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OPERATING EXPERIENCE

Measuring the Resistance of Resistors in the Winding Process with Insulated Wire

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Abstract—A method for measuring the resistance of resistors and dividers in the process of their winding using an insulated wire, along with their resistance distribution onto a frame according to a preset law, is proposed. The theory, error analysis, and possibilities of the method are studied.

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The maximum accuracy of high voltage measurements at a constant current is found to be achieved using high voltage resistive dividers of the voltage in their simplest case comprising two series-connected resistors R_1 and R_2 [1].

The measured high voltage being applied to such a divider is determined by the expression

$$U_1 = \left(1 + \frac{R_2}{R_1}\right)U_2 = (1+K)U_2, \qquad (1)$$

where K is the coefficient of the scale point of the divider, and U_2 denotes the measured R_2 voltage.

It follows from the Eq. (1) that the accuracy of voltagt measurement is determined by the accuracy and stability of coefficient K.

When discussing the measurement precision of high voltages at an alternate current using resistive dividers, one should note that, along with the K coefficient's accuracy, the exactness of its reactances ratio must be ensured. The resistive dividers consist of a microwire. Further, the wires are to be characterized by only their capacitive reactance, because the reactance of the inductive character is negligibly small in comparison with its resistive resistance [2]. The capacitive reactance of such dividers is determined by the type of the wire frame winding, by its resistance per unit of length, and by the uniformity of the wire's distribution with respect to the resistance in the winding. The resistors having a layer-winding* (the wire is placed only in one direction at a step of more (or less) than the diameter of the insulated wire or equal to it) and a uniform distribution of the wire in the winding with respect to the resistance have the minimal capacitive reactance.

With account for the peculiarities of the cast microwire, the continuous measuring of the resistance of the wire placed on the frame and the resistance of the length of the frame the wire is placed on is to be performed for achieving the uniform distribution (with regard to the resistance) of the cast microwave in the winding layer. Their percent ratio should be incessantly compared.

The known measuring methods insufficiently meet the above requirements, in particular, in the winding process of high-ohmic resistors and resistance dividers [3–5, 6–9].

The method discussed in this paper makes it possible to manufacture mean-ohmic resistors with a resistance error of no more than 1–2% at a uniform distribution of the resistance in the winding with the wire quantity required for the winding of ($l_w < 3/\sqrt{r\omega c}$) and at a particularly high accuracy when the wire quantity l_s in the recoil spool has the length

$$\left(l_w + \frac{3}{\sqrt{r\omega c}}\right) < l_s > l_w, \qquad (2)$$

which is the most often used length for the winding of high megohmic resistors.

The principle of the method is explained by the scheme shown in Fig. 1. A spool with a metal-frame-wound resistive wire (of the layer-winding type) can be represented at a sufficient approximation as a structure of R–C–O type with distributed electric parameters [6] or a double-wire line with distributed electric parameters.

One wire is a metal spool whose resistance is of a negligibly small value in comparison with this wire's resistance [7]. The equivalent electric resistance of such a line at its bipolar mode in the electric circuit is

$$Z_s = \sqrt{\frac{r}{j\omega c}}\,\mathrm{cth}\,\sqrt{r\omega c}\,l, \qquad (3)$$

