In this case, the electric field spreads at the distant edges of the guard electrodes that provides highly uniform longitudinal electric field in the measurement zone.

In [13], it is shown that guard electrodes with a length of 0.5R and the gap of (1...3) mm provide minimum dependence of the capacitance measurement result on the impact of the wire design parameters, insulation properties and changes in water conductivity.

III. BLOCK DIAGRAM FOR CAP-10

Fig. 5 shows the block diagram for CAP-10 which consists of alternating $U_m \sin \omega t$ voltage generator 1, ECMT 2, an analogue conversion unit 6, adapter 7, digital processing unit 8, and visualization unit 9. The ECMT output signal is current I_x, whose amplitude is proportional to the measured capacitance of the tested wire. This signal is applied to input analogue conversion unit 6, which includes current transformer (CT) 3, current-to-voltage converter (CVC) 4 and amplitude-phase detector (APD) 5.

CT is used for galvanic isolation of the electrode measuring circuit and the signal analogue conversion circuit. The CT output current I_x is applied to CVC, where it is converted into voltage, and then to the APD input, in which the real and imaginary parts of the signal measurement information are differentiated. The APD reference signal is the voltage of generator 1.

The APD output voltages (Re U и Im U) proportional to the amplitude values of the complex parts of the current in the measuring electrode circuit are applied to adapter inputs 7.

The adapter is a data acquisition board which is used as a USB3000 module, a universal high-speed eight-channel ADC. The adapter converts the analogue signal into a digital code and transmits it to the personal computer (PC). Digital processing unit 8 and visualization unit 9 are implemented on PC using LabView 8.5.

Digital processing unit 8 performs filtering, measurement data averaging within 1 second and digital processing. Visualization block unit 9 provides display of the measurement results in the form convenient for an operator [14].

IV. ALGORITHM FOR CONVERSION OF THE MEASURING SIGNAL

The algorithm of the ECMT output signal conversion is determined based on experimental studies. For the experiment, we used the ECMT with the basic design parameters chosen through computer simulation [13]. These parameters are as follows:

- the length of the measuring electrode is 200 mm;
- the length of the guard electrodes is 40 mm;
- the inner diameter of the electrodes is 20 mm;
- the inner diameter of the housing is 20 mm;
- the gap between the measuring electrode and the guard electrode is 1.5 mm.

The current value I_x (Fig. 1) in the measuring electrode circuit is linearly related to the capacitance per unit length C_w of the tested wire area:

$$C_{\mathrm{w}} = C_0 + k \cdot I_x , \tag{2}$$

where C_0 is a constant component, k is a proportionality factor whose values depend on the amplitude and frequency of voltage generator 7 and ECMT 2 design parameters [13]. Values C_0 and k are experimentally determined during the initial adjustment of the CAP-10.

The factor that affects measuring the wire capacitance is significant dependence of the values C_0 and k on the conductivity of water in the cooling bath.

The water conductivity varies due to changes in the concentration and composition of the salts, acids and bases of the cooling water, as well as changes in water temperature. In [5], [6], it is shown that the wire capacitance significantly depends on the electrical conductivity of the cooling water.

Without allowance for the actual water conductivity, the measurement error for the capacitance per unit length can reach 20% or more depending on the range of the water electrical conductivity variation.

In the developed device CAP-10, the offset from the impact of changes in water conductivity implies replacing the coefficients C_0 and k in conversion function (2) corresponding to the actual water conductivity (for example, when using

