In-process Measuring of Capacitance Per Unit Length for Single-core Electric Wires

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Abstract. The paper describes technical in-process implementation of the electrical method to measure the electrical capacitance per unit length of a single core electric wire. The basic design values of the electro-capacitive measuring transducer are determined. The impact of changes in water conductivity on measurement results is analyzed. Techniques to offset from the impact of changes in water conductivity on the results of the electrical capacitance per unit length control based on indirect electrical conductivity measurement are considered. An appropriate correction of the conversion function is made.

1. Introduction

Capacitance per unit length for electric cable and related impedance are considered to be important parameters for a number of cable products such as communication cables, radio-frequency cables and LAN-cables [1]. The cable capacitance is tested to meet the standard requirements according to GOST 27893-88 for final quality [2]. The drawback of this technique is that the cable cannot be tested along its entire length, and the quality of the product can be assessed after its manufacturing only.

This drawback can be eliminated through the in-process testing of the single core cable wire at the stage of the conductive core insulation. For this purpose, a tubular electrode is immersed in water (typically, in the extrusion bath with cooling water). During the in-process testing, the capacitance value of the capacitor is measured. The two electrical components of the capacitor are the wire core and the cooling water with the immersed tubular electrode. The water provides an electrical contact between the core sheath and the tubular measuring electrode. This technique is employed by the leading companies specializing in the production of inspection devices for the cable industry: Sikora, Zumbach [3–6].

2. Problem formulation

Figure 1 presents the design of the electro-capacitive measuring transducer (ECMT) used to implement the above testing technique.

The ECMT consists of cylindrical metal housing 1, tubular measuring electrode 2, a pair of cylindrical guard electrodes 3 and dielectric 4. The dielectric is placed between metal housing 1 and electrodes 2 and 3. Tested wire 5 continuously moves along the common axis of the three electrodes. The guard electrodes provide a uniform electric field in the adjacent ends of the measuring electrode.

The wire core and the transducer housing are earthed. The tubular electrodes are connected to alternating voltage generator $\dot{U}$ with circular frequency ω. The current in the measuring electrode electric circuit is measured using current transformer 6. The transducer and a segment of the tested wire core therein are immersed in the cooling water. The water is an aqueous solution containing salts, acids and bases.

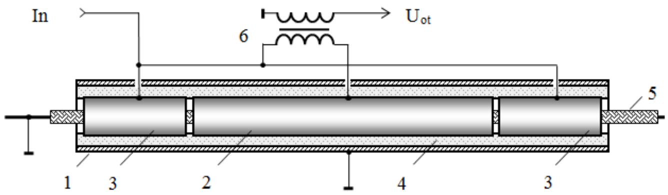

Figure 1. Design of the ECMT and switching circuit.

The purpose of the research: to study the impact of the basic ECMT design parameters and electrical conductivity of water on the conversion function of the ECMT, to select the optimal values for the ECMT design parameters to provide the maximum reliability of the method to test the capacitance per unit length of the electric wire, to develop an algorithm to offset from the impact of water conductivity on the results of capacitance per unit length measurement, and to experimentally check the effectiveness of the suggested techniques to offset.

3. Selection of the optimal design values for ECMT

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

An optimal ECMT design will provide the highest longitudinal (axial) uniformity of the electric field between the inner surface of the measuring electrode and the wire core of the tested electric wire. This minimizes the dependence of the function of the capacitance per unit length conversion into the ECMT output signal on the geometric dimensions of the wire, electrical insulation properties and changes in water conductivity.

The uniformity of the electric field is indicated through the identical values of the radial component E_r of the electric field intensity vector $\overline{E}$ and equality of the longitudinal component E_x (directed along the wire axis x) to zero for any specified value of the radius r inside the measuring electrode.

Variable β is introduced as a criterion of the electric field uniformity. Variable β is equal to the ratio of the linear capacitance in the central part of the measuring electrode (C_0) to the linear capacitance 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). For an optimal ECMT design β tends to 1. The central part of the measuring electrode, the length of which is equal to half of the total electrode length was assumed to be the region of a uniform field. The remaining part of the measuring electrode, for which the electric field uniformity was evaluated in the longitudinal direction, was assumed to be the measuring electrode.

