Development and research of an information-measuring system for quality control of agricultural products

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Abstract. The article presents the result of an information-measuring system development for quality control of agricultural products based on the assessment of their moisture content, chemical composition, presence of organic and mineral impurities. It also substantiates the relevance of the use of such systems by the agro-industrial complex enterprises. The proposed information-measuring system is based on the author's dielcometric method for determining the electrophysical parameters of capacitive sensors, the principle of which is to decompose the measuring process into two stages. The study of this method was carried out using simulation modeling in the SimInTech environment, while custom operational amplifier blocks and sample-and-hold circuit were built. As a result of the operational amplifier model research, graphs of the dependency of the output voltage on the change in the integration time constant and amplification gain were plotted, on the basis of which the optimal values of these quantities were selected. Studies of the constructed models of the first and second measurement stages using the proposed method showed a high accuracy in determining the electrophysical parameters of capacitive sensors filled with agricultural products, with a relative error not exceeding ±0.2%.

1 Introduction

The most important indicators of the agricultural products quality are moisture and the presence of impurities which have a significant impact on their safety, nutritional and consumer value, suitability for storage and processing, cost, etc. The presence of moisture in products leads to the acceleration of negative physicochemical and biological processes, such as germination, self-heating, respiration, the development of microorganisms, insects, mites, etc. [1].

The respiration of agricultural products is associated with the dissimilation process of complex organic substances to simpler ones - water, carbon dioxide and ammonia, the intensity of which directly depends on the initial moisture content and material contamination. For example, with a wheat moisture content of 15.5% or more, 0.05–0.2% of dry matter is lost per day, and the release of carbon dioxide CO_2 can reach 18 mg per 100 g of the product, which is associated with aerobic respiration, leading to an increase in heat release up to 16.7 MW/kg and self-heating material. This, in turn, creates conditions for the appearance of free moisture, which will sharply accelerate the microorganisms' development (bacteria, fungi, mold, etc.), insects and mites, which reduce the quality and change the chemical composition of products [2].

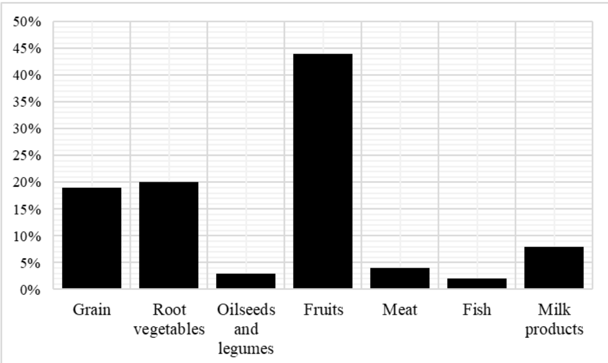

Fig. 1. The share of global losses of agricultural products (% of total losses).

As a result of these processes development, the loss of agricultural products can reach 1.3 billion tons per year (Fig. 1), which is a serious global problem that threatens food security and nutritional satisfaction of the population [3].

One of the ways to reduce losses is the rapid and accurate determination of moisture and impurities in products using modern technical solutions, for example, the information-measuring systems (IMS), which provide the ability to quickly obtain information about the quality of agricultural products and taking measures to bring the indicators to the established standards using technological operations of drying or cleaning [4].

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2 Materials and methods

At the moment, the advance research and development direction of such systems are dielcometric methods for determining the parameters of capacitive sensors (CS), based on indirect measurements of the material electrophysical properties, which make it possible to determine its moisture content, the presence of organic and mineral impurities, chemical composition, etc.

