Development of device CAP-10 to perform in-process testing of the single-core wire capacitance per unit length

Aleksander Goldstein, Galina Vavilova

Abstract— The paper descries the design of the electro-capacitive measuring transducer used to implement electrical-capacitive method to perform in-process measuring the single-core electric wire capacitance per unit length during its manufacturing. The ECMT optimal design parameters were chosen based on computer simulation of the interaction of the ECMT electric field with the wire using COMSOL Multiphysics. The block diagram of the device CAP-10 developed for implementation of the proposed method is presented. Physical configuration of the CAP-10 is shown, and its operating principle is described. An algorithm for conversion of the ECMT measuring signal that implements the technique of offsetting from the impact of changes in water conductivity on the control results is proposed.

Keywords— Capacitance per unit length, electro-capacitive measuring transducer, single-core wire, water conductivity.

I. Introduction

THE electric cable wave impedance is a significant parameter for a number of cable products such as communication cables, radio-frequency cables and LAN-cables [1]. The electric cable capacitance per unit length is the parameter which determines the wave impedance value.

The capacitance stability along the entire wire length ensures the quality of information transmission in the cable line.

The cable capacitance is tested to meet the standard requirements according to GOST 27893-88 [2]. This standard regulates final inspection. Since this technique of control is performed on a segment of the finished cable, the cable cannot be tested along its entire length. The quality of the product can be assessed after its manufacturing only [3], [4].

Testing of the wire capacitance performed at the stage of wire insulation is most effective. In [5, 6], the method of capacitance testing implies creation of the alternate field between the grounded wire core and the insulation surface via the electrical-capacitive measuring transducer (ECMT) immersed in the extrusion cooling bath. During in-process testing, the capacitance value of the capacitor is measured. This capacitor consists of a wire core as the first electrical component, and the cooling water in which the wire is immersed as the second electrical component. The water fills the space between the wire insulation surface and the ECMT with the test wire inside and provides electrical contact. The described test method is widely used in developments of the leading manufactures Sikora, Zumbach working in cable industry [4], [7]–[11].

The advantages of this technique compared to the technique of final inspection of the capacitance of cable products [2] is the possibility to control the electric wire along its entire length, and to obtain information on the wire quality during in-process testing [3], [4].

The described technique of the in-process testing of the single-core electric wire capacitance per unit length has currently no alternative.

II. Design ECMT

Fig. 1 shows the design of the ECMT used for implementation of the described method. The ECMT consists of tubular measuring electrode 1 and a pair of tubular guard electrodes 2, 3 located inside a metal housing 4 and isolated from it by air layer 5. Single-core electric wire 6 continuously moves inside the ECMT. The guard electrodes are connected to alternating voltage generator 7. The wire core and the ECMT housing are earthed. Tubular electrodes 1–3 are connected to alternating voltage generator 7 $\dot{U}$ with an angular frequency ω [5], [6]. The ECMT with the part of the tested cable located in it is immersed in the cooling water. This water is electrically conductive aqueous solution containing salts, acids and bases [12].

The basic ECMT design parameters are the length of the measuring and guard electrodes, the distance (gap) between these electrodes, the inner diameter of the electrodes and the inner diameter of the ECMT cylindrical housing.

An optimal ECMT design provides the highest uniformity in the longitudinal (axial) direction of the electric field between the inner surface of the measuring electrode and the wire core of the tested electric wire (Fig. 2).

In this case, the conversion function of the capacitance per unit length of the electric wire in the ECMT output signal will be minimally dependent on the geometry of wires, electrical properties of insulation and electrical conductivity changes of water.

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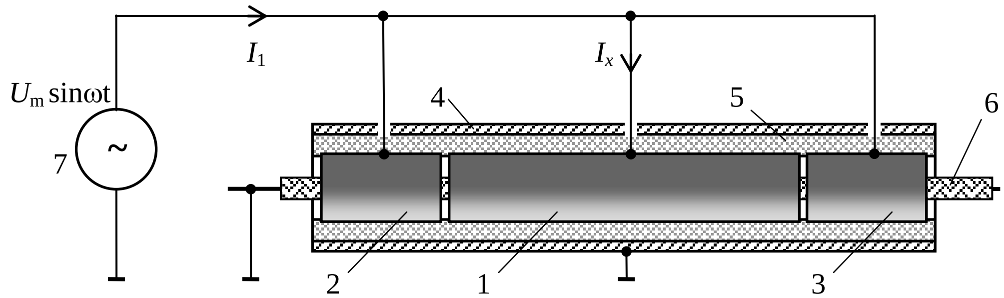

Fig. 1 ECMT design: measuring electrode (1), guard electrodes (2, 3), transducer housing (4), air layer (5), wire (6), alternating voltage generator (7).

