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# DETERMINATION OF THE SOIL SOUNDING DEPTH FOR THE EARTHING RESISTANCE CALCULATION OF SUBSTATIONS 35 KV

***Purpose. Determination of the minimum required sounding depth for calculation of the earthing resistance for substations with a voltage class of 35 kV. Methodology. For each ratio of electrical resistivity values of soil layers, earthing resistance was calculated with changing of the layers separation depth from 0.4 m to $h_{max}$, where $h_{max}$ is the layers separation depth in a two-layer soil at which the earthing resistance value becomes the same as in a uniform soil. Results. In the experiments carried out, a family of curves was obtained that describes the effect of separation depth of soil layers for various combinations of soil electrical resistivities and geometric dimensions of the earthing arrangement. The accumulated statistical data for substations with a voltage class of 35 kV made it possible to determine the required sounding depth depending on the maximum size of the earthing arrangement and the probability of the relative resistivity falling into the corresponding range of values. An algorithm is proposed for determining the required investigation depth by Wenner method as part of the electromagnetic diagnostics of the earthing arrangement of existing substations with a voltage class of 35 kV. Originality. For the first time, a probabilistic relationship was established between the ratio of the electrical resistivity of soil layers, the size of the earthing arrangement, and the necessary depth investigation of the geological medium. As a result it has been proven that there are substations for which the required sounding depth does not exceed the maximum size of the earthing arrangement. Practical value. The use of the algorithm developed in this work allows increasing the accuracy of the earthing resistance calculation of electrical installations with voltages above 1 kV operating in a network with isolated neutral.*** References 9, figures 4.
*Key words:* **earthing arrangement, earthing resistance, the soil sounding, Wenner installation, electromagnetic diagnostics.**

***Метою роботи є підвищення точності визначення опору заземлювального пристрою електроустановок напругою понад 1 кВ, що працюють в мережі з ізольованою нейтраллю. Для цього було проаналізовано величину необхідної глибини зондування ґрунту у процесі виконання електромагнітної діагностики стану заземлювального пристрою. Були проведені чисельні експерименти, які полягали у розрахунку електричних параметрів заземлювача, виконаного у вигляді прямокутника розмірами a × b з діагоналлю D і розташованого на глибині 0,3 м у двошаровому ґрунті. Було розглянуто різні варіанти співвідношення питомих електричних опорів ґрунту та розмірів заземлювального пристрою. Врахування статистичного розподілу вказаних параметрів для понад 500 підстанцій України класом напруги 35 кВ дозволило встановити двофакторну ймовірнісну залежність мінімально необхідної глибини зондування ґрунту установкою Веннера.*** Бібл. 9, рис. 4.
*Ключові слова:* **заземлювальний пристрій, опір заземлювального пристрою, зондування ґрунту, установка Веннера електромагнітна діагностика.**

***Целью работы является повышение точности определения сопротивления заземляющего устройства электроустановок напряжением выше 1 кВ, работающих в сети с изолированной нейтралью. Для этого была проанализирована величина необходимой глубины зондирования грунта в процессе выполнения электромагнитной диагностики состояния заземляющего устройства. Были проведены расчетные эксперименты, которые заключались в нахождении электрических параметров заземления, выполненного в виде прямоугольника размерами a × b с диагональю D и расположенного на глубине 0,3 м в двухслойном грунте. При этом были рассмотрены различные варианты соотношения удельных электрических сопротивлений грунта и размеров заземляющего устройства. Учет статистического распределения указанных параметров для более 500 подстанций Украины классом напряжения 35 кВ, позволил установить двухфакторную вероятностную зависимость минимально необходимой глубины зондирования грунта установкой Веннера.*** Библ. 9, рис. 4.
*Ключевые слова:* **заземляющее устройство, сопротивление заземляющего устройства, зондирование грунта, установка Веннера, электромагнитная диагностика.**

**Problem definition.** To ensure reliable and safe operation of energy objects in the case of a short circuit [1] or direct lightning strike [2], an earthing arrangement made in accordance with regulatory requirements is used. For electrical installations exceeding 1 kV operating in a network with isolated neutral (substations of 35 kV voltage class and below), the only electrical parameter that allows to estimate the condition of the earthing arrangement (EA) is its resistance ($R_{EA}$) [1]. According to [3], the value of the $R_{EA}$ should be periodically monitored and determined at least every 12 years. The measurement of the resistance of the EA, as a rule, is performed by the method of ammeter-voltmeter using a single-beam or two-beam circuit. Here, it is necessary to install measuring electrodes in the zone of zero potential, the distance to which, as a rule, several times exceeds the largest size of the EA [4].

