Agricultural products moisture content measurement error estimation with the use of a four-element capacitive sensor model

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Abstract. The article is devoted to the consideration of agricultural products moisture content measurement error estimation with the use of a four-element capacitive sensor model by means of the authors’ method for multi-element bipoles parameters determining. The results of the specified method mathematical modeling and experimental investigations, which confirm measurement accuracy increasing by reducing the resultant method error in comparison with known methods, are presented in the article.

1. Introduction
The most important quality indicator of agricultural products is moisture content, the determination of which involves the use of capacitive parametric sensors (CS), presented in the form of dual-, three- or more element sensor models consisting of series and parallel R, L, C circuits. Such models in turn are considered as passive multi-element bipoles (BP), the determination of the informative parameters of which allows to evaluate physical and chemical, technological, and other non-electrical properties of objects under research.
The studies in [1] show that the four-element capacitive sensor model presented in Figure 1 is preferable for agricultural products, and the model consists of the following components: through resistance $R_{1x}$, characterizing the through conductivity of the studied object; capacitance $C_{1x}$, which characterizes the deformation polarization describing the electrophysical properties of the object; relaxation resistance $R_{2x}$, characterizing the relaxation conductivity losses which depend on the salt content and the presence of impurities in the object; capacitance $C_{2x}$, characterizing relaxation polarization which is the main informative parameter because it depends directly on the number of dispersed water particles and their sizes, affecting the moisture content of the studied object.

2. Methods and materials

Existing methods and techniques for determining informative parameters have low accuracy, complexity in implementing [2–4], thus leading to the need to develop more advanced algorithms for moisture content measuring, which will be devoid of the specified disadvantages. One of the ways forward for solving this problem is developed by the authors of this article method for multi-element bipole parameters determining [5], based on a sequential two-stage measurement of informative parameters in steady and transient modes when a direct current spike is applied to the input of the measuring circuit.

3. Results and discussions

The testing of this method was carried out on the measuring setup shown in figure 2, which has been implemented on the basis of the Microchip ATmega328P AVR microcontroller. The information output and control are organized by means of a two-line liquid-crystal display WH 1602B YHI EM manufactured by Winstar Display Co., Ltd.

Figure 2. Measurement setup scheme.

To understand the presented setup operation algorithm, the table below provides the input-output ports states during the measurements where Hi-Z is the high-resistance state, GND is the ground, the output is the ports in the output mode (signal supply), the input (ADC) is the ports in the input mode (signal reception).
Table 1. Input-output ports states table.

| Mode   | Measurement $R_{1x}$ | Measurement $C_{1x}+C_{2x}$ | Measurement $R_{2x}$, $C_{2x}$ |
|--------|----------------------|-------------------------------|---------------------------------|
| PAØ    | Hi-Z                 | Hi-Z                          | Output                          |
| PA1    | Hi-Z                 | Output                         | Hi-Z                            |
| PA2    | Output               | Hi-Z                          | Hi-Z                            |
| PA3    | Input (ADC)          | Input (ADC)                   | Hi-Z                            |
| PA4    | GND                  | GND                           | Hi-Z                            |
| PA5    | Hi-Z                 | Hi-Z                          | Input (ADC)                     |

At the first measurement stage, the through resistance $R_{1x}$ and the sum of the capacitances $C_{1x}+C_{2x}$ are determined at the steady state. To do this, input/output PA4 is switched to a zero potential mode and presents a signal ground for the circuit, and inputs/outputs PAØ, PA1, PA5 are switched to the high-resistance state (Hi-Z), which completely excludes their influence on the measuring circuit. Then, an applied to the output PA2 (Output) voltage spike of a certain value $E_0$, passing through the measuring circuit, which includes the reference resistor $R_0$ and the object under study, enters the input PA3 (Input ADC) which measures the voltage $U_j$ value. Since the reference resistor $R_0$ and the object under study in the form of a multi-element bipole comprise a resistive voltage divider, the through resistance $R_{1x}$ is calculated by the formula:

$$R_{1x} = \frac{U_j R_0}{E_0 - U_j}$$  \hspace{1cm} (1)

After the capacitors are discharged and the potentials are removed from the measuring circuit, the sum of the capacitances $C_{1x}+C_{2x}$ is measured, which is accompanied by the transition of the inputs/outputs PAØ, PA2 and PA5 to the high-impedance state, while the input/output PA4 remains at ground. Then, through the output PA1, the second voltage spike $E_0$ is applied, while the reference capacitor $C_{0l}$ and the equivalent circuit capacitor $C_{1x}$ comprise a capacitive voltage divider. At the input PA3, the voltage $U_j$ is measured and the total value of the capacitors $C_{1x}+C_{2x}$ is calculated:

$$C_{1x} + C_{2x} = C_{0l} \frac{E_0 - U_j}{U_j}$$  \hspace{1cm} (2)

