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Methods for Calculating the Resistance of Grounding Devices with Backfilling Special Compositions

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Abstract. Traditional analytical methods for calculating and designing of grounding devices (GDs) in heterogeneous soils can lead to results that do not correspond to those obtained in practice. The empirical coefficients used in calculations of grounding systems given in various literature sources do not always give an explicable and significant discrepancy with the same initial data. In this paper, some well-known methods for calculating the spreading resistance of GDs are considered and the obtained results are compared with experimental data. It is shown that the recommendations and algorithms for calculating the resistance of GDs, presented in the well-known reference literature and regulatory documentation, do not give full and correct description for grounding devices installed in heterogeneous soil. In particular, it is shown that such a factor as the proportional ratio of soils with different resistivity practically does not affect the final result. This fact may mislead specialists, since the results obtained may differ significantly from what is observed in practice after the installation of GDs. The study proposes a calculation method and shows a fairly good convergence of the results with experimental data, and defines a further direction in optimizing calculation methods GDs.

Introduction

Currently, in the Republic of Belarus, there is a quantitative increase in the work carried out on the construction of new and reconstruction of previously installed electrical installations. This is explained both by the increased requirements for protection against electric shock and by the introduction of stricter industry standards regarding the efficiency of the functioning of working grounding systems, especially for telecommunications devices and installations.

According to the requirements [1, 2], GDs of electric stations and substations (SS) must be periodically inspected. However, operating enterprises often ignore this requirement, which in the future can lead to serious consequences caused by a violation of the fundamentals of electrical safety in terms of grounding electrical equipment. The characteristic construction defects of GDs and lightning arresters identified by the authors during the examination of one of the 110/10 kV SS of the Belarusian energy system are given in [3].

There is an intensification of developments in the world in the direction of increasing the reliability and efficiency of grounding systems. Such developments are aimed at reducing the resistance and material consumption of GDs, as well as artificially lowering of seasonal coefficient (SC) [4–6]. The CS establishes the maximum change in the value of the resistivity of the upper layers of the earth in relation to its value when measured, which in a given climatic zone can take place during the year [1].

The influence of SC in calculating the resistance of GDs of small electrical installations (for example, distribution network facilities) is significant, except in cases of using deep grounding electrodes with a length of 10 m or more, for which the CS is approximately equal to 1 [1].

Based on the accumulated experience gained in measuring the parameters of more than a thousand electrical installations in the Belarusian energy system, it can be concluded that the use of traditional calculation and design methods for grounding devices [1, 2, 7] do not always lead to correspondence of the practical measured result to the expected design value.

Moreover, the empirical coefficients used in the calculations and obtained without computer and statistical processing can lead to discrepancies in the assessment results under the same initial design conditions. Further, using the example of experimental grounding electrodes, the convergence of the expected calculated values and measured values of real GDs is considered, and a calculation algorithm is proposed that takes into account the use of soil-substituting mixtures during the installation of GDs.

1 The importance of correct source data

The Technological Regulations of the Belarusian energy system [1, 2, 7] recommend take the electrical resistivity of soil (ERS) from the data of natural measurements when carrying out calculations and design of GDs, and

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tabular data should be used only in the absence of such data.

In our opinion, the use of tabular data is highly undesirable due to the significant error introduced in the results of design calculations. Often the results of geological sounding which is usually conducted to a depth of up to 6 m are used as data on ERS, with further interpretation based on the known dependencies of ERS on the type of soil (as well as tabular data).

The use of reference data lead to errors in the calculations of the spreading resistance of GDs [8]. Thus, when commissioning the 330–750 kV OHL, the measured value of the spreading resistance of some supports exceeded the permissible limit specified by the standard [9] by 2–3 or more times. In this regard, a system for determining ERS at the locations of supports and SS has been implemented at RUE "Belenergosetprojekt", using the method of vertical electrical sounding (VES) [8].