For 35 kV substations, which are located in dense urban or industrial development with a branched communication system, this is practically impossible. Therefore, the only way to determine the resistance of the EA of such energy objects is to calculate it using special software systems. Therefore, improving the accuracy of $R_{EA}$ calculation is an urgent task in terms of electrical safety and reliability of electrical installations exceeding 1 kV with isolated neutral.

Initial data for the calculation of the resistance of the EA are a real diagram of design with indication of the depth of arrangement of the elements of the EA, the cross-section of earthers and electrophysical characteristics (EPC) of the soil (number of soil layers, their specific electrical resistance (SER) and thickness) [5].

Constructive execution of the EA of objects, which are in operation for a long time, is determined by the induction method when conducting the electromagnetic diagnostics of the state of the EA [4], the cross-section of the earthers is measured at a selective opening of the soil, and EPC of the soil according to the results of vertical electrical sounding (VES) near the substation. The soil EPC ratio (SER of the first layer $\rho_1$ and of the second layer $\rho_1$, as well as the thickness of the first layer $h_1$) and the geometric dimensions of the EA actually determine the required sounding depth and the technical parameters of the device for conducting the VES [6]. The authors from 1999 to 2019 conducted electromagnetic diagnostics of the state of over 500 substations of a 35 kV class voltage, which are located in all regions of Ukraine, so the accumulated statistics allow us to determine the characteristic sizes of substations' EAs and the limits of soil EPC values.

As the literature analysis in [7] shows, there is no clear relationship between the size of the EA and the required depth of sounding. Depth of sounding ($H_{\text{VES}}$) has been determined by Kostruba S.I. as early as 1983, as the dependence of the distance between the current electrodes from the square root of the EA area, only for the Burgsdorf installation, however, there is no similar or any other dependence was given for other VES installations (in particular, for the most common Venner installation) [6].

In [6, 8, 9] some data from the study of the required depth of sounding, obtained in the study of the dependence of the resistance of the EA on its area are given. From the analysis of the mentioned works, the following conclusion is reached: if the value of SER decreases with increasing depth, then it is necessary to determine the soil structure to a depth of at least $1.5\cdot\sqrt{S}$, and with increasing – several $(3–5)\sqrt{S}$. Thus, there is no clear dependence of the required sounding depth on the size of the EA and the soil EPC in the works on the VES for the purpose of designing or diagnostics of EA.

**The goal of the work** is the determination of the minimum required depth of sounding soil for the calculation of the resistance of the substations' EAs with a voltage class of 35 kV.

**Research materials.** The EA size, as indicated above, determines the required sounding depth $H_{\text{VES}}$ when conducting the diagnostics of the EA condition, so it is suggested to find it in the form of the product of the largest geometric size of the EA (diagonal) $D$ and the sounding coefficient $K_{\text{VES}}$:

$$H_{\text{VES}} = K_{\text{VES}} D. \quad (1)$$

Thus, the problem is actually reduced to determining the $K_{\text{VES}}$ coefficient, which depends on the corresponding diagonal size of the EA and the soil EPC.

To solve this problem it is necessary to analyze the influence of each of the factors within their values. To determine the effect of the size of the EA, we use the results obtained during the diagnostics of the state of the substations' EAs of the voltage class 35 kV, represented as the probability density of the maximum size $D$ [5].

From the analysis of Fig. 1 it follows that the value of the largest diagonal lies in the range from 10 m to 300 m, taking into account the substations at which the study was not conducted.

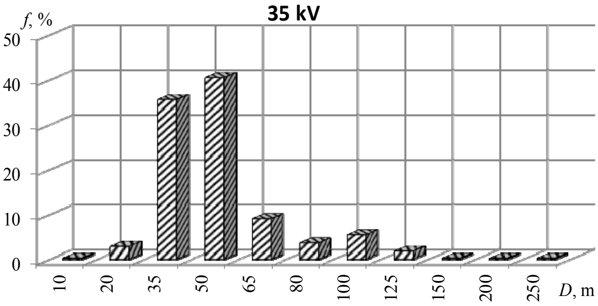



Fig. 1. Probability density of the size $D$ of the EA

Different soil SER ratios $\rho_2/\rho_1$ were also systematized: Fig. 2 shows the probability density of the relative SER value $\rho^*$ which was determined by the results of the VES in the framework of electromagnetic diagnostics of the EA of the studied substations in all regions of Ukraine.