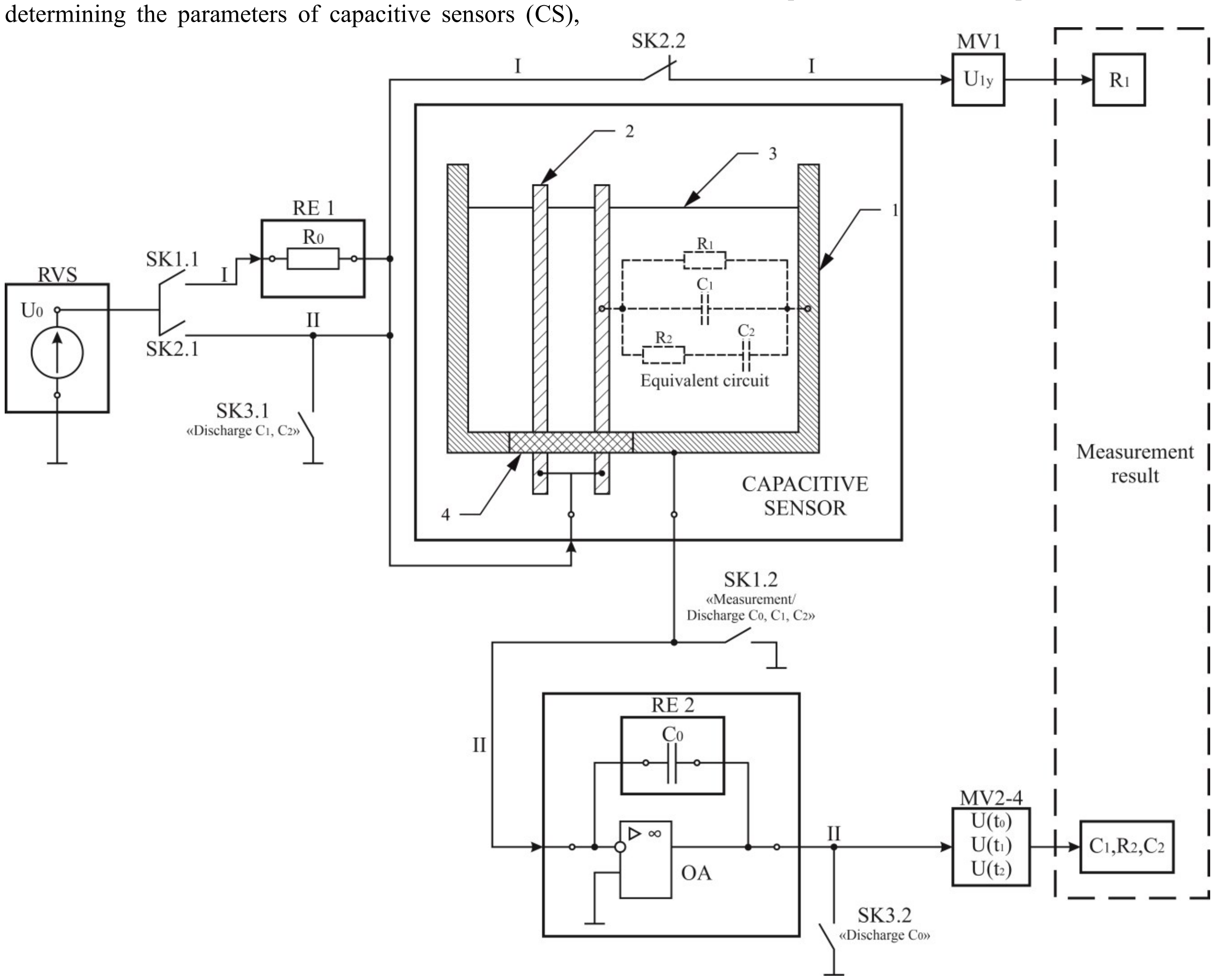

Fig. 2. Block scheme of the method for determining the electrophysical properties of agricultural products using capacitive sensors.

The use of capacitive sensors is due to their design simplicity and versatility in determining moisture and impurities in various agricultural products (wheat, rice, barley, corn, etc.), which provides unlimited opportunities for implementation in various technological processes of agricultural enterprises. For the system being developed, a coaxial capacitive sensor was used (Fig. 2), which is an aluminum container 1 filled with the test product 3 and is one of the electrodes in which internal aluminum rod electrodes 2 are built through a dielectric spacer 4.

Studies of similar capacitive sensors with agricultural materials placed in them in the works of Stuart O. Nelson [5] showed that their properties can be described by a four-element RC equivalent circuit (EC), including through resistance R_1 and capacitance C_1, relaxation resistance R_2 and capacitance C_2, while each of the elements characterizes individual electrophysical properties of the product. R_1 is organic impurities (leaves, weeds, stems, etc.); R_2 is mineral impurities (sand, pebbles, earth, etc.); C_1 is chemical composition (iron, phosphorus, sulfur, etc.); C_2 is the number of water particles and their sizes, i.e., humidity of the controlled environment.

The determination of the indicated properties of the material under study in the developed IMS can be implemented using the author's method [6], based on the decomposition of the measurement process into two stages. The first stage is performed in the steady operating conditions of the measuring circuit (MC) and allows determining the through resistance R_1. The second stage is carried out during a rapidly developing transient process in the MC and makes it possible to determine the rest of the electrophysical properties of the product - C_1, C_2 and R_2.