It is also shown in [10, 11] that the experimentally determined value of ERS in the location of the projected SS and overhead lines, along with the data of engineering and geological surveys, allows us to take into account the factor of soil corrosion factor of GDs of electrical installations. Moreover, taking into account seasonal changes in the soil condition when considering the choice of grounding electrode according to the condition of corrosion activity leads to an increase in ERS by 1.53–2.27 times [8].

2 The experimental part

To verify convergence, a test cycle (measurements of spreading resistance) was carried out on previously mounted GDs consisting of vertical and horizontal grounding electrodes.

The control grounding electrode was constructed with backfilling of initial soil, while the experimental grounding electrode was constructed with backfilling of soil with a significantly lower electrical resistivity.

To ensure the correctness of further comparison of the considered methods, the ERS was determined experimentally using the VES method with interpretation to a single-layer soil and taking into account the CS. At the same time, individual measurements of spreading resistance of all elements of GDs construction were carried out. The calculations of the resistance of GDs and modeling were carried out using both mathematical packages such as Maple, Origin, and specialized software ZYM [12].

The composite vertical grounding electrode is made of two interconnected steel rods with a diameter of Ø 18 mm and a total length of 3 m. The horizontal grounding electrode is made of 4x40 mm steel strip; it is mounted at a depth of 0.5 m; with low ERS is 0.8 Ohms·m; CS of soil is 2 (measured in the laboratory); CS of replaced soil is 1.48 (measured in the laboratory).

The spreading resistance of the control GD was 380 Ohms, and of the mounted GD with replaced soil was 114 Ohms. The measurements were performed using the MRU-200 meter (Sonel, Poland) according to a validated measurement procedure.

The results obtained made it possible to make an objective comparison of the methods, estimating the error of each of them.

3 Comparison of calculation methods

In [13], edited by Yu.G. Barybin, it is proposed to calculate the spreading resistance separately for horizontal and vertical electrodes. The resulting resistance of the GDs is based on the assumption that this configuration of the electrode system can be considered as a parallel connection of conductors.

The resistance of one vertical electrode R_v is determined by the formula (1):

$$R_V = \frac{0.366\rho}{L_V} \cdot \left(lg \frac{2L_V}{d} + \frac{1}{2} lg \frac{4t_V + L_V}{4t_V - L_V} \right), \quad (1)$$

where ρ – ERS, Ohm·m;
L_V – the length of the vertical electrode, m;
d – the diameter of the vertical electrode, m;
t_V – the laying depth of the vertical electrode (the distance from the ground surface to the middle of the electrode).

The total resistance of the grounding electrode part, consisting of vertical electrodes that are electrically connected, without considering the resistance of the connecting strip:

$$R_{\text{GDs.V}} = \frac{R_V \cdot k_V}{\eta_V}, \quad (2)$$

where k_V=1.45 – the coefficient for vertical grounding electrodes, taking into account the variation of ERS depending on the climatic region;

η_V=0.51 – the utilization coefficient of vertical electrodes for the configuration "Pipes arranged along the contour" with the ratio of the distance between the electrodes to the length of the electrode L_G / L_V =3/3=1.

The resistance of horizontal electrodes is determined by the formula (3), and the resistance of the horizontal grounding electrode, taking into account shielding and climatic region, is determined by the formula (4):

$$R_G = \frac{0{,}366\rho}{L_{\text{SUM.G}}} \cdot lg \frac{{L_{\text{SUM.G}}}^2}{d \cdot T}, \quad (3)$$

$$R_{\text{GDs.G}} = \frac{R_G \cdot k_G}{\eta_G}, \quad (4)$$

where k_G=3.5 – the coefficient for horizontal grounding electrodes, taking into account the variation of ERS depending on the climatic region;
η_G=0.31 – the utilization coefficient of horizontal electrodes;
T – the laying depth of the grounding electrode, m.