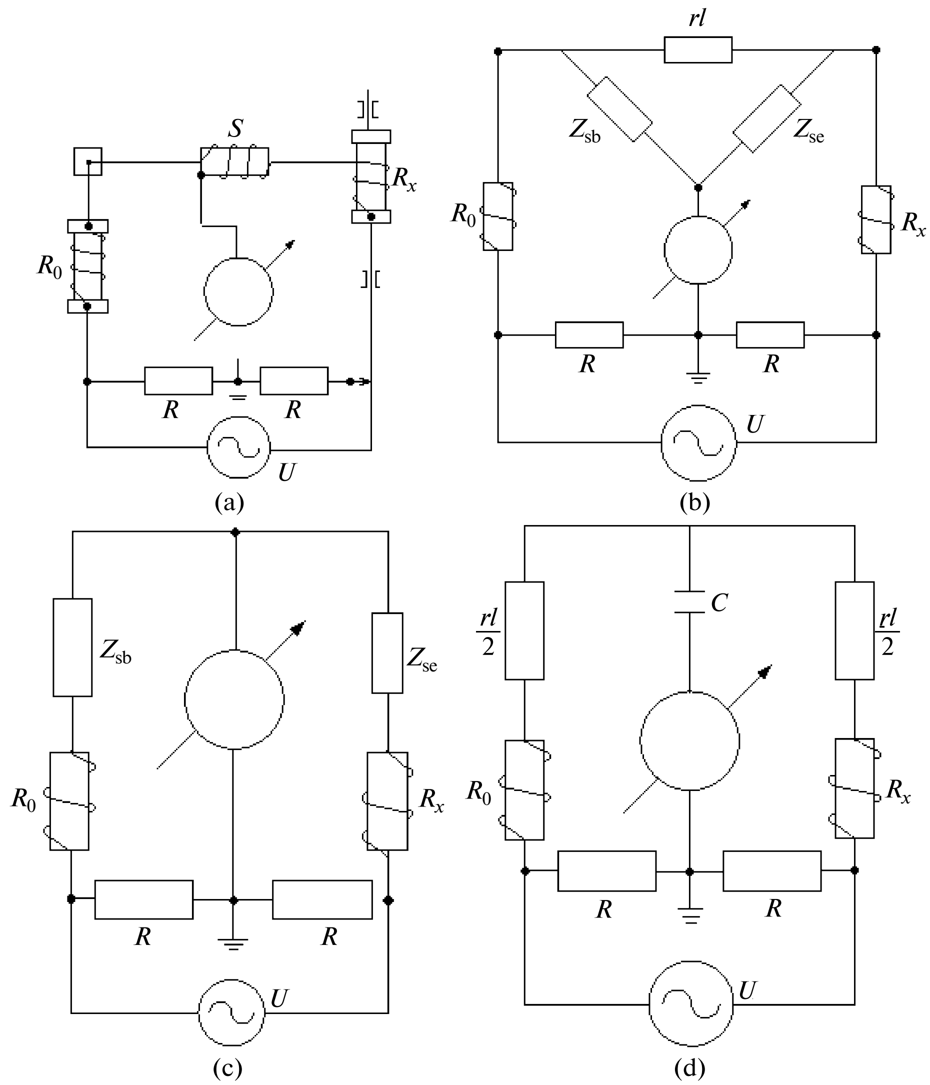

Fig. 1.

when $l < 3/\sqrt{r\omega c}$, u,

$$Z_s = \sqrt{\frac{r}{j\omega c}}, \tag{4}$$

when $l > 3/\sqrt{r\omega c}$, where r and C denote the resistance per unit of length of the wire itself and, correspondingly, its capacity per unit of length with respect to the metal frame.

In the above methods [3–5, 9], at the resistance measurement of the resistors in the winding process, the recoil spool with a wire enters the electric circuit as an electric bipolar unit and, along with the measured resistor, it may [9] or may not be a measured object. At $l_\delta < 3/\sqrt{r\omega c}$, it has a negative effect on the accuracy of the resistor's resistance measurement, thus increasing the manufacturing error of the resistor with respect to the resistance up to tens of percents.

This paper offers a tripolar mode of the spool in the electric circuit (Fig. 1a) and a bridge system for the resistor's resistance measurement (Fig. 1b). The resistance winding error of the resistor resulting from the finite value of the equivalent resistance of the spool with a wire can be substantially decreased and, in some cases, entirely removed.

Indeed, at $l_\delta > 3/\sqrt{r\omega c}$, $rl_\delta \gg Z_{sb}$, $rl_\delta \gg Z_{se}$, the scheme in Fig. 1c is simplified and takes the form of Fig. 1c, and the bridge balance takes place at the equality of

$$R_0 + \mathrm{Re}Z_{sb} = \mathrm{R}_x + \mathrm{Re}Z_{se}. \tag{5}$$

Here, two cases may occur:

(a) $\mathrm{Re}Z_{sb} = \mathrm{Re}Z_{se}$, and then

$$R_x = R_0; \tag{6}$$

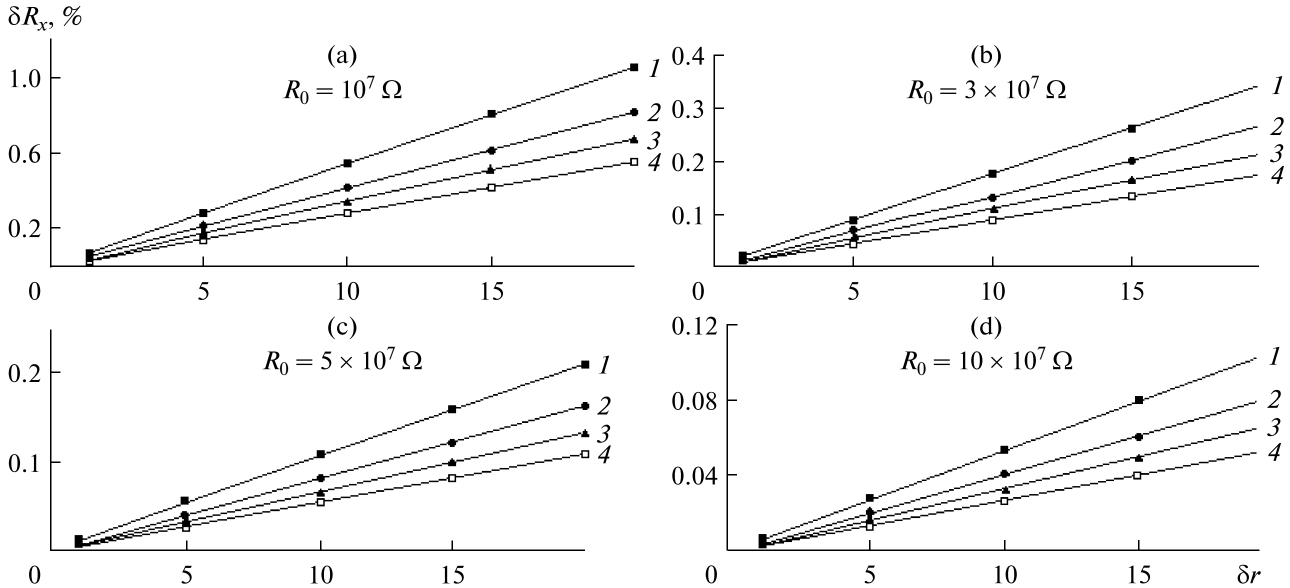

Fig. 2. r, kOhm/m: *1*—150, *2*—90, *3*—60, *4*—40; $r = (r_w - r_k)/r_k$, %.

(b) $RZ_{sb} \neq RZ_{se}$, and then

$$R_x = R_0 + \mathrm{Re}Z_{sb} - \mathrm{Re}Z_{se}. \quad (7)$$

Hence, the relative error in the resistor's manufacturing with respect to the resistance will be the following:

$$\delta R = \frac{R_0 - R_x}{R_0} = \frac{\mathrm{Re}Z_{sb} - \mathrm{Re}Z_{se}}{R_0} = \frac{1}{R_0}\frac{\sqrt{r_B} - \sqrt{r_E}}{\sqrt{2\omega C}}. \quad (8)$$

The values r_B and r_E denote the resistance per unit of length of the wire, correspondingly, of the beginning and of the end of the winding averaged over the length of $l = 3/\sqrt{r\omega c}$. In Figs. 2 and 3, some graphs of the probable resistance errors in the manufacturing of the resistors are shown when the averaged resistance per unit of length of the wire end differs from the averaged resistance per unit of length of its beginning; i.e., $r_B \neq r_E$.

At $l_\delta < 3/\sqrt{r\omega c}$; $rl_\delta < Z_{sb}$; $rl_\delta < Z_{se}$ (Fig. 1 d), the condition of the bridge's balance has the form

$$R_0 + \frac{rl}{2} = R_x + \frac{rl}{2}, \quad (9)$$

hence,

$$R_x = R_0. \quad (10)$$

The resistance in this case is averaged over the length of $3/\sqrt{r\omega c}$ both from the side of the spool's beginning and from the side of its ending.

It follows from the latter that, with account for the quantity of wire left on the spool ($l_\delta > 3/\sqrt{r\omega c}$), the resistance error of the resistor's winding is determined only by the error of the method and is independent of the value of the equivalent electric resistance either of the beginning of the spool (Z_{sb}) or of its end (Z_{se}).