The block scheme of the proposed author's method is shown in Figure 2 and includes the following designations: RVS is a reference voltage source; RE1-2 is reference elements; SK1.1-SK3.2 are switching keys; OA is an operational amplifier; MV1-4 is a measured value; I-II are measurement stages.

To confirm the operability and relevance of using the proposed method for determining the electrophysical properties of agricultural products based on a capacitive sensor, it was simulated in the modern environment of model-based design SimInTech (Simulation In Technic) [7], which allows the construction and calculations of complex dynamic RC circuits in the real-time mode.

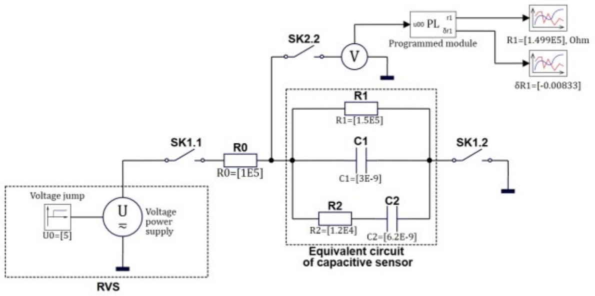

Fig. 3. MC model of the first stage of measurements.

The model of the first stage of measurements I is shown in Figure 3, while the measurement process is performed as follows. RVS, consisting of the standard blocks "Step" and "Controlled voltage source", forms a jump in DC voltage $U_0 = 5$ V, which through the switch SK1.1 and RE1 in the form of a resistor R_0, is supplied to the CS represented by a four-element EC grounded by the SK1.2. As a result of it the resistors R_1 and R_0 form a classic resistive divider, which makes it possible to determine the through resistance R_1 when measuring the voltage U_{1y} at the midpoint through the SK2.2 and the block “Voltmeter” according to the following expression:

$$R_1 = \frac{R_0 U_{1y}}{U_0 - U_{1y}}. \qquad (1)$$

The calculation according to the specified expression is implemented using a programmed module which, based on a programming language similar to C/C ++, allows you to perform calculations of any complexity (Fig. 4).

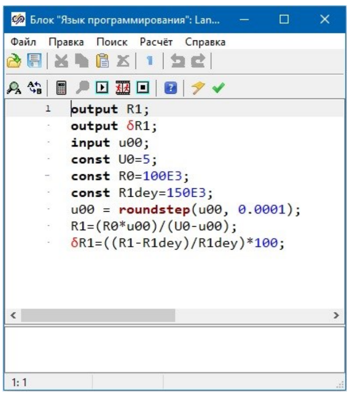

Fig. 4. Programmed module window.

To calculate the model, the values of the MC elements were taken from the known method for determining the parameters of bipolar circuits [8]: $U_0 = 5$ V; $R_0 = 100$ kOhm; $C_0 = 17$ nF; $R_1 = 150$ kOhm; $C_1 = 3$ nF; $R_2 = 12$ kOhm; $C_2 = 6.2$ nF; τ = 74.4 µs. As a result of the calculations we obtained $R_1 = 149$ kOhm with a relative error $\delta R_1 = -0.0083\%$, which indicates the high accuracy of the proposed method at the first stage of measurements.

When building the MC model of the second stage of measurements II, it was necessary to develop an OA model, since such a block is not available in the standard libraries of the SimInTech environment. For this, blocks "Aperiodic link of the 1st order" 1, a comparing device 2, voltmeters with additional ports of mathematical communication for outputting the instantaneous value of the measured voltage 3-4, a voltage supply with the ability to set voltage function through port 5 or, in other words, voltage-controlled voltage source (VCVS) (Fig. 5).

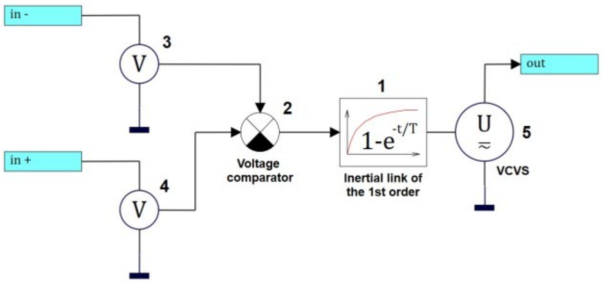

Fig. 5. Operational amplifier model.

The most important task in the construction of the OA model is the choice of the 1st order aperiodic link properties: amplification gain (transfer factor) at a constant input voltage k and time constant τ. The 1st order aperiodic link is the transfer function of the RC low pass filter and the transfer function of the integrator.