The values of the utilization coefficients were calculated using the linear interpolation method for the average values of interval tabular data [13]. Total spreading resistance of the GDs:

$$R_{\text{GDs}} = \frac{R_{\text{GDs.V}} \cdot R_{\text{GDs.G}}}{R_{\text{GDs.V}} + R_{\text{GDs.G}}}. \quad (5)$$

The following results were obtained based on formulae (1–5): R_V= 188.03 Ohms, R_{GDsV}=534.62 Ohms, R_G= 207.9 Ohms, R_{GDsG}=2346.71 Ohms, R_{GDs}=405.42 Ohms.

We will perform a similar calculation using the methodology authored by A.A. Fedorov and G.V. Serbinovsky, presented in [14].

It should be noted that the calculation of the GDs is based on the same principles and assumptions as in [13]; however, there are some differences:

1. The purpose of the calculation is to determine the number of necessary vertical electrodes based on a specified value of R_{GDs};
2. The tabular data does not match for different climatic zones. In [14], the values of the coefficients are higher than those in [13].
3. The mathematical formulae for calculating the spreading resistance of single electrodes differ somewhat; in [14], those for vertical and horizontal electrodes are presented:

$$R_V = \frac{\rho}{2 \cdot \pi \cdot L_V} \cdot \left(ln \frac{2L_V}{d} + \frac{1}{2} \cdot ln \frac{4t_V + L_V}{4t_V - L_V} \right), \qquad (6)$$

$$R_G = \frac{\rho}{2\pi \cdot L_{\text{SUM.G}}} \cdot ln \frac{{L_{\text{SUM.G}}}^2}{d \cdot \text{T}}, \qquad (7)$$

It is obvious, from a mathematical point of view, formulae (1) and (6), as well as (2) and (7), are identical.

After calculating the formulae (2, 4, 6, 7) for the considered GDs according to the methodology described in [10], the following results were obtained: R_V= 177.16 Ohms, R_{GDsV}=503.7 Ohms, R_G= 196.7 Ohms, R_{GDsG}=2537.62 Ohms, R_{GDs}=396.8 Ohms.

In the work [15] by R.N. Karyakin, special attention is focused on the definition of ERS. The authors point out that the electrical conductivity of the soil, if it does not contain high concentrations of conductive substances, is determined by the amount of water in it, its mineralization, and the nature of the distribution of water in the rock, and also depends on temperature.

For water-saturated rocks, the effect of temperature on resistance is similar to the effect of temperature on the conductivity of a saturated water electrolyte in the soil, which is in good agreement with the data obtained in [16]. The work contains an indication of the need for improvement, taking into account changes in the ERS at the sites of the soil-substituting mixture, as well as permissible fluctuations in the resistance of the grounding electrodes depending on temperature, that were given in [18-20].

According to [15, 16], resistance changes caused by temperature in electrolytes are approximated by the formula:

$$\rho_T = \rho_{20} \cdot e^{-0.022 \cdot (T-20)}, \qquad (8)$$

where ρ_T, ρ_{20} are the resistances at temperatures T and 20 °C, respectively.

According to the reference data given in [13], the second climatic region is characterized by an average long-term temperature (January) in the range from minus 14 °C to minus 10 °C. For calculations, we use an average value of minus 12 °C.

It was found that the ERS increased by 2.02 times. It is slightly higher than the correction factor for vertical rod electrodes K_V = 1.45, but also less than the correction factor for horizontal grounding electrodes
K_G = 3.5 [13]. According to [14], these coefficients are K_V = 1.5–1.8; K_G = 3.5–4.5.

It should be noted that as the depth of the soil increases, its temperature rises; therefore, using formula (8), it is possible to calculate the ERS at different depths depending on the soil temperature.