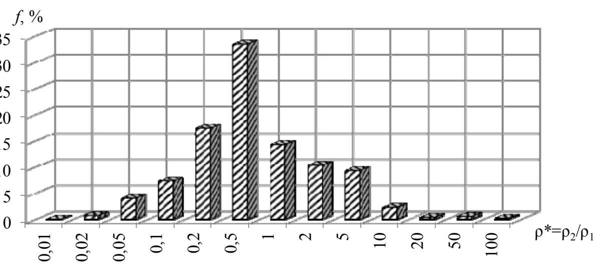
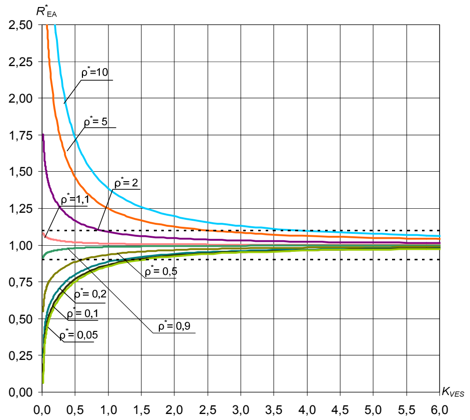



Fig.2. Probability density of the relative SER

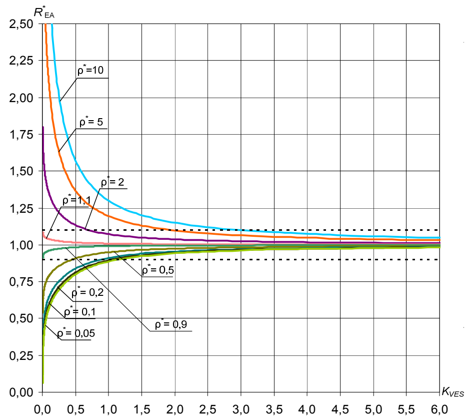
According to the results obtained, it is advisable to consider $\rho^*$ in the range [0.05; 10] which allows to cover 99 % of Ukraine's soils in the locations of existing substations.

Numerical experiments were carried out to determine $H_{\text{VES}}$ which consisted of calculating the resistivity of the EA ($R_{\text{EA}}$), made in the shape of a square $a \times a$ of diagonal $D$ and located at a depth of 0.3 m in two-layer soil. There are no internal cells in the EA as their effect on $R_{\text{EA}}$ is insignificant and does not exceed 10 % [6]. The required sounding depth was determined by the relative resistance of the EA based on the study of the effect on its of the depth of layer separation $h$. For each $\rho^*$, the value of $R_{\text{EA}}$ was calculated when the $h/D$ ratio varied from 0.4 m to $h_{\max}$, where $h_{\max}$ is the depth of layer separation in a two-layer soil, at which the resistance of the EA becomes equal to the resistance of the EA in a homogeneous soil ($R_{\text{EA}} = R_{\text{EAUNI}}$). In this case, the value of $\rho_1$ varied for the variation $\rho^*$, and the base $\rho_2$ was 1000 Ω·m which allows to cover all the ratios $\rho_2/\rho_1$ [5].

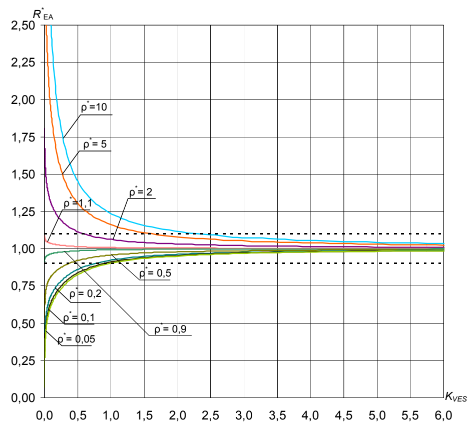
In the course of the experiments, a family of curves was obtained describing the effect of $h$ for different combinations of soil EPC and the geometric parameters of the EA $R^*_{\text{EA}} = f(h / D)$, where $R^*_{\text{EA}} = R_{\text{EA}} / R_{\text{EAUNI}}$. The results of calculations for the EA, which is made in the shape of a square with side $a$ = [10; 40; 100; 200] m and diagonal $D$ = [14; 56.6; 141; 282] m respectively, are shown in the graphs of Fig. 3.