The complex amplification gain (transfer factor) can be represented as follows:

$$\dot{K} = \frac{K_0}{1 + j\omega\tau} \qquad (2)$$

where K_0 is the DC amplification gain of the operational amplifier;

ω is the angular frequency of the input signal, rad/s;

τ is the time constant of the low-pass RC filter, corresponding to the integration time constant of the OA.

Based on this, the modulus of the gain transfer function will be equal to:

$$\left|\dot{K}\right| = \frac{K_0}{\sqrt{1+\omega^2\tau^2}} = \frac{K_0}{\sqrt{1+4\pi^2 f^2 \tau^2}}. \qquad (3)$$

Then the dependence of the integration constant τ_{OY} on the frequency of unity gain ω_1 of the OA model at $\left|\dot{K}\right|$ =1:

$$\tau_{OA} = \sqrt{\frac{K_0^{\,2} - 1}{\omega_1}}. \qquad (4)$$

Therefore, the complex amplification gain (transfer factor) according to expression (2) can be represented as:

$$\dot{K} = \frac{K_0}{1 + j\omega \dfrac{K_0}{\omega_1}} = \frac{K_0}{1 + j\omega \dfrac{K_0}{2\pi f_1}}. \qquad (5)$$

To select the correct properties of the 1st order aperiodic link, which describes the frequency characteristics of the operational amplifier, it is extremely important to establish the relationship between the value of the integration time constant τ_{OY} and the time constant of the measuring RC-circuit (MC) τ_{MC} connected to the inverting input of the operational amplifier (Fig. 6). When choosing these properties, one should take into account the transient processes occurring both in the MC and in the operational amplifier model itself, operating in the mode of a summing integrator connected according to an inverse circuit.

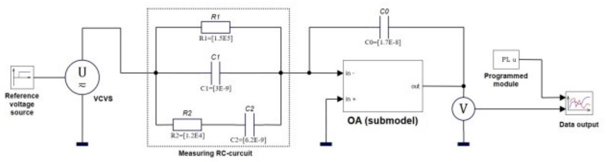

Fig. 6. Scheme for research of the OA model.

It is known that the output voltage at the operational amplifier can be described by the following expression [9]:

$$U_{out}(t) = \frac{U_0 C_1}{C_0} + \frac{U_0}{R_1 C_0} t + \frac{U_0 C_2}{C_0}\left(1 - e^{-\frac{t}{R_2 C_2}}\right) \qquad (6)$$

where U_0 is the reference voltage, V;

C_0 is the standard capacitor, pF;

R_1, R_2 are MC elements in the form of resistances, Ohm;

C_1, C_2 are MC elements in the form of capacitances, pF.

The above expression is obtained on the basis of the conversion function of the inverting amplifier:

$$U_{out}(t) = -U_{input}(t) \cdot \frac{Z_{feedback}}{Z_{input}} \qquad (7)$$

where Z_{feedback} is the feedback resistance OA, Ohm;

Z_{input} is the resistance at the inverting input OA, Ohm.

The input signal is formed by step action on the input circuit and is an aperiodic function. In such a situation, when building an OA model, it is advisable to consider not the frequency characteristics, but the rate of aperiodic function change at the output, which has the following form:

$$\frac{dU_{out}}{dt} = \frac{U_0}{R_1 C_0} + \frac{U_0 C_2}{C_0} \cdot \frac{1}{\tau} e^{-\frac{t}{\tau}}. \qquad (8)$$

From which it follows that the output voltage is inversely proportional to the time constant $\tau = R_2 C_2$. The above reasoning allows us to formulate the following recommendation for choosing the properties of the 1st order aperiodic link of the OA model - for a given practically significant gain $K_0 = 10^5$, the integration time constant τ_{OA} of the model can be determined using the expression:

$$\tau_{OA} = \frac{1}{K_0 \cdot \tau_{MC.calc.}} \qquad (9)$$

where K_0 is the given amplification gain of the OA;

$\tau_{MC\ calc.}$ is the calculated value of the MC time constant, established on the basis of preliminary data on the object of research and refined during the modeling process.

