Improving a parameter determination method for multi-element bi-poles used in digital dielcometric hygrometer of agricultural products

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Abstract. The article examines the possibility of determining the parameters of multi-element bi-pole using the author's method of aggregate measurements. Mathematical modeling of measuring circuits is performed, the random error of the results of measurements of parameters of a four-element bi-pole by the Monte Carlo method is estimated and determination result of the methodological and random components of the measurement errors of parameters of circuit elements is presented. The relevance of the application of the combined method of research with measurements in steady-state and transient modes for determining the moisture content of agricultural products is justified. The reduction of the resulting methodological error and the possibility of reducing the number of analog-to-digital transformations without deteriorating the target accuracy are proved.

1. Introduction

The existing methods for determining the parameters of multi-element bi-poles (MB) are usually divided into direct methods based on the study of the reaction of the measuring circuit (MC) to the external influence of a complex form and balancing methods based on the process of comparing the measured value with the measure [1-4].

The positive and negative sides of these methods were considered in works [5-7] in which the main disadvantages were noted. This disadvantages indicate the relevance of the task of improving existing methods and developing new methods for determining the humidity of agricultural products with improved characteristics of accuracy, speed and versatility.

One of these methods is a method for determining the parameters of multi-element bi-poles that the authors of this article has previously developed [8, 9]. It is based on a sequential two-stage measurement of informative parameters in steady state and transient modes when a DC voltage surge is applied to the input of the measuring circuit.

The most important metrological task in creating new and improving known methods for measuring physical quantities is the determination the effect of the error of the initial data on the measurement result.

With regard to this task in the present work, it is necessary to establish the influence of voltage measurement error in the measurement circuit on the parameter calculation error of the multi-element bi-poles equivalent circuit.
2. Results

The estimation of random error of the results of calculation of parameters of four-element bi-pole depending on the error counts of the voltage at the output of the measuring circuit is carried out for given nominal values of the equivalent circuit parameters of four-element bi-pole and support elements $C_{1x} = 2000 \text{ pF}$, $C_{2x} = 1500 \text{ pF}$, $R_{1x} = 1 \text{ MOhm}$, $R_{2x} = 150 \text{ kOhm}$, $U_0 = -2 \text{ V}$, $C_0 = 200 \text{ pF}$, $R_0 = 100 \text{ kOhm}$.

The mathematical model of the proposed measurement method in MathCAD has the following form:

\[ U_r := U_0 \frac{R_{1x}}{R_0 + R_{1x}} \]

\[ U_c := U_0 \frac{C_0}{C_0 + C_{1x} + C_{2x}} \]  

\[ -\left( U_0 \frac{U_0 - U_c}{U_c} \right) - \frac{U_0 t_1}{C_0 U_r \left( \frac{R_0}{U_0 - U_r} \right)} + \frac{C_2 U_0 e^{-t_1 \tau}}{C_0} \equiv U_1 \]  

\[ -\left( U_0 \frac{U_0 - U_c}{U_c} \right) - \frac{U_0 t_2}{C_0 U_r \left( \frac{R_0}{U_0 - U_r} \right)} + \frac{C_2 U_0 e^{-t_2 \tau}}{C_0} \equiv U_2 \]

where $U_r$ is the output voltage of the MC; $U_c$ is the output voltage of the MC; $R_0$, $C_0$, $U_0$ are reference values: resistor, capacitor, voltage, respectively; $R_{1x}$, $C_{1x}$, $R_{2x}$, $C_{2x}$ are known nominal parameter values; $U_1$, $U_2$ are known voltage counts at the output of the MC at times $t_1$ and $t_2$, respectively.

Equations (3) – (4) are derived from the voltage function at the output of the MC, which has the form:

\[ u(t) = -\frac{C_2 U_0}{C_0} \left( 1 - e^{-t R_{2x} C_{2x}} \right) - \frac{U_0 t}{C_0 R_{1x}} - \frac{U_0 C_{1x}}{C_0} \]  

\[ u(t) = -\frac{U_0 \left( C_{1x} + C_{2x} \right)}{C_0} - \frac{U_0 t}{C_0 R_{1x}} + \frac{C_{2x} U_0 e^{-t R_{2x} C_{2x}}}{C_0} \]

As noted above, measurements on (1) – (2) are performed at DC in steady state mode, measurements (3) – (4) are performed during the developing transition process in the MC. These measurements are the basis of the proposed method for determining parameters of the four-element replacement circuit of the measuring converter.

It is easy to notice that the system of equations (1) – (4) has an exact analytical solution. Expressing the value $R_{1x}$ from equation (1) and the values $(C_{1x} + C_{2x})$ from equation (2), and substituting them in equation (5) for two counts, we get a system of two equations, i.e. equations (3), (4). We get the following equation by grouping the known and unknown quantities:

\[ \frac{C_{2x} U_0 e^{-t_1 \tau}}{C_0} = U_1 + U_0 \frac{U_0 - U_c}{U_c} \]

where $U_r$ is the output voltage of the MC; $U_c$ is the output voltage of the MC; $R_0$, $C_0$, $U_0$ are reference values: resistor, capacitor, voltage, respectively; $R_{1x}$, $C_{1x}$, $R_{2x}$, $C_{2x}$ are known nominal parameter values; $U_1$, $U_2$ are known voltage counts at the output of the MC at times $t_1$ and $t_2$, respectively.
\[ \frac{C_{2x}U_0}{C_0} \cdot e^{\frac{t_2}{\tau}} = U_2 + U_0 \frac{U_0 - U_c}{U_c} + \frac{U_0^2}{U_c R_0} \frac{U_c R_0}{U_0 - U_r} \] (8)

