THE EXPERIMENTAL VALIDATION OF THE GROUNDING DEVICE RESISTANCE MEASUREMENT METHOD

Purpose. The paper considers experimental research of three-electrode units for measuring the resistance of grounding devices for different purposes. Methodology. The experimental study of the method of resistance measurement of grounding devices for any design in any soil structure using the method of physical modeling is presented. Results. By results of model operation the set of equations of the sixth order is solved. It allowed to determine the own and mutual impedance in the three-electrode unit with high accuracy without searching the point of zero potential. Features of measuring and defining the own and relative resistances of various combinations of electrodes for three-electrode measuring unit are considered. Originality. The necessity of finding a zero potential point is excluded. Practical value. The proposed method provides the smallest possible spacing of potential electrodes outside the grounding devices. This reduces the wiring length measurement circuit in several times, increases the ratio «signal – noise», removes the restrictions on building of the territory outside the test grounding device. References 7, tables 10, figures 5.
K key words: experimental research, grounding device, the resistance measurement method, three-electrode unit, the method of physical modeling, experimental validation.

Introduction and problem definition. Currently, the three-electrode measuring device for measuring the resistance of grounding devices (GD) is widespread [1]. One of the main problems to be solved to get to this setting, sufficiently accurate results, is as specified in [2], the right choice of locations of measuring electrodes, i.e. such their arrangement in which the resistance of the measured value differs from its true value by not more than 10 % in either direction. However, in many cases (50 %) measuring the GD resistance for urban and industrial substations poses a serious problem to the present.

Analysis of recent investigations and publications. The problem of improving the accuracy of measurement of electrical parameters of the earth and GD are engaged many scientists both domestic and foreign.

Calculation method for determining the optimal position of the measuring electrodes in the measurement of GD resistance of large dimensions allowing to place the electrodes at short distances from the GD is described in [3]. However, it is noted that the calculations with the help of considered GD models have only limited application due to their external fields.

Analysis of Tagg methods for measurement of GD resistance given in [4] is shown that Tagg method is not suitable in soils with increasing of soil resistivity by depth.

The theoretical possibility of precise measurement of the GD resistance for each character of the soil heterogeneity and of any size and configuration of GD without the use of computer codes is noted in [5]. However, unfortunately, in this case it will be necessary to determine the location of the potential electrode by finding the point of zero potential on-site measurements.

Mathematical modeling of the process of GD resistance measurement current of industrial frequency in multilayer soil is presented in [6] which describes an algorithm for calculating measurement errors at different locations of the measuring electrodes and an example of the construction of lines of equal errors for GD of complex shapes in a four ground. Unfortunately, as the authors note [6], choose a layout of electrodes, in which the measured GD resistance equals true, experimentally in measurements on the ground impossible.

In [7] the author provides a theoretical basis of a new method of GD resistance measurement with a three-electrode measuring setup with any character of soil heterogeneity, of any size and configuration of GD and the arbitrary placement of the measurement electrodes without finding the point of zero potential.

The goal of the work is the experimental validation of the method [7] for measurement of GD resistance by means of a three-electrode measuring unit without finding a point of zero potential.

Experimental technique. For the study models of GD in the form of discs of different diameters \(d_1 = 10\) cm, \(d_2 = 5\) cm, \(d_3 = 9\) cm were accepted. The locations of GD in the electrolytic bath are shown in Fig. 1 and did not change in all experiments. The minimum distance between the edges of GD were \(a = b = c = 1\) cm. Several series of experiments were performed.

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In the **first series** measurements of flowing from the GD current \(I_{10}, I_{20}, I_{30}\) and voltage \(U_{10}, U_{20}, U_{30}\) were performed to determine the internal resistance of GD, i.e. of each in its place in the absence of the others as shown in Fig. 2 for GD 1 and dashed to GD 2 and 3. The results of measurements and calculations of own GD \(R_{10}, R_{20}, R_{30}\) resistances are presented in Table 1.

Similar measurements were made for cases source connection between the bath housing and the GD 2, and then GD 3. The results are shown in Table 2.

The **second series** of experiments was carried out using the three GD. In this case, a source connected to the earth electrode 1 and the bath body, i.e., current is injected into the first GD. We conducted \(I_{10}\) current measuring circuit, the voltage on the grounding conductors 1, 2 and 3 with respect to the bath housing \(U_{10}, U_{20}, U_{30}\), the voltage between grounding 1 and 2 \(U_{12}\), GD between 1 and 3 \(U_{13}\), and the GD 2 and 3 \(U_{23}\) in the circuit shown in Fig. 3.