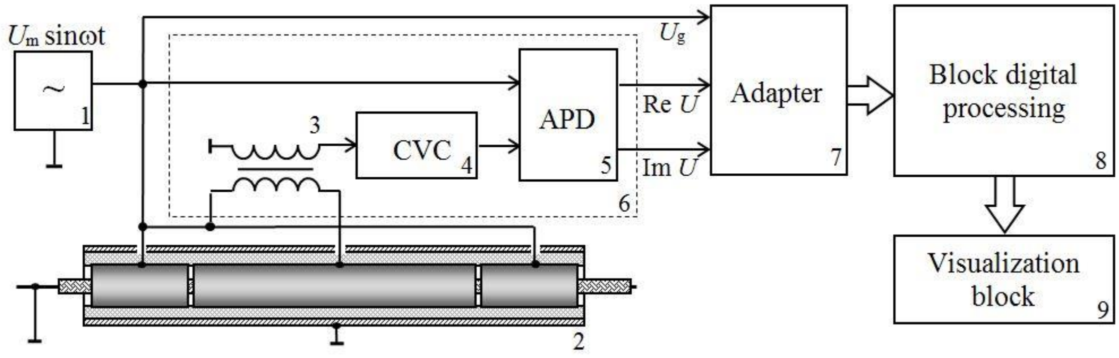


Fig. 5 block diagram of CAP-10: alternating voltage generator (1), ECMT (2), current transformer (3), current-to-voltage converter (4), amplitude-phase detector (5), analogue conversion unit (6), adapter (7), digital processing unit (8), visualization unit (9) distilled water with the saline concentration $\lambda \to 0$) with their corrected values $C_{01}(t)$ and $k_1(t)$.

The coefficients $C_{01}(t)$ and $k_1(t)$ are found based on indirect measurement of water conductivity. The ratio $t = \mathrm{Re}\,\dot{I} / \mathrm{Im}\,\dot{I}$ depends on the actual water conductivity and indicates the change in the phase angle φ between the vector current $\dot{I}_x$ and the imaginary axis of the complex plane. Both of the functions can be approximated by the second order polynomials whose coefficients are found experimentally during the initial adjustment of the CAP-10.

V. TECHNICAL IMPLEMENTATION OF CAP-10

Physical configuration of the CAP-10 is shown in Fig. 6. The CAP-10 components are ECMT, an analogue conversion unit, a USB3000 module and a personal computer (laptop).

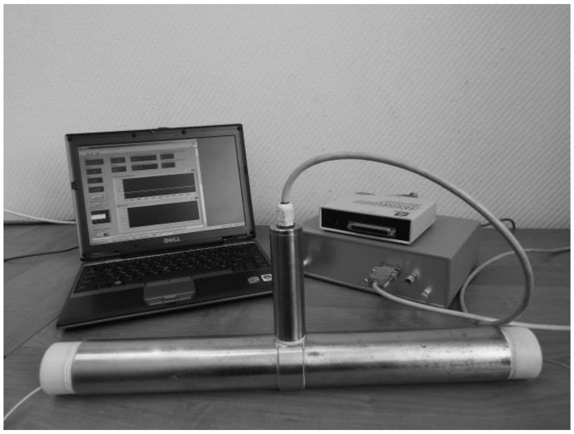
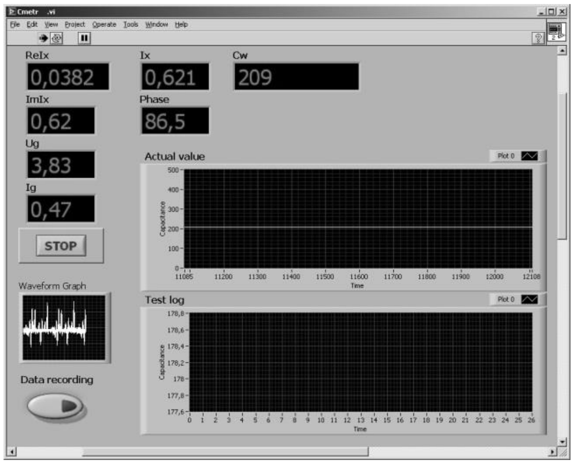


Fig. 6 physical configuration of the CAP-10

The main control program of the CAP-10 is Cmetr.vi implemented via LabView 8.5. The program Cmetr.vi performs filtration, averaging within 1 second and digital processing of measuring signal. Digital processing of the measuring signal is conducted according to the algorithm for digital conversion of the measuring signal. The measurement result is obtained through the conversion function based on the evaluation of the measuring electrode current phase.

The front panel (Fig. 7) displays the following information:

- the complex parts of the measured current "$\mathrm{Re}\,\dot{I}_x$" и "$\mathrm{Im}\,\dot{I}_x$";
- the output voltage and current of the generator "U_g" and "I_g";
- the calculated amplitude values for the measured current "I_x" and its phase "Phase";
- the waveform graph for the wire capacitance per unit length "Actual value";
- the calculated value of the wire capacitance per unit length "C_w";
- the button "STOP" to stop measurement;
- the waveform graph "Test log" to record the data array of the capacitance per unit length within a specified time interval;
- the button "Data recording" to start and stop test log file.