The problem lies in the fact that in the formula for calculating the resistance of the GDs in a single-layer soil, this difference in specific resistivity cannot be taken into account in any way. Therefore, this method can only solve the problem by switching to the method of calculating multi-layer soil, in which it will be possible to take into account the difference in the resistivity of layers of homogeneous soil at different temperatures. At the same time, when calculating the resistance of the GDs using the single-layer soil method, the resulting values will exceed those obtained using the multi-layer soil method. These values create a margin for an increase in resistance when designing GDs.

In general, the resistance of a complex grounding electrode, consisting of a horizontal strip with vertical electrodes placed at its nodes, is determined by the formula:

$$R_{\text{GDs}} = \frac{\rho_{\text{T}}}{\pi \cdot L_G} \cdot \frac{\lambda \cdot \text{C}_{11} \cdot \text{C}_{22} - {\text{C}_{12}}^2}{\text{C}_{11} + \lambda \cdot \text{C}_{22} - 2 \cdot \text{C}_{12}}, \qquad (9)$$

$$\lambda = \frac{L_G}{n \cdot L_V} = \frac{3}{1 \cdot 3} = 1, \qquad (10)$$

where C_{11}, C_{22}C, and C_{12} are coefficients for calculating grounding electrodes [15].

As a result of the calculation, it was found out that the spreading resistance of the GD in a single-layer soil was 93.61 Ohms. The obtained value was significantly lower than previously obtained using the methods outlined in [13, 14], and lower than the actual values obtained in practice (Table 1).

Table 1. Calculation results

Calculation method	Result, Ohm
Practical measurements	380
According to Yu. G. Barybin [13]	405.42
According to A. A. Fedorov and G. V. Serbinovsky [14]	396.8
According to R. N. Karyakin [15]	93.61

4 Calculation of GDs resistance with the condition of using soil-substituting mixtures

Currently, during the installation and repair of GDs, backfilling with so-called compensating mixtures or mixtures for optimizing the electrophysical parameters of GDs is actively used. This solution is quite well known [11, 17] and is used, among others, by the authors of this work. However, none of the previously mentioned methods allows us to assess GDs resistance when using such mixtures, as they have significantly lower resistance than the initial soil.

The issues of reducing GDs resistance by using soil treatment with moisture-stabilizing additives that are not aggressive to the grounding electrode material are considered in [18]. The most common and well-known method of assessing resistance when using soils with low resistance is given in [18]. This method describes the calculation of the grounding electrode when it is filled with coal chips.

The spreading resistance of a single vertical electrode in coke fines is determined by the formula:

$$R_v = 0.37k_1 \cdot \frac{\rho}{l_V} \cdot \left(ln\frac{2l_V}{d_{\text{eq}}} + 0{,}5\, ln\frac{4t_V + 3l_V}{4t_V + l_V} + \frac{\rho_1}{\rho} \cdot ln\frac{d_1}{d_V} \right), \quad (11)$$

where k_1 – the freezing coefficient that takes into account seasonal soil temperature fluctuations for vertical grounding electrodes;
d_{eq} – $0{,}95b$;
ρ_1 – electrical resistivity of the coke fines, Ohms·m;
d_1 – the outer diameter of the coke backfill, m.
The spreading resistance of a single horizontal electrode or connecting strip in coke fines at l_g> > d_g and t_g<<l_g/4 is determined by the formula:

$$R_g = 0.37k_2 \frac{\rho}{l_g} \left(lg\frac{2l_g}{d_g} + lg\frac{l_g}{2l_g} + \frac{\rho_1}{\rho} lg\frac{d_1}{d_g} \right), \quad (12)$$

where k_2 – the freezing coefficient that takes into account seasonal soil temperature fluctuations for horizontal grounding electrodes.

$$R_{overall} = \frac{R_g R_v}{\mu_1 R_v + \mu_2 n R_g}, \quad (13)$$

where μ_1 – the utilization coefficient of extended grounding electrodes;
μ_2 – the utilization coefficient of vertical grounding electrodes;
n – the number of vertical grounding electrodes.
After calculating based on the initial data, the following results were obtained: R_V= 502.18 Ohms, R_G=243.26 Ohms, $R_{overall}$=163.88 Ohms, 43 % higher than the experimentally obtained data.