As an example, let's calculate τ_{OA} for the simulated circuit at $K_0 = 10^5$ and time constant $\tau_{MC} = 100$ μs:

$$\tau_{OA} = \frac{1}{10^5 \cdot 10^{-4}} = 0.1\,\text{s}. \qquad (10)$$

With the indicated values, the amplitude-frequency characteristic (AFC) of the OA model will be as follows (Fig. 7). For clarity, the AFC is built on a logarithmic scale, on which the cutoff frequency is marked $\omega_{slice} = \dfrac{1}{\tau}$

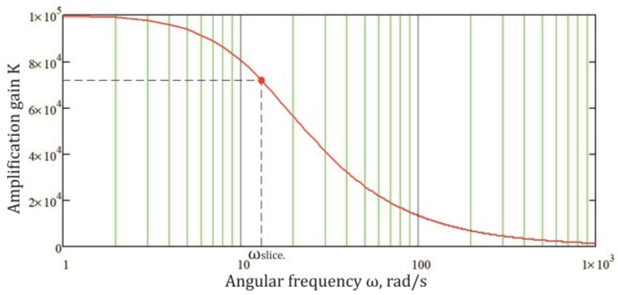

Fig. 7. AFC of the constructed OA model.

In order to confirm the operability of the constructed OA model, we will research the influence of the integration time constant and the amplification gain on the output voltage value $U_{out}(t)$ with the output of data in the form of appropriate graphs with a variation range for $\tau_{OA} = 0.1 \div 9.0$ s and $K = 10^5 \div 10^1$.

To do this, it will be necessary to add four additional circuits in parallel to the circuit for research and set the indicated parameters in the properties of the 1st order aperiodic link (Fig. 8).

As a result of the simulation, it was found that a change in the value of the integration time constant τ_{OA} leads to a change in the output signal $U_{out}(t)$ of the OA model in a wide range (Fig. 9), while the most optimal value is 0.1 s, which is confirmed by the maximum proximity of the constructed curve at the specified value to the ideal design curve obtained as a result of calculations in the programmed module. The constructed curves at values $\tau_{OA} = 0.5 \div 1.0$ s are quite close to the calculated ones and have a deviation not exceeding 0.4 - 0.6 V at each integration step, which is not applicable within the framework of the developed OA model due to the accumulation of additional error, leading to degradation of further calculation results in the MC models. The values τ_{OA} = 5.0÷9.0 s lead to an unacceptable deviation of the curves from the calculated one and will not be applied to the developed OA model.

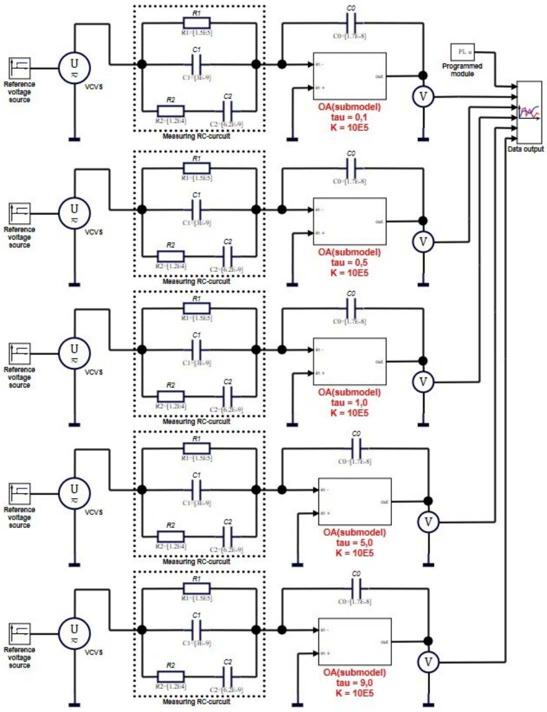

Fig. 8. Scheme of studying the influence of the integration time constant τ_{OA} on the OA model.

By analogy with the circuit in Figure 8, a circuit was built to assess the effect of the amplification gain K on the OA model, as a result of which it was found that changing the value of the gain K has a significant effect on the output voltage U out(t) of the OA model, while in comparison with the previous research, the range of change is more pronounced, and changes in the exponent shape of the transient process have cardinal differences from the calculated curve. The optimal value of the amplification gain K for the developed OA model is 10^5, which is confirmed by the superposition of the curve with this gain and the calculated curve. Invalid gain values are 10^4÷10^1, as evidenced by the deviations of the output voltage values from the ideal curve in the range from 0.45 to 2.5 V, while the last two curves have a linear voltage change, which does not completely correspond to the waveform of the output signal on the OA.