ReIx 0,0382
Ix 0,621
Cw 209
ImIx 0,62
Phase 86,5
Ug 3,83
Ig 0,47

Fig.7 front panel of the CAP-10.

The performance of the CAP-10 and the efficiency of the proposed technique to offset from impact of changes in water conductivity on the results of measuring wire capacitance were assessed experimentally.

The experimental data was obtained for single-core electric wires with the capacity ranging from 160°pF/m to 460°pF/m and saline concentration of water varying in the range of (0…4)°g/l.

The real values of the capacitance of the single-core wire per unit length were determined in accordance with GOST 27893-88 [2] using fresh water at room temperature +(22±1)°C and saline concentration close to zero $\lambda \to 0$. The studies obtained are shown in Fig. 8.

Fig. 8 shows the range of the measured values for capacitance per unit length C_x under variation of water conductivity for different wires (with different real values of the capacitance per unit length C_r) without offset from the impact of changes in water conductivity (dotted lines), and for the case of the offset (solid lines).

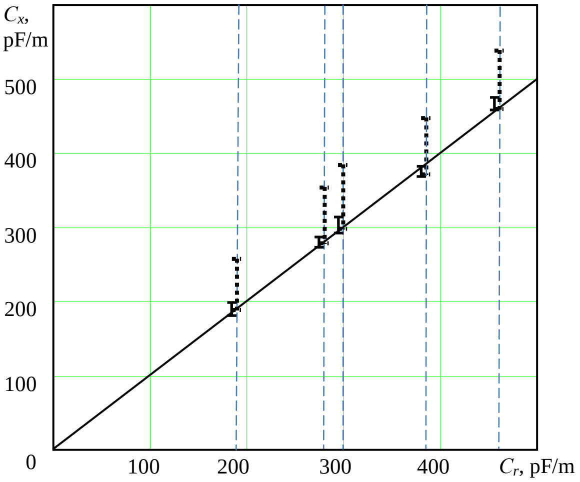


Fig. 8 range of the measured values for capacitance per unit length without correction (dotted lines) and with correction (solid lines).

The analysis of these results shows that without offset from the impact of changes in water conductivity the relative measurement error can reach 20 %, however, when offsetting, the values of the capacitance per unit length calculated by formula (2) for these ranges of parameters affecting the actual values differ by not more than 2.5 %. A limited range of changes affecting the parameters allows many-fold reduction in the measurement error.

VI. TECHNICAL CHARACTERISTICS OF THE CAP-10

The device CAP-10 is designed to perfume in-process testing of the single-core wire capacitance per unit length at the stage of applying wire insulation. This device provides comparing the measured values with the maximum permissible values of the capacitance and performs the measurement result indication. It creates and stores an array of measurement data for a predetermined period of time.

The main technical characteristics device CAP-10 are as follows:

- the test object is single-core insulated wire;
- the range of the measured capacitance per unit length is (50…750) pF/m;
- the outer diameter of the wire insulation varies from 0.5 mm to 12 mm;
- the maximum permissible measurement error for the capacitance per unit length is 2.5% from its nominal value in the range of the change in water conductivity equivalent to the variation in the NaCl concentration range (0 ... 4) g/l.

The conducted laboratory and factory testing of the device CAP-10 confirms the effectiveness of the proposed offsets from the impact factors. The device CAP-10 is going to be used for mass production.

VII. CONCLUSION

Thus, the ECMT design for in-process testing of the capacitance per unit length of the electric wire has been developed.

The results of computer simulation of the interaction of the ECMT electric field with the electric wire were used to choose the optimal design parameters: the inner diameter of the tubular electrodes, the length of the measuring and guard electrodes, the distance (gap) between these electrodes and the inner diameter of the ECMT cylindrical housing.

The ECMT design is considered optimal if the ratio of the capacitance per unit length in the central part of the measuring electrode to the capacitance per unit length along the total length of the measuring electrode is equal to unit.

The device CAP-10 for in-process measurement of the single-core wire capacitance per unit length was developed on the basis of the ECMT immersed in the extrusion cooling bath. The values of the basic design parameters for ECMT were selected.

The design of the ECMT, the block diagram of the CAP-10 and the algorithm for measuring signal conversion are presented.

The conversion function is corrected based on indirect measurement of water conductivity. The techniques to offset from the impact of changes in water conductivity on the test result are suggested.

Significant decrease in the error in measurement of the capacitance per unit length of the wire proves the efficiency of the suggested technique.

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