amplifier's voltage gain A or the conversion factor of the current/voltage converter's 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 circuits for measuring the capacitance. In both cases mentioned above a simple relation between the adjustable parameter and the quantity being measured in the quasi-equilibrium state is obtained. 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

$$B = B_0 = \text{const} \tag{12}$$

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

$$\Phi_{WA} = \operatorname{arccotan}\left[\frac{\frac{B_0}{A_0} - \frac{A}{A_0}\operatorname{Im}(Z_X)}{\frac{A}{A_0}\operatorname{Re}(Z_X)}\right] = \operatorname{arccotan}\left[\frac{\left(1-\frac{A}{A_0}\right)\operatorname{Im}(Z_X)}{\frac{A}{A_0}\operatorname{Re}(Z_X)}\right] \tag{13}$$

where Φ_{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 tg δ_X of this impedance

$$\frac{\operatorname{Re}(Z_X)}{\operatorname{Im}(Z_X)} = \operatorname{tg}\delta_X \tag{14}$$

hence Equation (13) can be written as follows:

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

Figure 2 shows the dependence of the signal being detected, Φ_{WA}, on the adjustable parameter A relative to the value of A_0 for different typical values of tg δ_X.

3. 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 [8].

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 the measuring channels was carried out by a program executed in the LabVIEW graphical programming environment.

The amplifier voltage gain or the conversion factor of a current/voltage converter may be the adjustable parameter in this system. 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 Eq. (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 $A = A_1$ the indication of a phase-sensitive detector Φ_{WA_1} is determined (point 1 in Figure 4),
- the setting of A is changed and for $A_2 \neq A_1$ the indication of a phase-sensitive detector Φ_{WA_2} is again determined (point 2 in Figure 4),
- according to the relationships presented in the system of equations (16) the setting A_0 corresponding to the selected quasi–equilibrium state $\Phi_{WA} = \pi/2$ is determined (point 0 in Figure 4).

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

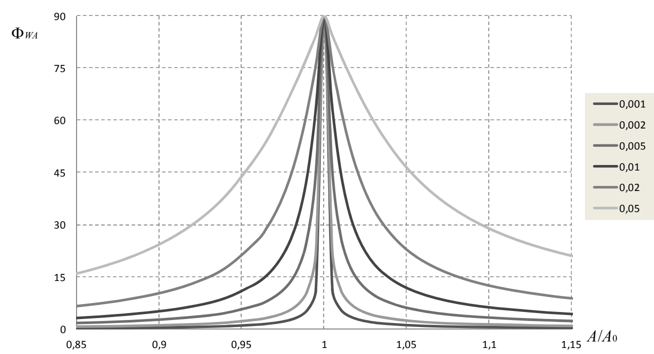

Figure 2. Φ_{WA} signal vs. relative parameter A/A_0 for different loss factor tg δ_x values.

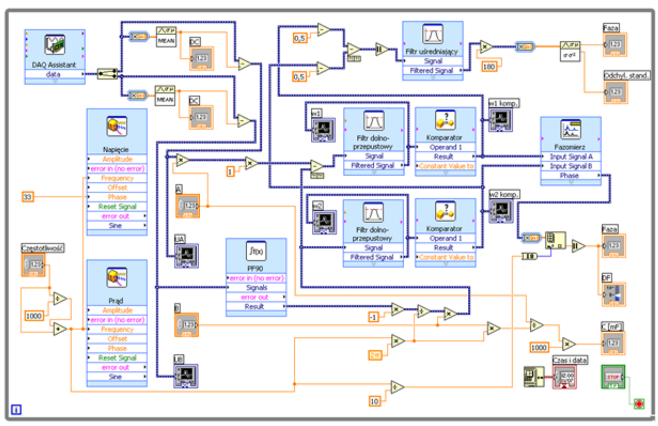

Figure 3. The LabVIEW realization of the virtual capacitance meter.

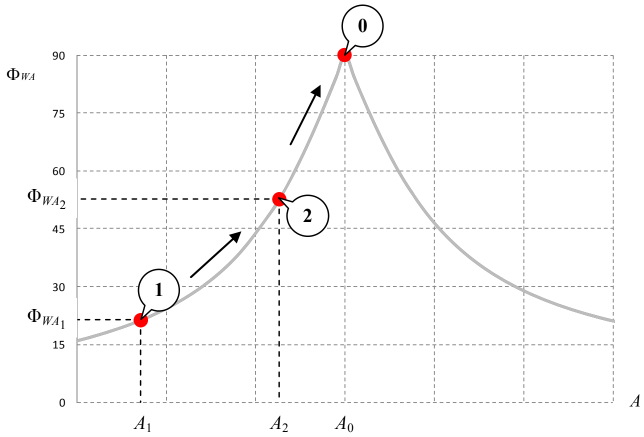

Figure 4. Φ_{WA} signal vs. parameter A for unknown loss factor tg δ_x values (conversion characteristic).