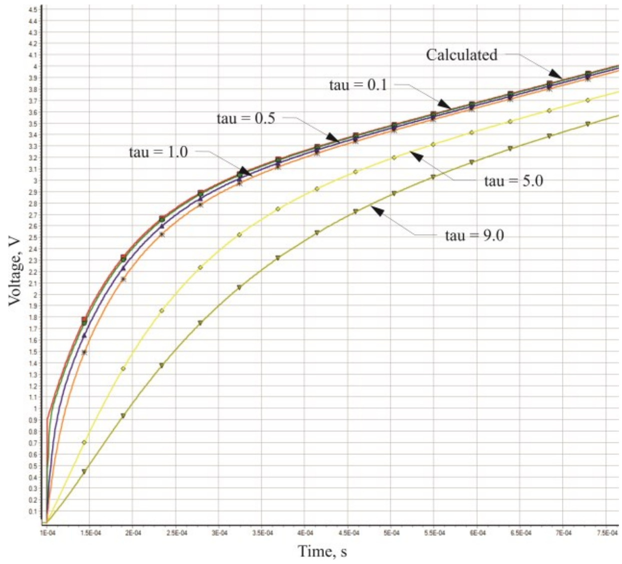

Fig. 9. Set of curves in the study of τ_{OA} influence on the OA model.

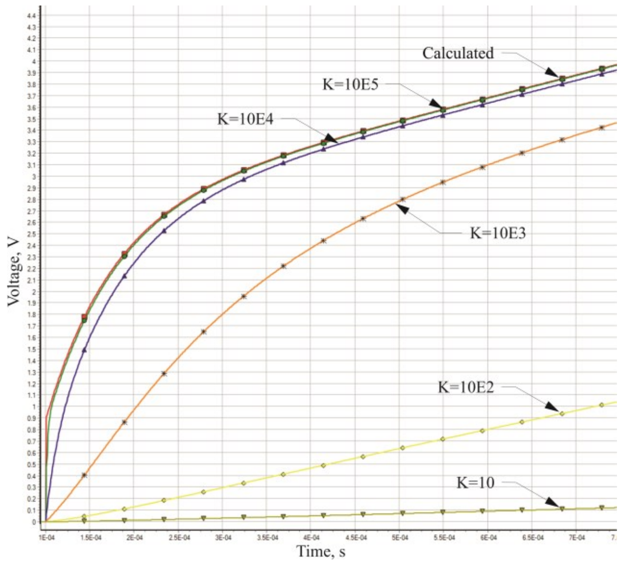

Fig. 10. Set of curves in the study of K influence on the OA model.

After confirming the performance and selecting the parameters of the OA model (Fig. 5), it was transferred to the constructed MC model of the second stage of measurements II according to the proposed method for determining the electrophysical parameters of the CS in the form of a submodel (Fig. 11).

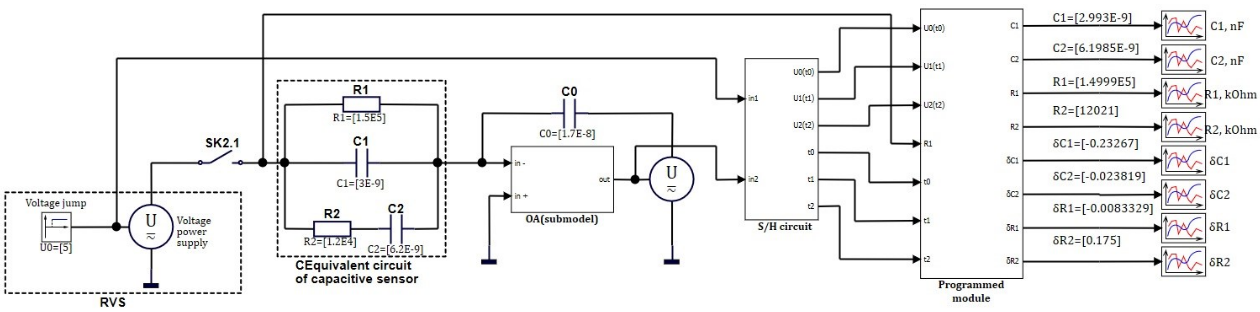

Fig. 11. MC model of the second stage of measurements II.

To obtain accurate time readings, signal sampling and accurate voltage values $U(t_0)$, $U(t_1)$, $U(t_2)$ during the developing transient process, the MC model implements a sample-and-hold circuit (S/H circuit), which is built using blocks «Impulse», «Turn-on delay» and «Storing the signal value», while similarly to the previous cases, the S/H circuit is combined into a separate submodel.