To provide the longitudinal uniformity of the field inside the measuring electrode, the tubular electrodes are to be with a minimal inner diameter and maximal length. However, for free movement of the tested wire inside the ECMT to provide local testing, the inner diameter of the tubular electrodes is to be at least two times larger than the outer diameter of the wire sheath, and the measuring electrode length is to be of the order of (200 ... 300) mm.

To minimize the initial capacitance value of the ECMT (without the test object), the inner diameter of the cylindrical metal housing should be two times higher than the outer diameter of the tubular electrodes and an insulator is the air gap. The optimal values of the other design parameters may be determined through computer simulation of the ECMT. The 3D model of the transducer was made using COMSOL Multiphysics 3.5a.

The following parameters of the model were specified. The diameter of the wire core was 2 mm, the diameter of the wire insulation was 6 mm, the length of the measuring electrode was 200 mm, the inner diameter of the electrodes was 20 mm, the inner diameter of the housing was 40 mm, the thickness of the electrode and the housing wall was 1 mm, the amplitude of the electrode potential was 5 V, and the field frequency was 10 kHz. In the simulation, two versions of the electrical properties of water were set: distilled water (conductivity $\sigma = 10^{-4}$ S/m) and salt water ($\sigma = 0.8$ S/m).

The equipotential lines and color spectrum in figure 2 show the distribution of the electric potentials for the interaction of the ECMT electric field with the electrical wire for the case when no guard electrodes and distilled water are used.

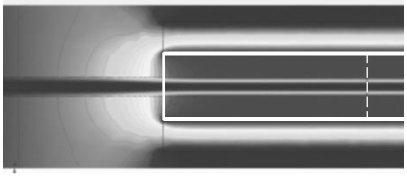

Figure 2. Electric field created by the ECMT without guard electrodes (distilled water).

The analysis of the simulation results (figure 2) shows that in the absence of the guard electrodes "buckling" of the electric field occurs at the ends of the measuring electrode and, as a consequence, the field in these areas is highly non-uniform.

The value of the capacitance between the measuring electrode and the core wire can be determined by the mathematical expression, which identifies the relationship between the electric field energy of the capacitor *W*, the potential difference of its electrodes *U*, capacitance of the capacitor *C*, the electric field intensity *E* and the electric field induction *D* [7]:

$$W = \frac{CU^2}{2} = \int_V \frac{\bar{D}\bar{E}}{2} \mathrm{d}V \tag{1}$$

where *V* is the volume of the electric field.

From (1), we can obtain an expression to calculate the capacitance value by the numerical method using COMSOL Multiphysics: $C = \frac{1}{U^2}\int_V \bar{D}\bar{E}\,\mathrm{d}V$. For the case of the ECMT without guard electrodes, the calculated values are: $C_0 = 1.259\,pF$; $C_1 = 1.499\,pF$; $\beta = \frac{C_1}{C_0} = 1.9$.

Thus, in this case, the degree of the longitudinal (axial) uniformity of the electric field is approximately 20%, which causes a methodological error of the same order of magnitude in measuring capacitance per unit length. Distilled water used instead of salt water provides qualitatively similar pattern of the field and quantitatively similar parameters.

Radical increase in the longitudinal uniformity of the electric field along the entire length of the measuring electrode can be achieved by means of the guard electrodes.

Figure 3 shows the distribution of the electric potentials in the interaction of the ECMT electric field with the electrical wire for the case of guard electrodes and distilled water used. The length of the guard electrodes is equal to the inner diameter of the measuring electrode *R* = 10 mm, and the distance (gap) between the measuring electrode and the guard electrode is 1 mm.

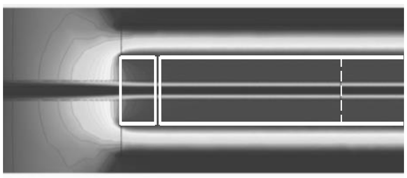

Figure 3. Electric field created by the ECMT with guard electrodes with a length of 1R and a gap of 1 mm (distilled water).

Figure 4 shows the distribution of the values of the longitudinal E_x and radial E_r spatial components of the ECMT electric field intensity vector along the longitudinal axis.