Then, studies were carried out in the **third series** with three GD without their connection with the bath. In this case the source is introduced between GD 1 and 2 as shown in Fig. 4. In this case, measured flowing in the current circuit \(I_{12}\) and the voltage between GD 1 and 2 \(U_{12}\), between GD 1 and 3 \(U_{13}\), between 2 and 3 \(U_{23}\), and the voltage between each GD (1, 2 or 3) and the wall (casing) of bath, i.e. \(U_{10}, U_{20}\) and \(U_{30}\) as shown in Fig. 4 for GD 3.
Similar measurements were made while entering the source between GD 2 and 3, and between GD 1 and 3. The results of these measurements are presented in Table 3.

Table 3

| Measured parameter | Source entering between GD 1 and 2 | Source entering between GD 1 and 3 | Source entering between GD 2 and 3 |
|--------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $I_1$, mA          | 70.4                              | –                                 | –                                 |
| $I_2$, mA          | –                                 | 103.6                             | –                                 |
| $I_3$, mA          | –                                 | –                                 | 70.1                              |
| $U_{12}$, V        | 8.97                              | 4.175                             | 5.447                             |
| $U_{13}$, V        | 3.27                              | 8.65                              | 3.05                              |
| $U_{23}$, V        | 5.7                               | 4.475                             | 8.5                               |
| $U_{10}$, V        | 2.34                              | 3.58                              | 0.65                              |
| $U_{20}$, V        | 6.62                              | 6.2                               | 6.1                               |
| $U_{30}$, V        | 0.94                              | 9.1                               | 2.4                               |

In the fourth series of experiments, measurements were made with two GD, i.e., in the absence of the third one and without their connection with bath housing. Sources include grounding between 1 and 2, as shown in Fig. 5. In this case, we measured flowing in the current circuit ($I_{12}$), the voltage between the GD 1 and 2 ($U_{12}$) and the voltage between the bath housing and GD 1 ($U_{10}$), and between the bath housing and the GD 2 ($U_{20}$).

![Fig. 5. Measurement circuit for two GD without their connection with bath housing](image)

Similar measurements were made and when the source is turned on between the GD 1 and 3, and between the GD 2 and 3. The measurement results are shown in Table 4.

Table 4

| Measured parameter | Source entering between GD 1 and 2 | Source entering between GD 1 and 3 | Source entering between GD 2 and 3 |
|--------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $I_{12}$, mA       | 71.6                              | –                                 | –                                 |
| $I_{13}$, mA       | –                                 | 105.3                             | –                                 |
| $I_{23}$, mA       | –                                 | –                                 | 69.8                              |
| $U_{12}$, V        | 8.9                               | –                                 | –                                 |
| $U_{13}$, V        | 8.8                               | 3.7                               | 2.8                               |
| $U_{10}$, V        | 6.5                               | 5.1                               | 2.8                               |

Comparative analysis of the results of physical modeling of three-piece group of GD and the results of determination by the developed method of measuring own and mutual resistances of GD. According to the results of experiments for the measurements of earth models derived parameters that are given in the Table 5. In this case, the definition of resistivity of the medium gives $\rho = 12 \Omega \cdot m$, i.e. $\Delta R = 3.8 \Omega$ - the amendment to the final dimensions of the bath as determined by the formula for the hemisphere.

![Fig. 5. Measurement circuit for two GD without their connection with bath housing](image)

In the fourth series of experiments, measurements were made while entering the source between GD 2 and 3, and between GD 1 and 3. The results of these measurements are presented in Table 3.

Table 3

| Measured parameter | Source entering between GD 1 and 2 | Source entering between GD 1 and 3 | Source entering between GD 2 and 3 |
|--------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $I_1$, mA          | 70.4                              | –                                 | –                                 |
| $I_2$, mA          | –                                 | 103.6                             | –                                 |
| $I_3$, mA          | –                                 | –                                 | 70.1                              |
| $U_{12}$, V        | 8.97                              | 4.175                             | 5.447                             |
| $U_{13}$, V        | 3.27                              | 8.65                              | 3.05                              |
| $U_{23}$, V        | 5.7                               | 4.475                             | 8.5                               |
| $U_{10}$, V        | 2.34                              | 3.58                              | 0.65                              |
| $U_{20}$, V        | 6.62                              | 6.2                               | 6.1                               |
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In the fourth series of experiments, measurements were made with two GD, i.e., in the absence of the third one and without their connection with bath housing. Sources include grounding between 1 and 2, as shown in Fig. 5. In this case, we measured flowing in the current circuit ($I_{12}$), the voltage between the GD 1 and 2 ($U_{12}$) and the voltage between the bath housing and GD 1 ($U_{10}$), and between the bath housing and the GD 2 ($U_{20}$).

