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A TECHNIQUE OF FULL-SCALE MEASUREMENTS OF THE RESISTANCE OF THE GROUNDING DEVICE

Purpose. The measurements of the resistance of grounding devices for various purposes using a three-electrode installation under real conditions are considered. **Methodology.** On the basis of the use of a three-electrode installation, a technique for full-scale measurements of the resistance of a grounding device of any design in an arbitrary soil structure is presented. **Results.** Based on the measurement results, a system of sixth-order equations is solved which allows to determine the own and mutual resistances in a three-electrode installation with a sufficiently high accuracy. **Originality.** It is not necessary to find a point of zero potential. **Practical value.** The proposed technique allows to perform measurements in conditions of dense urban and industrial development. References 9, tables 6, figures 2.

Key words: grounding device, grounding resistance, full-scale measurements, technique, three-electrode installation, zero potential point, system of equations.

Рассмотрены измерения сопротивления заземляющих устройств различного назначения с помощью трехэлектродной установки в реальных условиях. На основе использования трехэлектродной установки представлено обоснование методики измерения сопротивления заземляющего устройства любой конструкции в произвольной структуре грунта. По результатам измерений решается система уравнений шестого порядка, что позволяет определить собственные и взаимные сопротивления в трехэлектродной установке с достаточно высокой точностью и без отыскания точки нулевого потенциала. Библ. 9, табл. 6, рис. 2.

Ключевые слова: заземляющее устройство, сопротивление заземления, натурные измерения, методика, трехэлектродная установка, точка нулевого потенциала, система уравнений.

Introduction and problem definition. At present, a three-electrode measuring installation has been widely used to measure the resistance of grounding devices (GDs) [1]. One of the main tasks that must be solved in order to obtain sufficiently accurate results with this installation is, as indicated in [2], the correct choice of the locations of the measuring electrodes, i.e. such their arrangement at which the measured value of resistance differs from its true value by no more than 10 % in one direction or another. However, in a number of cases, the measurement of the resistance of the GD of urban and industrial substations presents a serious problem to this day.

Analysis of recent investigations and publications. Many domestic and foreign scientists solve the problem of increasing the accuracy of measuring the electrical parameters of the earth and GD.

The calculation method for determining the optimal arrangement of measuring electrodes at measuring the resistance of large-sized grounding devices with the help of the considered models has only limited application due to their external fields [3].

On the basis of a critical analysis of existing methods for determining the grounding resistance, a refined version of its definition was considered in [4]. By introducing the concept of special and quasi-equipotential regions of the grounding device, a new technique for measuring its resistance was proposed and experimentally tested. However, the proposed method in a number of cases does not allow measuring the resistance of grounding devices with acceptable accuracy.

In [5] a method of increased accuracy was proposed for measuring the grounding resistance of a substation at connecting a transmission line by measuring the grounding current using a specially developed wireless current sensor using GPS. Despite the fact that testing the method at an operating substation of 500 kV confirmed its

validity, in some cases its use raises many questions and requires a serious and detailed analysis.

The principal possibility of an accurate measurement of the resistance of the grounding device was noted in [6]. However, unfortunately, in this case it will also be necessary to determine the location of the potential electrode by repeatedly finding the zero potential point at the measurement site.

Mathematical modeling of the process of measuring the resistance of the grounding device to the current of the power frequency in a multilayer soil showed [7] that it is impossible to choose by the experimental method for measurements on the terrain such an arrangement of electrodes in which the measured resistance of the grounding device is equal to the true.

In [8] the theoretical, and based on the use of the method of physical modeling in [9] the experimental justifications of a new method of measuring the resistance of the grounding device with the help of a three-electrode measuring installation for any character of ground heterogeneity, any size and configuration of GD and arbitrary placement of measuring electrodes without finding the zero potential point are presented.

The goal of the work is the development of a technique for full-scale measurements of the resistance of the grounding device by means of a three-electrode measuring installation without finding a zero potential point.