As practice shows, considering the modern measuring methods of the wire's resistance per unit of length during the wire's casting and the casting control methods, the inhomogeneity of the wire's resistance per unit of length does not exceed 10–15% [8].

The scheme shown in Fig. 4 explains the principal of the uniform distribution of the wire on the layer-winding resistor. A uniform distribution of the wire's resistance in the winding decreases its capacitive reactance, which makes it possible to use microwire resistors in alternating current circuits. For the uniform distribution of the wire's resistance in the resistor winding, according to the method proposed in this paper, the R_0 of the sample resistor and the operating length L of the frame of the resistor being wound are divided into N sections with the R_0/N and L/N values, correspondingly. Each of the sections with the R_0/N resistance of the sample resistor has a terminal that is galvanically connected with the N fixed contact of the S switch. The variable resistor VR with the R_0/N resistance (that operates in the rheostatic control mode) is connected in series with the sample resistor through the movable contact of the switch S. The above variable and sample resistors form a sample arm of the measuring bridge. The axis of the VR resistor is kinematically connected with the G_{LD} guide of a wire lay-down device WLD. The above connection is selected so that a full rotation of the VR resistor moving cursor (0–360°) is relevant to the displacement of the guide of the wire lay-down device along the resistor frame axis for the L/N length, and the resistance of the VR resistor introduced into the sample arm increases from 0 to R_0/N. Proportionally to the resistance growth law