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

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

Having finished the automated quasi-balancing of the circuit of Figure 1, one can determine the capacitance of the tested capacitor from Equation (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.

4. DOUBLE QUASI-BALANCED CIRCUITS

In general quasi-balanced circuits only allow the measurement of one impedance component, but it is possible to build circuits to measure two components of impedance, for example in parallel quasi-balanced circuits. Some quasi–balanced circuits allow the measurement of the mutual relationship between the components of the impedance, e.g. quality factor. In such systems, double quasi - balancing in two successive steps is applied. The circuit of the quasi-balanced bridge, designed to measure the quality factor of real inductors is presented in Figure 5. The symbols in Figure 1 represent respectively: R_3 a standard variable resistor; V_S the power supply voltage, R a potentiometer resistance; n a potentiometer setting ($0 < n < 1$) and I_1, I_2 the currents of the branches of the bridge. The object under test is modeled as a series connection of resistance R_X and inductance L_X.

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	Φ_{WA_0}	C_X, µF
				1.0357	90.00	0.3294
The automated quasi-balance method						
A_1	Φ_{WA_1}	A_2	Φ_{WA_2}	A_0	Φ_{WA_0}	C_X, µF
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

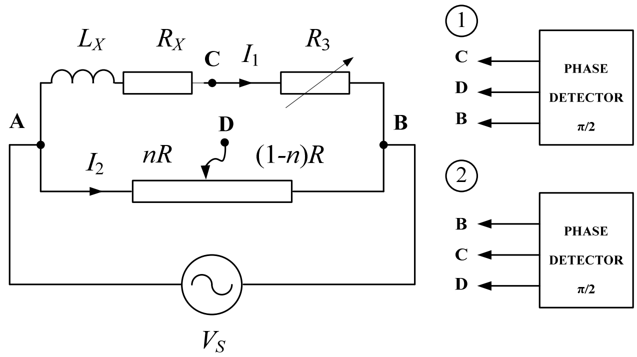

Figure 5. Diagram of the quasi-balanced bridge for loss factor measurement.

The quasi-balancing process requires two steps. In the first state of quasi-equilibrium the phase angle between V_{AD} and V_{DC} equals $\pi/2$. The slider of the potentiometer R is located in the position for which n = ½ and the regulatory element is a resistor R_3. In the second quasi-balance state the phase angle between V_{DC} and V_{CB} also equals $\pi/2$. The control element is the potentiometer R. In the second quasi-balance state the n parameter is read and then the relationship for the determination of the measured quality factor Q_C is:

$$Q_C = \frac{\sqrt{1-2n}}{n}. \quad (18)$$

Based on the analysis of the bridge in Figure 5 it is possible to build a non-bridge structure, performing the same operations on the current and voltage signals of the tested impedance. The procedure of deriving a non–bridge circuit has been presented in [9]. The non-bridge circuit has the structure shown in Figure 6. This circuit processes the measurement signals according to the principle of operation of the bridge from Figure 5.

The selected signals are phase shifts between w_{11} and w_{12} signals and w_{21} and w_{22} signals. It can easily be implemented as a virtual instrument.

Figure 7 shows a view of the prototype of the quality factor meter built according to the previously described

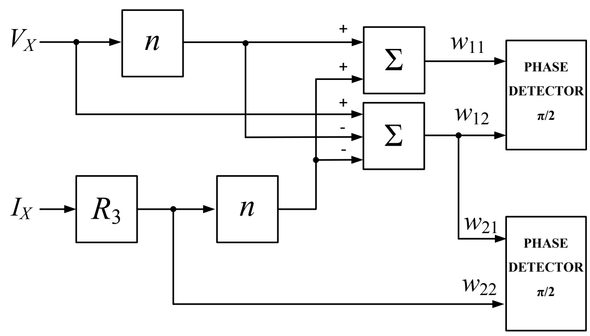

Figure 6. Block diagram of a quasi-balanced circuit with dual quasi-balancing.