Substituting the notation, we get:

\[ A = U_1 + U_0 \frac{U_0 - U_c}{U_c} + \frac{U_0^2}{U_c R_0} \frac{U_c R_0}{U_0 - U_r} \] (9)

\[ B = U_2 + U_0 \frac{U_0 - U_c}{U_c} + \frac{U_0^2}{U_c R_0} \frac{U_c R_0}{U_0 - U_r} \] (10)

The solution is given below:

\[ \tau = \frac{AC_0}{B} = \frac{t_2 - t_1}{\ln \frac{A}{B}} \] (11)

\[ C_{2x} = \frac{AC_0}{U_0} \cdot \frac{1}{e^{\frac{t_1}{\tau}}} \] (12)

\[ R_{2x} = \frac{\tau}{C_{2x}} \] (13)

The Monte Carlo method was used to simulate the random error in calculating the parameters of a four-element bi-pole.

To indicate the uniform distribution law of the probability of results of voltage measurements \( U_n, U_c, U_1, U_2 \) the MathCAD function \( \text{runif}(x, a, b) \) is used.

The function \( \text{runif} \) creates a vector of a uniformly distributed random sequence of a given dimension, which equal to the number of implementations of this sequence.

\( A \) and \( b \) parameters define the distribution interval of a random value. To model a random sequence, the number of implementations is assumed \( X=10^6 \).

The built-in MathCAD function \( \text{stdev}(X) \) is used to calculate the standard deviation of desired parameter values of the substitution scheme elements.

The limits of permissible relative random error of the voltage measurement results were set in the range \( \delta U = \pm 0.005 \% \) to \( \delta U = \pm 0.05 \% \).

As an example, the simulation results are shown below in the following forms:

- histograms of the probability distribution density of the results of calculating the values of the desired values \( R_{1x}, C_{1x}, R_{2x}, C_{2x} \);
- the value of the standard deviation of the results of the desired values calculations;
- values of the random component of the relative error of the results.
0.2

Figure 1. Histogram of the probability distribution density of the results of calculating the $C_{1x}$ capacitance with a voltage measurement error $\delta U = \pm 0.01 \%$; standard deviation $C_{1x} = 4.29$ pF; random component of the relative error $\delta C_{1x} = \pm 0.143 \%$

Figure 2. Histogram of the probability distribution density of the results of calculating the $C_{2x}$ capacitance with a voltage measurement error $\delta U = \pm 0.01 \%$; standard deviation $C_{2x} = 4.015$ pF; random component of the relative error $\delta C_{1x} = \pm 0.065 \%$

Figure 3. Histogram of the PDD of the results of calculating the resistance $R_{1x}$ with an error in voltage measurement $\delta U = \pm 0.01 \%$; standard deviation $R_{1x} = 138.671$ Ohm; random component of the relative error $\delta R_{1x} = \pm 0.092 \%$

Figure 4. Histogram of the PDD of the results of calculating the resistance $R_{2x}$ with an error in voltage measurement $\delta U = \pm 0.01 \%$; standard deviation $R_{2x} = 16.181$ Ohm; random component of the relative error $\delta R_{2x} = \pm 0.135 \%$

In the example the value of the voltage measurement error equal to $\delta U = \pm 0.01 \%$ is taken in order to correctly compare the proposed method of calculating the desired parameters with the known method given in the article [10].

Figure 5. Graphs of the dependence of the relative error random component of the desired circuit parameter calculations on random error of voltage measurements: a – a previously-known method, b – the proposed method
The proposed method allows identifying four main parameters of equivalent circuit, which characterizes the research object:
- $R_{1x}$ is through active resistance which characterizes the through active conductivity of the medium;
- $C_{1x}$ is capacitance which characterizes instantaneous polarization depending on the electrophysical and natural properties of the medium;
- $R_{2x}$ is active relaxation resistance, which characterizes the relaxation conductivity of the medium that depends on the salt content and the presence of impurities in the medium;
- $C_{2x}$ the capacity which characterizes relaxation polarization and that is the main informative parameter, because it has a direct dependence on the number of water particles and their sizes, i.e. on the humidity of the controlled medium.

3. Conclusions
1. Analysis of the study results shows that in comparison with the known method the proposed method has a significant advantage in terms of the minimum random component of the result error of calculating values of the desired values $R_{1x}$, $C_{1x}$, $R_{2x}$, $C_{2x}$.
2. It is appropriate to conduct output voltage counts at a time interval commensurate with the time constant of the measuring circuit to achieve maximum accuracy of dynamic measurements.
3. When using the proposed method of desired quantity calculation, the possibility of carrying out measurements of counts of the measuring circuit output voltage with a relative error $\delta U$ does not exceed 0.01 %. It gives the possibility to reduce parity of analog-to-digital converters to 14 bit.
4. The proposed method has wide possibilities for application in various industries, agriculture and construction because determining the humidity of materials is the main production task that affects the quality of products, allowing reducing energy consumption during storage and processing and its cost, preserving technical and nutritional values and useful consumer properties.
5. The considered method makes it possible to determine not only the humidity of the studied agricultural products, but also the presence of organic, mineral and extraneous matter. It is of great importance in determining the quality class, variety and type of the object.

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