Recommended method of full-scale measurements in a group of grounding devices and processing of measurement results to obtain the values of own and mutual resistances in a three-element system. Preparation and carrying out of measurements of electrical parameters of the GDs of operating substations of voltage class above 1 kV must exclude dangerous situations that may arise in this case. For example, in

conditions of industrial or urban development, the removal of electrodes over long distances is associated with the possibility for potential outflow which poses a serious danger.

Wires and cables connecting the source of electricity, instruments, grounding devices, usually have a significant length, especially at large dimensions of the tested grounding device. In this case, it is necessary to observe two rules [2]:

a) the connecting lines must not be laid parallel or at a slight acute angle to the overhead line (OL) route. The position of the electrodes (grounding conductors), in addition to the tested one, should be chosen so that the connecting lines are located with respect to the OL route either at an angle close to the right angle or in the direction opposite to the OL route connected for the substation (the latter only applies to the dead-end substations);

b) first the current ground electrode and the potential electrode are mounted and the connecting wires are connected to them. Then they begin to unfold and connect to the subject.

At the end of the work, the measuring circuit is disassembled in the reverse order. Initially, the connecting wires are disconnected from the GD device and from the devices, then the wires are rewound and only at the end are disconnected from the current and potential electrodes.

In connection with the above, the technique of full-scale measurements in a group of grounding devices is as follows.

Fig. 1 shows in the plan the circuit for the implementation of the method of measuring the resistance of individual interacting grounding devices in a sequence of operations.

In the initial state, a system of three independent (to check the absence of galvanic connection) grounding electrodes 1, 2, 3 is used each having its own value R_{xi} , where $i = 1, 2, 3$. One of the grounding electrodes can be set to measure its resistance, others or already exist, or are created additionally. In general, the grounding electrodes 1, 2 and 3 are located in the ground.

Below we consider a system of three interacting grounding electrodes in the shape of circular plates with a diameter of 4 m, 2 m and 3.6 m. The plates are made of foamed polystyrene foam and placed on the surface of a water basin (30x20 m) with a specific resistance of water $\rho = 12 \Omega \cdot m$ at distances between them of 0.4 m. First, the resistance of the grounding electrodes was measured by a single-beam circuit [1], i.e. by the existing method (see Table 6 for the values). Measurements were made in early spring.

According to the new technique, a series of measurements are made in experiments A (Fig. 1,a), B (Fig. 1,b) and C (Fig. 1,c).

The circuit of the measurement circuit is assembled: the voltmeter 8 is connected to a pair of grounding electrodes (1-2) by means of wires 7, the voltmeter 10 is connected to a pair of grounding electrodes (2-3) by means of wires 9, the voltmeter 12 is connected to a pair of grounding electrodes (1-3) by means of wires 11. The source 6 of the current monitored by the ammeter 5 is

connected to a pair of grounding electrodes (1-2) by means of wires 4 and ensures current flow through the circuit (Fig. 1,a). We record the readings of the ammeter 5 (I_{1-2}), voltmeter 8 (U_{1-2}), voltmeter 10 (U_{2-3}), voltmeter 12 (U_{1-3}). From the grounding electrode 2 we disconnect wire 4, move it to grounding electrode 3 and connect to it. We provide the current flow through the circuit (Fig. 1,b). We record the readings of the ammeter 5 (I_{1-3}), voltmeter 8 (U_{1-2}), voltmeter 10 (U_{2-3}), voltmeter 12 (U_{1-3}). From the grounding electrode 1, we disconnect the wire 4, move it to the grounding electrode 2 and connect to it. We ensure the current flow through the circuit (Fig. 1,c). We record the readings of the ammeter 5 (I_{2-3}), voltmeter 8 (U_{1-2}), voltmeter 10 (U_{2-3}), voltmeter 12 (U_{1-3}).