The electric field is homogeneous if at any fixed value of the radius r in the measuring electrode, the values of the radial component E_r of the electric field intensity vector $\overline{E}$ are similar, and the longitudinal component E_x (directed along the cable axis x) is equal to zero (Fig. 2).

The coefficient β is taken as a criterion of the electric field uniformity inside the measuring electrode. The variable β is equal to the ratio of the capacitance per unit length in the central part of the measuring electrode (C_0) to the capacitance per unit length along the total length of the measuring electrode (C_1) (in the central part of the measuring electrode, the electric field is known to be uniform).

$$\beta = \frac{C_1}{C_0}. \quad (1)$$

For an optimal ECMT design β tends to 1.

Computer simulation of the interaction of the ECMT electric field with the electric wire in COMSOL Multiphysics enables determination of the ECMT optimal design parameters to minimize the systematic error of the wire capacitance measurement [13].

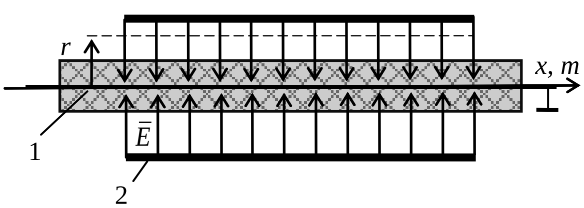

Fig. 2 field inside the transducer: wire (1) and measuring electrode (2)

Fig. 3 shows the distribution of the electric potentials for interaction of the ECMT electric field with the tested wire plotted in equipotential lines and shades of gray for the case of guard electrodes.

The guard electrode length is equal to the inner radius R of the measuring electrode and the distance (gap) between these electrodes is 1 mm.

Fig. 4 shows the distribution of the values of the longitudinal E_x and radial E_r components of the electric field intensity vector along the longitudinal axis in the middle part of the wire insulation.

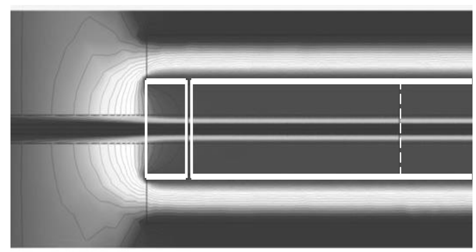

Fig. 3 electric field created by the ECMT with guard electrodes with a length of 1R and a gap of 1 mm.

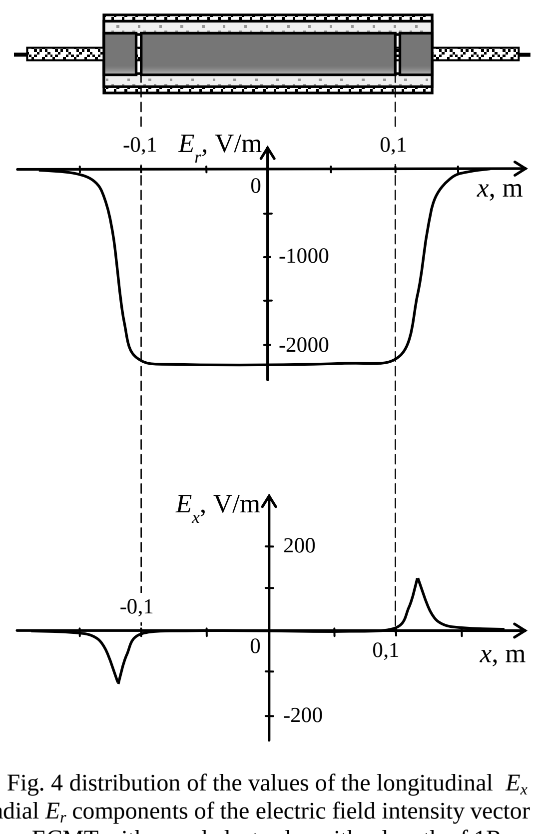

Fig. 4 distribution of the values of the longitudinal E_x and radial E_r components of the electric field intensity vector in the ECMT with guard electrodes with a length of 1R and a gap of 1 mm