The measurement process at the second stage is as follows: a DC voltage jump is supplied from the RVS, which, through the SK2.1 goes to the CS connected to the inverting input of the OA, the negative feedback of which is implemented by the RE2 in the form of the capacitor C_0, after which the signal is sent to the S/H circuit, performing voltage readings $U(t_0)$, $U(t_1)$ and $U(t_2)$ at fixed times and transferring them to a programmed module that performs the calculation based on the following system of equations:

$$\begin{cases} U(t_0) = A_0 + A_1 t_0 + A_3\left(1 - e^{-\frac{t_0}{\tau}}\right) \\ U(t_1) = A_0 + A_1 t_1 + A_3\left(1 - e^{-\frac{t_1}{\tau}}\right) \\ U(t_2) = A_0 + A_1 t_2 + A_3\left(1 - e^{-\frac{t_2}{\tau}}\right) \end{cases} \tag{11}$$

The solution of this equations system, taking into account the through resistance R_1 obtained at the first stage, allows us to establish the ratios of the coefficients A_0, A_1, A_3 and the time constant τ:

$$A_0 = U(t_0) \tag{12}$$

$$A_1 = \frac{U_0}{R_1 C_0} \tag{13}$$

$$A_3 = \frac{\left(U(t_1) - A_0 - A_1 t_1\right)^2}{2U(t_1) - A_0 - U(t_2)} \tag{14}$$

$$\tau = \frac{t_1}{\ln\left(\dfrac{U(t_1) - A_0 - A_1 t_1}{U(t_2) - U(t_1) - A_1 t_1}\right)} . \tag{15}$$

Based on these parameters, the search values of C_1, C_2, R_2 of the studied CS, represented by a four-element EC, can be found using the following expressions:

$$C_1 = \frac{A_0 C_0}{U_0} \tag{16}$$

$$C_2 = \frac{A_3 C_0}{U_0} \tag{17}$$

$$R_2 = \frac{\tau}{C_2} . \tag{18}$$

3 Results and discussion

The calculation results of the MC model of the second measurements stage in the programmed module were (Fig. 11): C_1 = 2.993 nF; C_2 = 6.198 nF; R_2 = 12.021 kOhm. In this case, the relative error was: $\delta C_1 = \pm 0.232\%$; $\delta C_2 = \pm 0.023\%$; $\delta R_2 = \pm 0.175\%$. The positive results of modeling the proposed method in the SimInTech environment allow us to conclude that it is appropriate to use it in the developed quality control system for agricultural products based on the determination of their moisture content and impurities.

In this regard, the next stage in the development of IMS was the construction of its functional diagram (Fig. 12) in accordance with the known requirements for such systems [10], the operating principle of which is as follows. In one container of the CS we placed agricultural product with unknown moisture content W_x and the amount of impurities AdS_x, acting as a sample or object of study. The same product is placed in another container, pre-dried to the set value W_0 and cleaned of impurities AdS_0, which is a standard or measure of comparison. They, according to a given method determination of the electrophysical parameters of the CS, are connected to the measuring circuits (MC) 1-2, which include MC of the first and second stages of measurements with reference elements in the form of a resistor R_0 and a capacitor C_0. As a result of it, the parameters R_{1x}, C_{1x}, R_{2x} and C_{2x} of the research object are determined and R_{10}, C_{10}, R_{20} and C_{20} of the standard, which enter the comparison links in the form of comparators, where the input signals are compared and their ratio is established. They are transmitted through data links R_1, C_1, R_2 and C_2 to the data analysis unit, which performs the final calculations of product humidity $W_{res.}$ and impurities AdS_{res} based on the information received from the comparators and the calibration characteristics recorded in the long-term memory ROM.

Such IMS scheme makes it possible to further improve the accuracy of determining the product quality indicators by comparing with the measure, as well as reducing constant systematic and multiplicative errors. However, in real conditions of agricultural objects, the calibration characteristics stored in the system memory will act as a standard.

As a «Data analysis» block in the proposed system, it is recommended to use modern AVR microcontrollers. They have versatility, the required speed, built-in analog-to-digital converters (ADC), digital-to-analog converters (DAC), timers, a sufficient number of input / output ports for control switching in the MC, low power consumption, large amount of RAM and Flash memory, easy programming and customization flexibility.