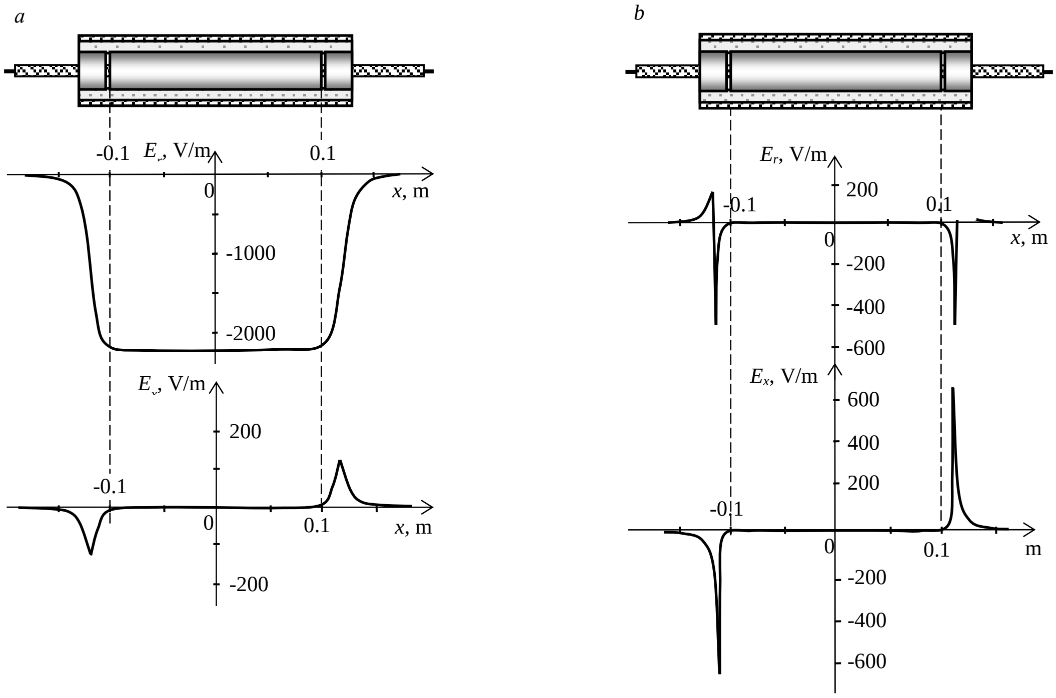

Figure 4. Distribution of the radial E_r and longitudinal E_x components of the electric field intensity vector in the middle part of the wire sheath (a) and near the inner surface of the measuring electrode (b) for ECMT with guard electrodes with a length of 1*R* and a gap of 1 mm.

The analysis of the simulation results (figure 4) shows that in case of using guard electrodes, the electric field "buckling" occurs at the distant edges of the guard electrodes. The electric field in the longitudinal direction is found to be highly uniform along the entire length of the measuring electrode. In this case, the value β is equal to 1 that corresponds to the optimal version of the ECMT design.

The developed computer model was used to study the impact of the guard electrode length on the degree of the electric field uniformity. The electric field is highly uniform in the longitudinal direction if the length of the guard electrodes is 0.5R or more. Virtually the same results were obtained for salt water.

The effect of the gap between the measuring and guard electrodes on the ECMT electric field was investigated as well. Summarizing the results on the effect of the guard electrode length and the gap between the guard electrodes on the ECMT characteristics, it can be concluded that the optimal ECMT design parameters when using both distilled and salt water are the guard electrode length equal to (0.5...1)*R* and the gap equal to (1...3) mm.

4. Experimental study on the impact of water conductivity on the ECMT conversion function

To study the effect of water conductivity on the results of the electric wire capacitance measurement, we used a single-core electric wire with an outer diameter of 4°mm, the capacity ranging from 160°pF/m to 460°pF/m, and similar values of the dielectric loss factor. The actual value of the wire capacitance per unit length was determined in compliance with GOST 27893-88 [2]. NaCl was solved in fresh water to change the electrical conductivity of water. The salt concentration of water λ varied from (0…4)°g/l.

For experimental studies we used the ECMT with the basic design and electrical parameters similar to those used in mathematical modeling.

Figure 5 presents the hodograph diagrams to show the dependence of the relative current $\dot{I}^*$ on the change in the wire capacitance per unit length C_p (solid line) and saline concentration/ salt concentration λ (dotted line).

The value of the current for the case of ECMT with no wire used (which corresponds to the value of the wire capacitance per unit length C_p=0) and $\lambda \to 0$ (distilled water) was taken as a fiducial value of the current.