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:

$$C_{\mathrm{w}} = C_0 + k \cdot I_x , \quad (2)$$

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

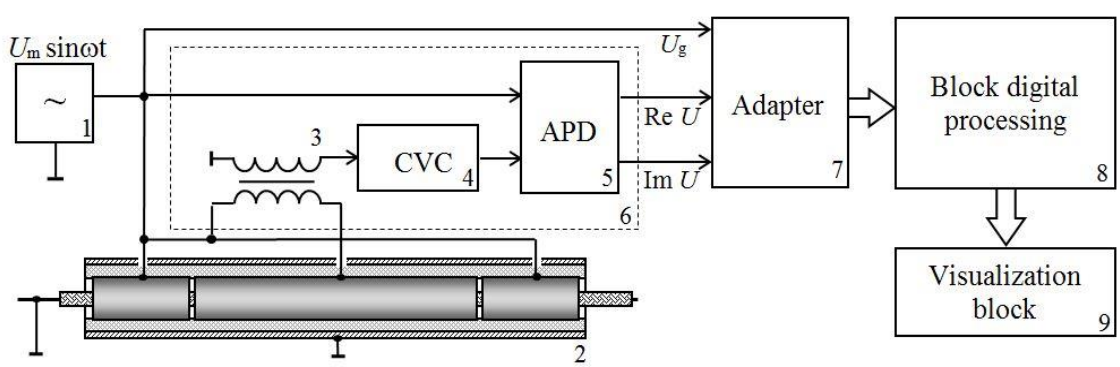

Fig. 5 block diagram of CAP-10: alternating voltage generator (1), ECMT (2), current transformer (3), current-to-voltage converter (4), amplitude-phase detector (5), analogue conversion unit (6), adapter (7), digital processing unit (8), visualization unit (9) distilled water with the saline concentration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

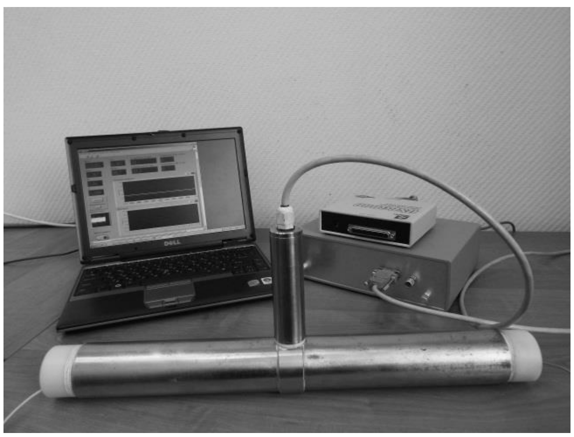

Fig. 6 physical configuration of the CAP-10

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.

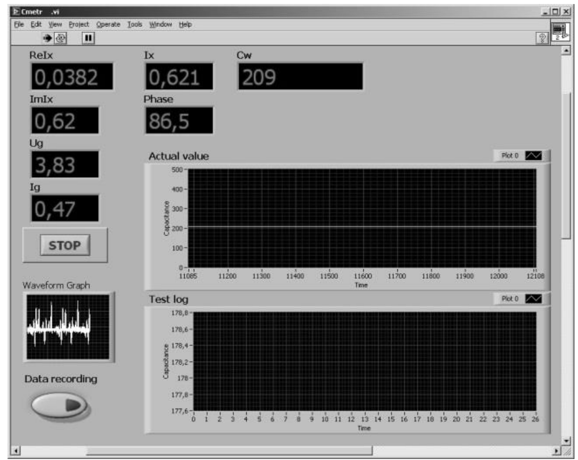

Fig.7 front panel of the CAP-10.

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).

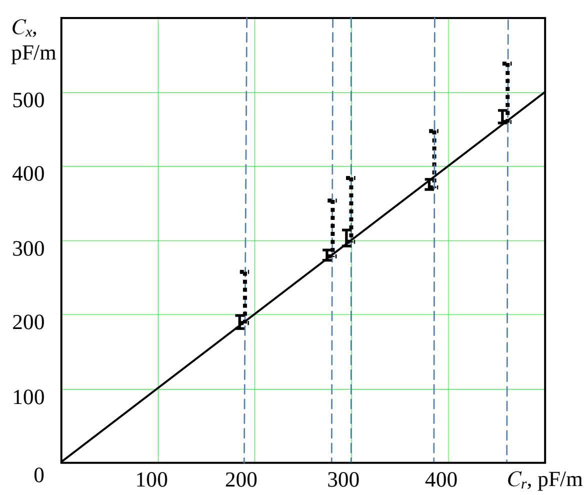

Fig. 8 range of the measured values for capacitance per unit length without correction (dotted lines) and with correction (solid lines).

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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