4 Conclusion

Thus, the proposed quality control system for agricultural products has improved accuracy characteristics, due to the use of an improved method for determining the electrophysical parameters of CS with a low relative error of measurement results, not exceeding

±0.2% and confirmed by modeling in the SimInTech environment. And it also meets modern requirements versatility and speed, due to the use of a simple hardware-software implementation based on high-speed AVR microcontrollers, operational amplifiers, comparators and analog-to-digital converters.

The use of this IMS will allow agricultural enterprises to minimize losses by reducing the response time to product quality deviations such as excessive moisture, an increased amount of organic and mineral impurities, chemical composition. At the same time, due to the simplicity of the components design used in the system, in particular the CS, it can be concluded that there is a great potential for its implementation in the technological processes of harvesting, transporting, processing and storing agricultural products.

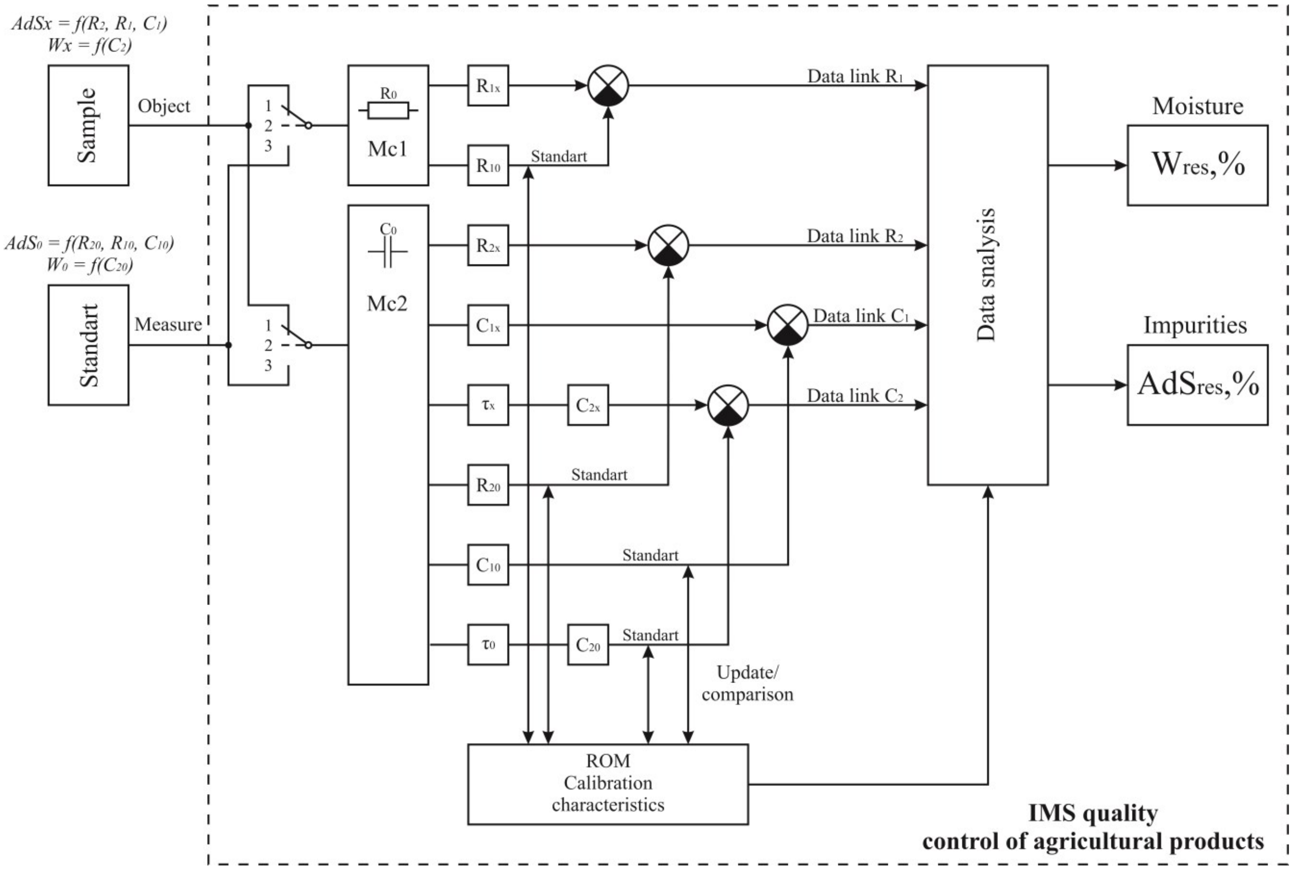

Fig. 12. Functional diagram of IMS quality control of agricultural products.

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