With partial replacement of the soil around the electrodes, the resistance of grounding electrodes will change slightly. It contradicts experimental studies and indicates the impossibility of applying this calculation method when using soils with low resistance or mixtures to optimize the electrophysical parameters of grounding, without introducing a correction coefficient. This coefficient should reflect the change in the resistivity of the soil directly in the near-electrode space.

Our previous studies [11, 17, 19–21] make it possible to empirically describe the reduction of GDs resistance as a value that depends on change in the ERS:

$$\rho_{\text{eq}} = \rho \cdot 0{,}98^{\frac{d_{\text{mix}}}{d_{\text{GDs}}}} \cdot \left(\frac{\rho_{\text{mix}}}{\rho} \right)^{\frac{1}{3\pi}}, \quad (14)$$

where ρ_{eq} – the required calculated resistivity, Ohms·m;
ρ – ERS, Ohms·m;
d_{mix} – equivalent diameter of the mixture around the grounding electrode, m;
d_{GDs} – diameter of grounding electrode, m;
ρ_{mix} – the resistivity of bulk soil or soil mixtures, Ohms·m.

This formula has been tested on samples with different ERS. Comparing it with the one presented in [18] for coke fines and making the necessary calculations, it can be seen that the resulting formula more accurately describes the effect of soil replacement on the overall GDs resistance.

After calculating the GDs with the proposed coefficient, it was learnt that the grounding electrode resistance is 123.07 Ohms.

Table 2. Comparison of results using calculation methods recommended for multilayer soils.

Calculation method	Result, Ohm	Deviation, %
Experimentally measured value	114	–
According to R. N. Karyakin [15]	93.61	17.9
According to the method described in [17]	163.88	43.8
Proposed method	123.07	7.9

When using low-resistance soils for backfilling, the volume of the initial soil in the near-electrode space of GD is partially replaced by soil or a mixture of soils with a much lower resistivity. The effectiveness of such a replacement depends on the resistivity of the initial soil, the resistivity of the bulk soil, and the volume of the replacement. However, using the method given in [11], we see that the calculated grounding electrode resistance depends extremely little on the volume of backfilling, which contradicts practical experience, since it is obvious that the parameter affecting the change in resistivity will be the area of contact between the mixture and the initial soil, and in the case of applying the mixture along the entire length of the electrode, it will be the contact perimeter. Thus, with an increase in the volume of backfilling, the grounding electrode resistance as a whole should also change. This is well aligned with our proposed formula for the equivalent resistivity of the soil. Applying it in conjunction with the methods outlined in [13, 14], calculated values match the experimental results within 10%.

Conclusion

The results of calculating the spreading resistance of the GD according to the methods described in [13, 14] align quite well. The main differences are observed in the fact that the algorithm in [13] is designed to calculate resistance based on a known configuration of the GD, while in [14] it is intended to determine the configuration of the GD based on a given value of the spreading resistance. These methods include various coefficients for calculating the ERS depending on the climate zone. Moreover, the mentioned methods do not allow for correct calculations of the GD's resistance for two-layer soil. The source [15] contains a method for calculating the GD located in a two-layer soil, but the resistance value of the GD in this case significantly exceeds the values obtained in [13, 14].

However, none of the above methods makes it possible to take into account changes in ERS based on the example obtained by the authors using empirical coefficients or those given in [20]. Using the formula obtained in the work together with the methods described in [13, 14], it allows us to describe experimental results, while the convergence of the results with experimental data is within 10%.

The empirical formula for an effective ERS obtained on the basis of experimental data makes it possible to adapt known calculation methods for the use of both soils with low resistivity and soil-substituting mixtures, while also achieving sufficient convergence with experimental data.

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