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| $I_{12}$, mA       | 71.6                              | –                                 | –                                 |
| $I_{13}$, mA       | –                                 | 105.3                             | –                                 |
| $I_{23}$, mA       | –                                 | –                                 | 69.8                              |
| $U_{12}$, V        | 8.9                               | –                                 | –                                 |
| $U_{13}$, V        | 8.8                               | 3.7                               | 2.8                               |
| $U_{10}$, V        | 6.5                               | 5.1                               | 2.8                               |

Results of measurements for two GD without their connection with bath housing

| Measured parameter | Source entering between GD 1 and 2 | Source entering between GD 1 and 3 | Source entering between GD 2 and 3 |
|--------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $I_1$, mA          | 71.6                              | –                                 | –                                 |
| $I_2$, mA          | –                                 | 105.3                             | –                                 |
| $I_3$, mA          | –                                 | –                                 | 69.8                              |
| $U_1$, V           | 8.9                               | –                                 | –                                 |
| $U_2$, V           | 8.8                               | 3.7                               | 2.8                               |
| $U_3$, V           | 6.5                               | 5.1                               | 2.8                               |

The measurement results shown in Table 4 can determine the input resistance at the input source between GD, for example as 1 and 2, by the expression

$$R_{12} = \frac{U_{12}}{I_{12}} \approx 124.3 \Omega$$

Similarly we obtain $R_{13}$ and $R_{23}$. Results are presented in Table 6.

Table 6

| Input resistances between GD, $\Omega$ | $R_{12}$ | $R_{13}$ | $R_{23}$ |
|--------------------------------------|----------|----------|----------|
| Parameter value                      | 124.3    | 83.6     | 126.0    |

The obtained results for the input resistances (see Table 6) make it possible to determine the approximate values their own resistances of separate GD as follows. Measurements performed for the respective pairs of GD, i.e., input resistance between the GD (Table 6) allow us to write the following equations

$$R_1 + R_2 - 2R_{12} = R_{12}$$
$$R_1 + R_3 - 2R_{13} = R_{13}$$
$$R_2 + R_3 - 2R_{23} = R_{23}$$

Neglecting (assumption) mutual resistances ($R_{12}$, $R_{13}$ and $R_{23}$) within a couple and the influence of the third electrode we obtain a system of three equations with three unknowns. We carry out solution to this system, and the results of calculations of its own approximate values of GD resistances are summarized in Table 7.

Table 7

| Approximate values of own GD resistances |
|-----------------------------------------|
| Determined parameter | $R_1$ | $R_2$ | $R_3$ |
| Parameter value      | 40.95 | 83.35 | 42.65 |

We calculate approximate values of the mutual resistances of the corresponding pairs of GD based on the fact...
that the mutual resistance of two interacting GD resistance is always less than the least of them. [4] On the basis of the relation (1):

$$R_{12\text{mut}} = (R_1 + R_2 - R_{12\text{op}})/2 = (58.08 + 108.56 - 124.3)/2 = 21.17 \, \Omega.$$  

Similarly, we obtain mutual resistances $R_{13\text{mut}}$ and $R_{23\text{mut}}$ and summarize results in Table 8.

### Table 8

| Parameter value | Mutual resistances between GD, $\Omega$ |
|-----------------|---------------------------------------|
|                 | $R_{12\text{mut}}$ | $R_{13\text{mut}}$ | $R_{23\text{mut}}$ |
| 21.17           | 18.79                  | 22.8                |

However, due to the processes taking place at the surface of the electrodes when the current flows the current change occurred more noticeable. This affects the results which are shown in Table 9 and Table 4, and it should be excluded.

Obviously, this can be attributed to the resulting discrepancy between calculated and experimental results. In the real world measurements, these differences should be significantly less. In all cases possible real conditions discrepancy can expect less than 10 %.

It should also be emphasized that the definition of the own and mutual GD resistances as the initial values was performed and the results of measurements in the three-element system (Table 3). The values obtained for GD own and mutual resistances have a slight difference from the similar values obtained for the respective pairs of GD in the absence of a third grounding (Table 4). Substitution of these values as the initial program for calculating own and mutual resistances of GD gives the same result as in Table 10. This important factor must be used when performing on-site measurements.

### Conclusions

Firstly, experimental investigation in the electrolytic bath at the NTU «KhPI» of a three-electrode unit for measuring the resistance of grounding devices for different purposes is carried out.

On the basis of the method of physical modeling experimental validation of the method of resistance measurement of grounding devices of any design in any soil structure is presented.

By simulation results the system of the sixth-order equations is solved that allowed to determine own and mutual resistances in three-electrode unit with high accuracy and without finding a point of zero potential.

The proposed method provides the smallest possible spacing of the measuring electrodes outside the grounding devices. This is several times reduces the length of the connecting wires of the measuring circuit increases the ratio «signal - noise», removes the restrictions on the development of the territory outside the tested grounding device.

The obtained results showed that developed in [7] method provides fairly accurate results in all cases of measurements of resistance of grounding devices of electrical equipment.

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