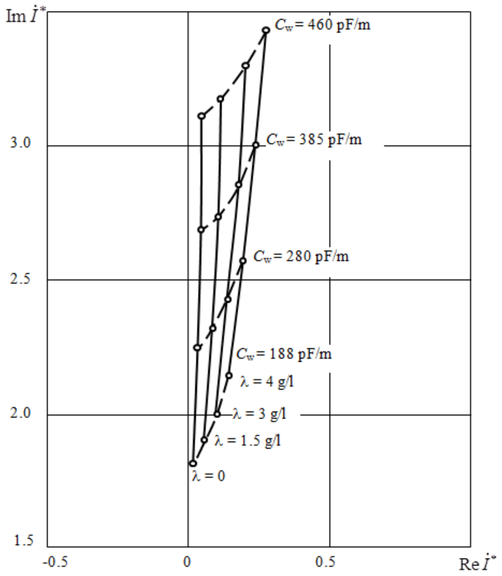

Figure 5. Hodograph diagram of the signal of the transducer (ECMT) for the change in the wire capacitance per unit length C_w and salt concentration λ.

The analysis of the dependencies (figure 6) shows that the amplitude of the current $\dot{I}^*$ increases linearly as the wire capacitance per unit length grows. Therefore, it is expedient to use the current amplitude as an informative parameter of the ECMT output signal when measuring the wire capacitance per unit length. The change in the salt concentration in the studied range changes the current amplitude in the range from 10 % for large capacitance values to 20 % for small capacitance values. Consequently, measurement of the capacitance per unit length with no account for the impact factor causes poor measurement accuracy.

5. Techniques to offset from the impact of changes in water conductivity on ECMT conversion function

The experimental results (figure 6) were used to find the function of the inversion of the measured current value into the value of the wire capacitance per unit length with the account for the impact of water salinity:

$$C_w = C_{01}(\lambda) + k_1(\lambda) \cdot I^* \quad (2)$$

where $C_{01}(\lambda)$ is a constant component, $k_1(\lambda)$ is a proportionality factor.

Both of the functions depend on the salt concentration of water λ and they can be approximated by the second order polynomials. The coefficients of the functions are determined by the ECMT design parameters. In this paper, the techniques to offset from the impact of changes in the salt concentration of water on measurement results are investigated based of indirect measurements.

As can be seen in figure 6, as salt concentration of water increases, the phase angle φ between the vector current $\dot{I}^*$ and the imaginary axis of the complex plane monotonically grows. Consequently, $t = \frac{\operatorname{Re} \dot{I}^*}{\operatorname{Im} \dot{I}^*}$ and tg φ tend to grow. Therefore, the results of measuring the complex current components $\dot{I}^*$ can be used to offset from the impact of changes in water conductivity.

By analogy with (2), the equation of the inverse conversion of the amplitude of the current $\dot{I}^*$ into the wire capacitance per unit length is described by the linear dependence:

$$C_w = C_{02}(t) + k_2(t) \cdot I^* \quad (3)$$

where functions $C_{02}(t)$ and $k_2(t)$ are the values *t* indicating water conductivity.

Functions $C_{02}(t)$ and $k_2(t)$ as well as functions $C_{01}(\lambda)$ and $k_1(\lambda)$ can be described by the second order polynomials. The coefficients of these polynomials are determined by the ECMT design parameters and are found experimentally during the initial ECMT calibration.

A numerical experiment was carried out using conversion function (2) to assess the efficiency of the described technique to offset from the impact of changes in water conductivity on the results of the electrical capacitance per unit length testing. The experimental data was obtained for single-core electric wires with the capacity ranging from 160°pF/m to 460°pF/m and salt concentration of water varying from (0…4)°g/l.

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 (3) 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.

6. Conclusion

Based on the results of computer simulation of the interaction of the electric field of the ECMT for capacitance per unit length meter with an electric wire, the optimal design parameters of the main elements of the ECMT are selected: the inner diameter of the tubular electrodes, the length of the measuring and guard electrodes, the distance (gap) between the measuring and guard electrodes, the inner diameter of the ECMT cylindrical housing. It is shown that the change in water conductivity significantly impacts the results of the in-process measuring of the wire capacitance per unit length. The change in water conductivity can be caused by changes in salinity of water, in which the ECMT is immersed, as well as the changes in its temperature and composition of impurities contained in water. Based on indirect measurement of water conductivity and error correction in the conversion function, the techniques to offset from the impact of these factors on measurement results are suggested. It is shown that these offset techniques allow multifold increase in the measurement accuracy.

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