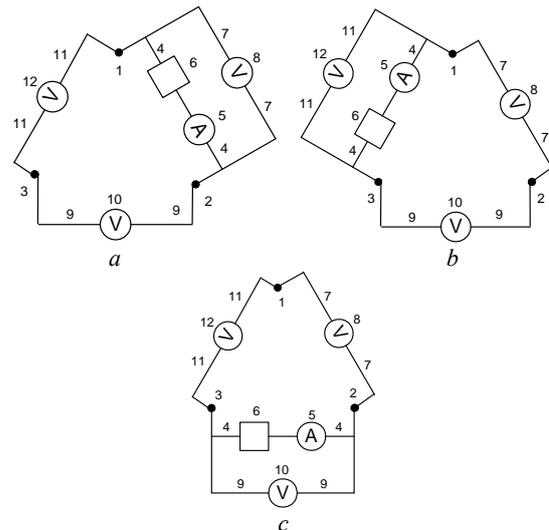


Fig. 1. . Schematic location of grounding electrodes and connection of measuring instruments

As a result of measurements, we obtain the values of parameters which we enter in Table 1.

Table 1
Results of full-scale measurements of parameters

Experiment	A	B	C
Measured parameter	Source introducing in points 1, 2	Source introducing in points 1, 3	Source introducing in points 2, 3
I_{12}, A	112.64	–	–
I_{13}, A	–	165.76	–
I_{23}, A	–	–	112.16
U_{12}, V	379.9	169.41	243.275
U_{13}, V	128.296	351.4	124.273
U_{23}, V	251.638	182	367.5

The treatment of given in Table 1 data allows to obtain input resistances for each pair of grounding electrodes in a system of three interfering grounding electrodes. The input resistance at input of a source between grounding electrodes, for example 1 and 2, is determined by expression

$$R_{12inp} = U_{12} / I_{12}.$$

Similarly, we obtain the values of the input resistances R_{13inp} и R_{23inp} . The results are summarized in Table 2.

Table 2
Input resistances for corresponding pairs of grounding electrodes

Determined parameter	Input resistances between grounding electrodes, Ω		
	R_{12inp}	R_{13inp}	R_{23inp}
Parameter value	3.37	2.11	3.27

According to the results of Table 2 and taking into account Fig. 2 we compose a system of three equations with six unknown values of a three-element grounding system:

$$\begin{aligned} R_1 + R_2 - 2R_{12} &= R_{12inp}; \\ R_1 + R_3 - 2R_{13} &= R_{13inp}; \\ R_2 + R_3 - 2R_{23} &= R_{23inp}. \end{aligned} \quad (1)$$

Neglecting (as an assumption) the mutual resistances (R_{12} , R_{13} and R_{23}) and the influence of the third grounding electrode within each pair, by solving the system of three equations with three unknowns obtained in this way, we calculate the approximate values of the own resistances of grounding electrodes (R_{10} , R_{20} and R_{30}) and summarize them in Table 3.

Table 3
Approximate values of the own resistances of grounding electrodes

Determined parameter	Own resistances, Ω		
	R_{10}	R_{20}	R_{30}
Parameter value	1.11	2.26	1

The obtained approximate values of the own resistances of grounding electrodes make it possible to estimate the approximate values of the mutual resistances between the grounding electrodes within each pair. Such an estimate is based on the fact that the mutual resistance between two grounding electrodes is always less than the smallest of them. The results of calculations are summarized in Table 4.

Table 4
Estimation of mutual resistances between the corresponding pairs of grounding electrodes

Determined parameter	Mutual resistances between grounding electrodes, Ω		
	R_{12mut}	R_{13mut}	R_{23mut}
Parameter value	1	0.8	1

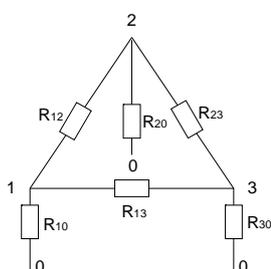


Fig. 2. Substitution circuit of the system of three interfering grounding electrodes

According to the measurement data (Table 1) of the currents (I_{12} , I_{13} , I_{23}) and voltages (U_{12} , U_{13} , U_{23}) obtained in each current measurement, we form a system of six equations with six unknowns representing the substitution