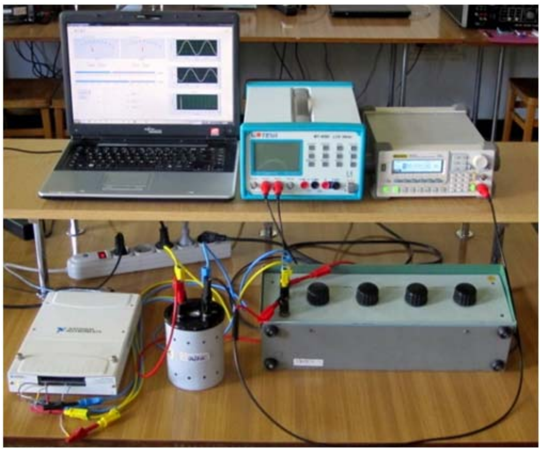

Figure 7. View of the prototype of the quality factor meter realized as the quasi-balanced circuit with dual quasi-balancing.

concept.

A coil under test was powered from the Rigol DG1022 DDS generator. The current of the object was converted to a voltage across the 1 kΩ standard resistor with accuracy class 0.01. The voltage of the object and the voltage proportional to its current were connected to the 16-bit DAQ NI USB-6251 [10].

The LabVIEW 2011 software package was used to build the virtual instrument [10]. The diagram of the virtual instrument is shown in Figure 8 and its front panel in Figure 9.

The first tests were done as a simulation. The simulations confirmed the usefulness of the system to measure the quality factor of inductors.

Tests of the circuit were performed for the reference inductance in the range from 0.05 H to 1 H at a frequency of 100 Hz. The results were compared with the results obtained from the meter Motech MIC-4090, for which the manufacturer declares a quality factor accuracy of 0.5%. The exemplary dependence of the errors versus the measured quality factor is shown in Figure 10.

5. CONCLUSIONS

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

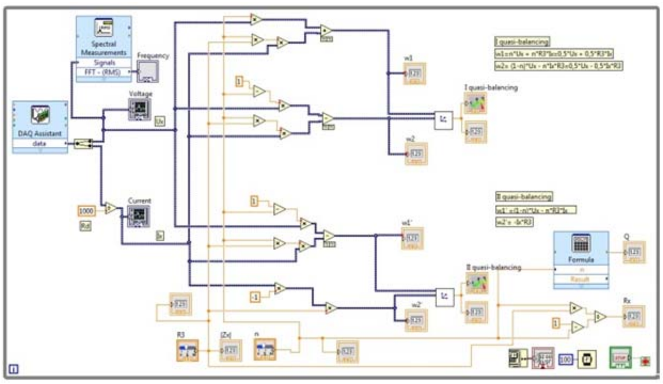

Figure 8. Block diagram of a quasi-balanced circuit with dual quasi-balancing.

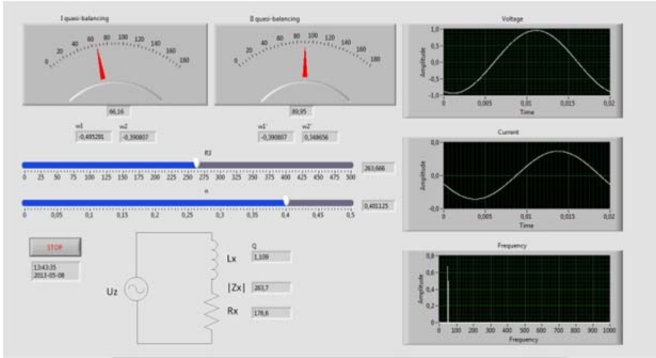

Figure 9. Front panel of a quasi-balanced meter with dual quasi-balancing.

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 an insignificant influence of the circuit conversion characteristic shape was observed (Figure 4). Also the selection of the points on this characteristic had neglible influence on the accuracy of achieving the quasi–equilibrium state.

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

The theory and implementation of a non-bridge quasi-balanced measuring circuit with dual quasi-balancing, designed for measurements of the quality factor have been presented as well. The main advantage of the circuit is maximum convergence and a simple measuring process. It requires two independent controls. The circuit described above has been implemented as a virtual system, using the LabView package. Simulation tests and tests carried out on real objects confirmed the usefulness of the proposed

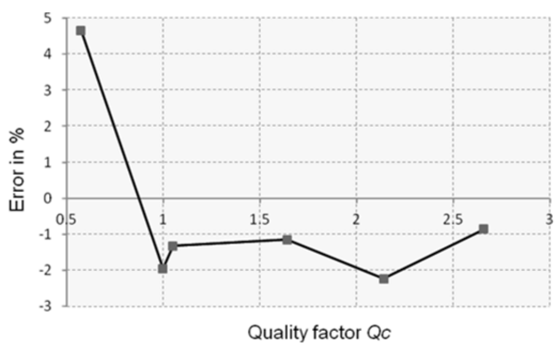

Figure 10. Error vs. the measured quality factor.

solutions. The level of errors reaches 5%, but the study was focused on the prototype, which will be even improved.

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