Then, the microcontroller proceeds to the second measurement stage, which allows to determine the relaxation resistance $R_{2x}$, and the relaxation capacitance $C_{2x}$. To do this, the inputs/outputs PA1 – PA4 are transferred to a high-resistance state, after which the next voltage spike $E_0$ is applied through the input/output PAØ and passes through the measuring circuit, which includes the operational instrumentation amplifier (OA) 2 INA128P, in the feedback of which the reference capacitor $C_{0l}$ and the object under study in the form of a multi-element bipole are connected. During the developing transient process, the instantaneous voltage values $u(t_1)$ and $u(t_2)$ are measured at fixed points of time at the input PA5:

$$u_x(t_1) = \frac{E_0 C_{1x}}{C_{0l}} - \frac{E_0 C_{2x}}{C_{0l}} - \frac{E_0 t_1}{C_{0l} R_{1x}} + \frac{E_0 C_{2x}}{C_{0l}} \cdot e^{-\frac{t_1}{\tau}}$$  \hspace{1cm} (3)

$$u_x(t_2) = -\frac{E_0 C_{1x}}{C_{0l}} - \frac{E_0 C_{2x}}{C_{0l}} - \frac{E_0 t_2}{C_{0l} R_{1x}} + \frac{E_0 C_{2x}}{C_{0l}} \cdot e^{-\frac{t_2}{\tau}}$$

Based on the obtained values, the final calculation of the unknown values – the relaxation capacitance $C_{2x}$ and the relaxation resistance $R_{2x}$, characterizing the moisture content and the presence of impurities in the test substance, respectively – is performed as follows:

$$C_{2x} = \frac{u_{1\text{rated}} c_{02} \tau}{E_0 e^{-\frac{\tau}{\tau}}}$$  \hspace{1cm} (4)
\[ R_{2x} = \frac{\tau}{C_{2x}} \]  

(5)

where \( U_{1\text{rated}} \) is the rated voltage, V;
\( \tau \) is the time constant, s.

Performing measurements in two stages allows to increase the accuracy of measurements by reducing the resultant method error [6-8]. The estimation of the method error of the four-element CS model equivalent circuit parameters measurement results with the use of a known method and the proposed one was carried out by mathematical modeling in the MathCAD environment.

The equivalent circuit parameters are determined by solving a system of equations that connect the obtained samples and the parameters of the measuring circuit output voltage components taking into account the functional relationships between them and the equivalent circuit parameters. This measurement method is commonly called aggregate measurements [9].

The system of equations for the known measurement method modeling in the MathCAD environment is as follows:

\[
\begin{align*}
- \left( U_0 \cdot C_1 \right) - \left( \frac{U_0}{C_0} \cdot t_{i_1} \right) - \frac{C_1 U_0}{C_0} \left( 1 - e^{-\frac{t_{i_1}}{R C_2}} \right) &= u_{i_1} \\
- \left( U_0 \cdot C_1 \right) - \left( \frac{U_0}{C_0} \cdot t_{i_2} \right) - \frac{C_1 U_0}{C_0} \left( 1 - e^{-\frac{t_{i_2}}{R C_2}} \right) &= u_{i_2} \\
- \left( U_0 \cdot C_1 \right) - \left( \frac{U_0}{C_0} \cdot t_{i_3} \right) - \frac{C_1 U_0}{C_0} \left( 1 - e^{-\frac{t_{i_3}}{R C_2}} \right) &= u_{i_3} \\
- \left( U_0 \cdot C_1 \right) - \left( \frac{U_0}{C_0} \cdot t_{i_4} \right) - \frac{C_1 U_0}{C_0} \left( 1 - e^{-\frac{t_{i_4}}{R C_2}} \right) &= u_{i_4}
\end{align*}
\]  

(6)

where \( U_0 \) is the reference voltage, V;
\( C_0 \) is the capacitance of the reference capacitor, F;
\( C_1, R_1, C_2, R_2 \) are the desired quantities, F, Ohm;
\( t_{i_1}, t_{i_2}, t_{i_3}, t_{i_4} \) are the time instants of the taken samples, s;
u_{i_1}, u_{i_2}, u_{i_3}, u_{i_4} \) are the voltage values, corresponding to the sampling times, at the measuring circuit output, V.