(Fig. 2) of a system of three interfering grounding electrodes. The system has the following form:

$$\begin{cases} R_{(1-3)A} = \left[(R_1 - R_{12}) - \frac{(R_{13} - R_{32})R_{13}}{R_3} \right] - (R_{13} - R_{32}); \\ R_{(3-2)A} = \left[(R_2 - R_{12}) + \frac{(R_{13} - R_{32})R_{32}}{R_3} \right] + (R_{32} - R_{13}); \\ R_{(1-2)B} = \left[(R_1 - R_{13}) - \frac{(R_{23} - R_{12})R_{12}}{R_2} \right] - (R_{23} - R_{12}); \\ R_{(3-2)B} = \left[(R_3 - R_{13}) + \frac{(R_{23} - R_{12})R_{23}}{R_2} \right] - (R_{23} - R_{12}); \\ R_{(1-2)C} = \left[(R_2 - R_{32}) + \frac{(R_{13} - R_{12})R_{12}}{R_1} \right] + (R_{12} - R_{13}); \\ R_{(1-3)C} = \left[(R_3 - R_{32}) - \frac{(R_{13} - R_{12})R_{13}}{R_1} \right] + (R_{12} - R_{13}). \end{cases} \quad (2)$$

The obtained approximate values of the parameters of the circuit (see Table 3, 4), in accordance with the procedure described in [8], are used as initial values for the solution of the system of six equations with six unknowns (2) for which the left-hand sides are presented on the basis of the measurements given in Table 1 as follows.

For example, in experiment A, the results of measuring the voltages U_{13} and U_{23} and the current I_{12} when a source is input between grounding electrodes 1 and 2 make it possible to obtain input resistances, i.e. the left-hand sides of the system of equations (2):

$$\begin{aligned} R_{13A} &= U_{13} / I_{12}; \\ R_{32A} &= U_{23} / I_{12}. \end{aligned}$$

The results of similar calculations for the input of a source between grounding electrodes 1 and 3 (experiment B), as well as grounding electrodes 2 and 3 (experiment C), are summarized in Table 5.

Table 5
The results of estimating the left-hand sides of the equations in the input of the source between the respective grounding electrodes

The source connection	Points 1, 2		Points 1, 3		Points 2, 3	
	R_{13A}	R_{32A}	R_{12B}	R_{32B}	R_{12C}	R_{13C}
Parameter value, Ω	1.139	2.234	1.022	1.098	2.169	1.108

Using the as initial approximate values of own (Table 3) and mutual (Table 4) resistances of the grounding electrodes and substituting the resulting left-hand parts (Table 5) into equations (2), we solve the system of equations using the program developed in the Mathcad package and summarize the results in Table 6.

Table 6
Results of measurements of own and mutual resistances of grounding electrodes by new and existing techniques and estimation of discrepancies

Parameter, Ω	R_1	R_2	R_3	R_{12}	R_{13}	R_{23}
Initial value	1.11	2.26	1	1	0.8	1
Using new technique	1.534	2.694	1.594	0.525	0.464	0.565
Using existing technique	1.5	2.7	1.6	0.53	0.47	0.57
Discrepancy, %	2.26	0.22	0.37	0.94	1.27	0.87

Analyzing the data of Table 6, we come to the conclusion that the results of the calculations agree satisfactorily with the results of measurements obtained in the experiments. In this case, the discrepancy does not exceed 2.3 %, which is a very good error result.

Thus, we obtain the required values of the own and mutual resistances of the grounding electrodes making up the three-element system.

Conclusions

For the first time, the technique of full-scale measurements of the resistance of grounding devices for various purposes using a three-electrode installation without finding a zero potential point is presented.

The proposed technique provides the minimal possible separation of measuring electrodes outside the GD which removes restrictions on building up the area outside the investigated GD, by several times reduces the length of the connecting wires of the measurement circuit which increases the signal-to-interference ratio.

Experimental full-scale measurements showed that the developed technique allows to obtain a fairly accurate result in all cases of GD resistance measurements of electrical installations.

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