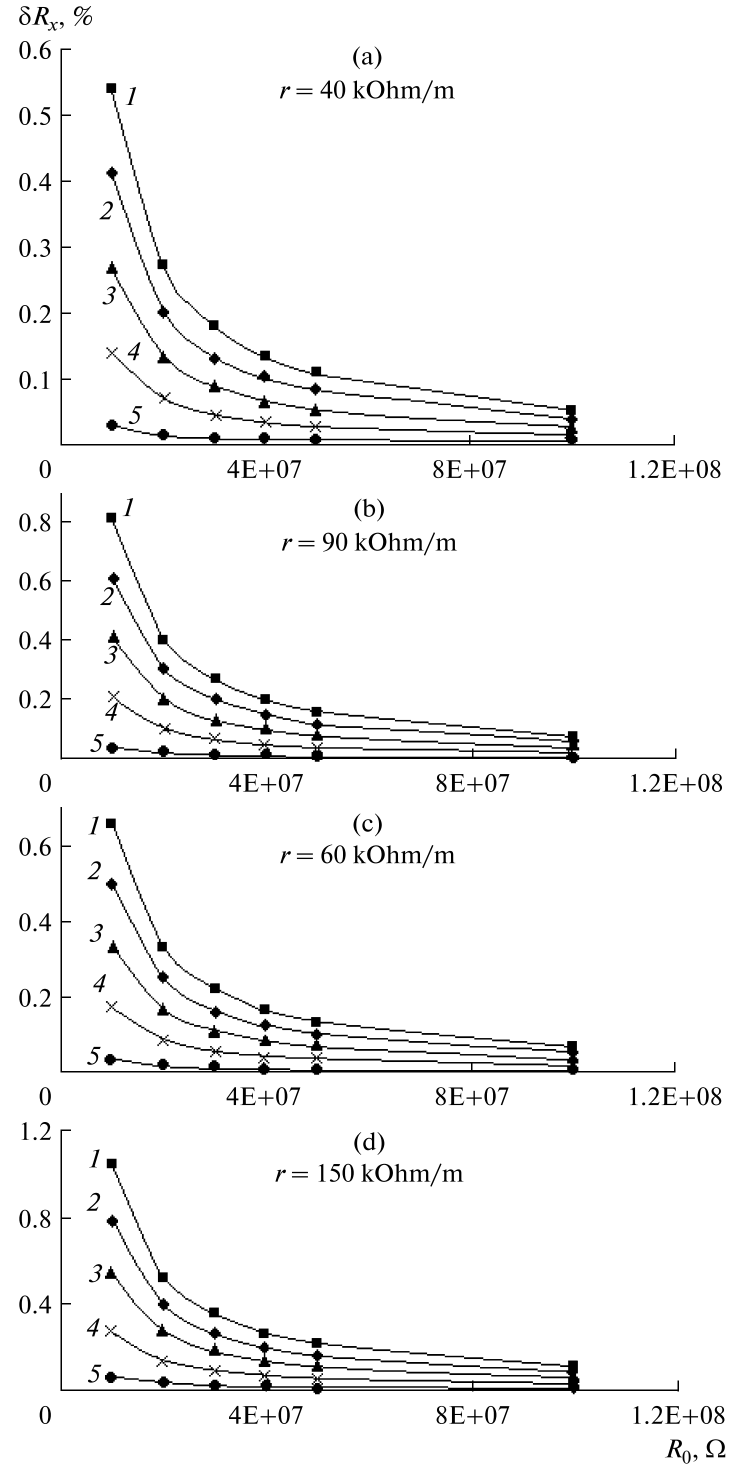

Fig. 3. δr, %: *1*—20; *2*—15; *3*—10; *4*—5; *5*—1.

of the *VR* resistor introduced into the sample bridge arm, the resistance of the wire wound on the resistor frame also increases, forming the bridge arm being measured. Using the winding rate control, the quantity of the resistance of the wire placed onto the frame is maintained equal to the resistance quantity of the *VR* resistor introduced into the sample arm. Maintaining the equality of these resistances in the winding pro-

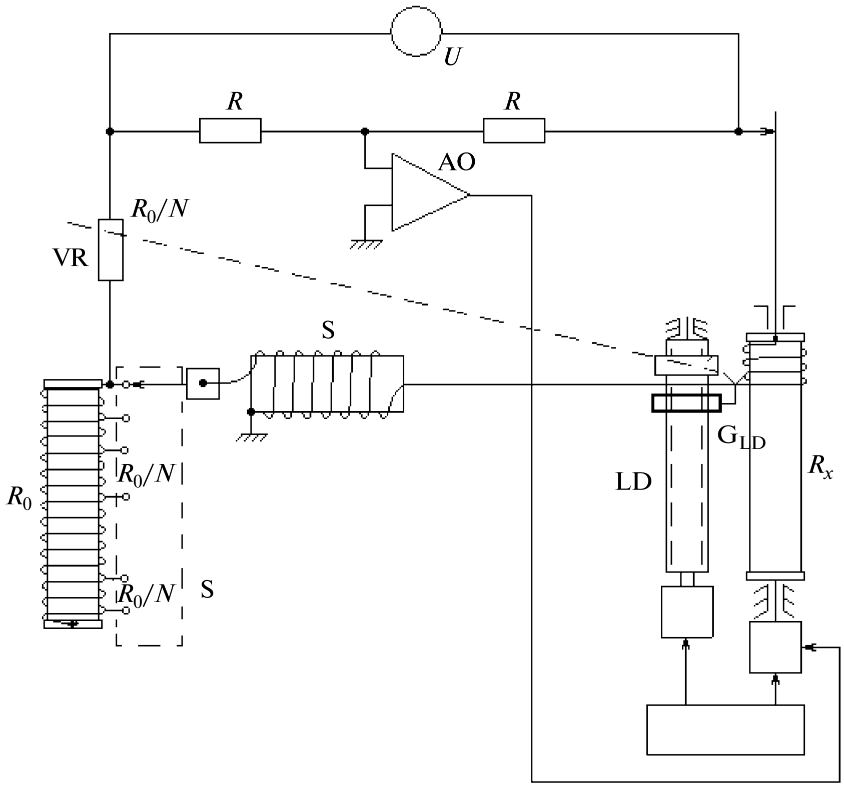

Fig. 4.

cess provides for the resistance of the frame-wound wire to be distributed according to the law of variation of the variable resistor's resistance in time.

After the *VR* resistor's first rotation, its moving cursor returns to the zero initial position (0`), and the first section of the sample resistor with the R_0/N resistance is introduced into the sample bridge arm instead of the resistor of the alternative resistance. The cycle is repeated until the $(N - 1)$ sections of the resistance of the sample resistor are introduced into the sample bridge arm, the wire with the resistance of $R_x = R_0$ is wound on the frame of the manufactured resistor, and the guide of the wire lay-down device covers the length L. This is where the resistor winding process finishes.

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