The system of equations for modeling the proposed measurement method in the MathCAD environment is presented below:

\[
\begin{align*}
- \left( U_0 \cdot \frac{U_0 - uC}{uC} \right) - \left( \frac{U_0}{C_0} \cdot t_{i_1} \right) + \frac{C_1 U_0}{C_0} \cdot e^{-\frac{t_{i_1}}{R C_2}} &= u_{i_1} \\
- \left( U_0 \cdot \frac{U_0 - uC}{uC} \right) - \left( \frac{U_0}{C_0} \cdot t_{i_2} \right) + \frac{C_1 U_0}{C_0} \cdot e^{-\frac{t_{i_2}}{R C_2}} &= u_{i_2}
\end{align*}
\]  

(7)

where \( U_0 \) is the reference voltage, V;
\( C_0 \) is the capacitance of the reference capacitor, F;
\( C_2, R_2 \) are the desired quantities, F, Ohm;
\( t_{i_1}, t_{i_2} \) are the time instants of the taken samples, s;
u_{i_1}, u_{i_2} \) are the voltage values, corresponding to the sampling times, at the measuring circuit output, V;
\( R_1 \) is the known quantity equal to the resistance \( R_{1x} \) from formula (1);
u\( uC \) is the known quantity equal to the voltage \( U_i \) from formula (2).
Note that the first component in the system of equations (7) was obtained by substituting equation (2) into the system of equations (6) provided that $C_0$ and $C_{01}$ values are equal. The system of equations (7) corresponds to two voltage samplings conducting at the measuring circuit output at a time interval not exceeding the transient process completion time.

For mathematical models of the known method and the proposed one for determining the parameters of the equivalent circuits of the measuring circuit, the study of the dependence of the relative method error in calculating the desired quantities on the relative sampling time, which is the ratio of the current sampling time to the measurement circuit time constant $\tau$, was made. The modeling was carried out at the interval from 0 to $3\tau$, the sampling resolution was 0.01$\tau$, the intervals between the samples were equal. That is why, in models, the sampling times and their corresponding voltages are represented with the changing $i$ indices.

The following values were chosen as the rating values of the parameters of the equivalent circuits and support elements: $C_1 = 2000$ pF, $C_2 = 1500$ pF, $R_1 = 1$ M$\Omega$, $R_2 = 150$ k$\Omega$, $U_0 = -2$ V, $C_0 = 200$ pF, $R_0 = 100$ k$\Omega$. The rating values are selected for reasons of practical relevance with regard to the used experimental setup presented in figure 2.

Relative method errors of the main informative parameters are determined according to the following formulae:

$$\delta C_{2i} = \left| \frac{(C_{2i} - C_2)}{C_2} \right| \cdot 100\%$$  \hspace{1cm} (8)

$$\delta R_{2i} = \left| \frac{(R_{2i} - R_2)}{R_2} \right| \cdot 100\%$$  \hspace{1cm} (9)

The results of the modeling are presented in figures 3 – 6.

![Figure 3](image)

**Figure 3.** Graph of capacitance $C_2$ calculating relative method error dependence on the relative sampling time according to the proposed method.
Figure 4. Graph of capacitance $R_2$ calculating relative method error dependence on the relative sampling time according to the proposed method.

Figure 5. Graph of capacitance $C_2$ calculating relative method error dependence on the relative sampling time according to the known method.
The measuring setup calibration was carried out using reference samples of various bulk products with known moisture mass fraction: flour, starch, sugar. The moisture mass fraction was determined according to GOST 9404-88 [10]. Calibration curves in the form of the dependence of the electrical parameters of the products on their moisture content are presented in figure 7. The stable qualitative repetition of the dependence of the electrical parameters of the products on their moisture content is observed in the statistically processed experimental data.
4. Conclusion
1. In order to achieve maximum accuracy of dynamic measurements, it is advisable to conduct output voltages samplings at a time interval commensurate with the time constant of the measuring circuit.
2. The proposed method for measuring the parameters of CS with a four-element equivalent circuit has a significant advantage over the known method under consideration according to the criterion of relative method error due to the reduction of computational procedures while halving the equations system order.
3. The calibration characteristic shows that the most informative parameters in aggregate measurements are $C_1$, $C_2$, and $R_2$, since they have the maximum relative increase in $\Delta C/C$ and $\Delta R/R$ values for the moisture content measurement range.

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