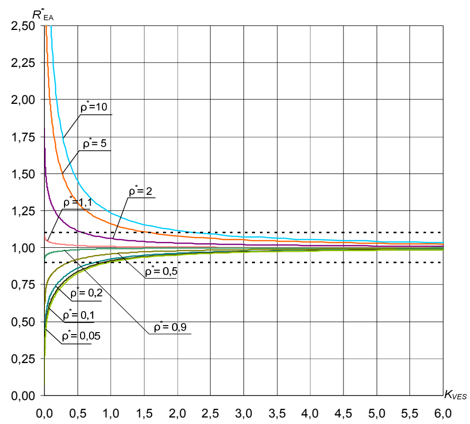

*a*




*b*




*c*




*d*

Fig. 3. Dependencies of the relative resistance on the coefficient of the depth of sounding:
*a* – *a* = 10 m, *D* = 14 m; *b* – *a* = 40 m, *D* = 56.6 m;
*c* – *a* = 100 m, *D* = 141 m; *d* – *a* = 200 m, *D* = 282 m

The graphs indicate the 10 % deviation by the dotted line. As it can be seen, for the EA with a diagonal of 14 m to calculate with an error of not more than 10 % it is necessary to sound the soil to a depth of not less than 4 *D*, and for the EA with a diagonal of 56 m – 3 *D*. Considering the individual ranges of values of $\rho^*$, we can state that at placement of $\rho^*$ in the range [0.05; 2] (corresponding to 95 % of the substations studied in Ukraine) sounding depth is 1.5·*D* for 14 m and 1.0·*D* for 56 m. That is, for example, reducing the probability of $\rho^*$ falling into the $p_{EA}$ range from 0.99 to 0.95, it is possible to significantly reduce (by three times) the calculated value of the required sounding depth for the same substation ($D$ = 56 m) from $H_{VES}$ = 3$D$ to $H_{VES}$ = $D$. This significantly reduces the labor costs of performing the VES while maintaining the accuracy of the calculations.

The possibility of reduction of probability is determined based on prior information about the structure of the soil in the relevant geographical area (for example, it is unacceptable for mountainous terrain where it is known that the resistance of the lower layers of rocks will be an order of magnitude greater than the resistance of the upper sedimentary rocks, i.e. $\rho^*\geq 10$).

In general, the dependence of the resistance of the EA on its geometric dimensions is nonlinear in nature, and with a conditional infinite increase in the size of the EA the value of the resistance is included in the "saturation" [6, 9]. The analogy with the dependence of the $K_{VES}$ coefficient on the diagonal of the EA, which in turn determines the required sounding depth, seems logical. Taking into account the graphs presented (see Fig. 3), the $K_{VES}(D)$ function was obtained for the studied ranges of values with a given probability (see Fig. 4):

- $\rho^* \in$ [0.05; 10], which corresponds to the probability of falling into the range $p_{EA}$ = 0.99;
- $\rho^* \in$ [0.05; 5], which corresponds to $p_{EA}$ = 0.98;
- $\rho^* \in$ [0.05; 2], which corresponds to $p_{EA}$ = 0.95.

The obtained graphs allow to determine the required sounding depth, depending on the maximum size of the EA and the probability of falling $\rho^*$ in the range according to expression (1).

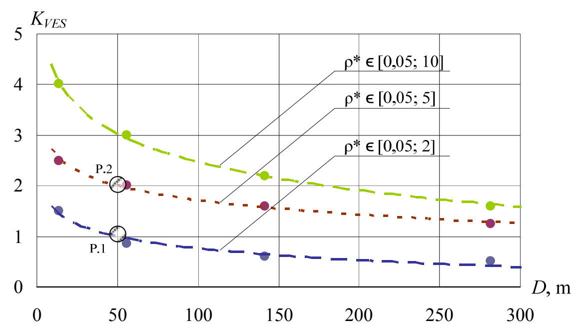



Fig. 4. Dependence of the sounding coefficient on the size of the EA

In addition, the analysis of the obtained data shows that there are such soil ratios and sizes of EAs for which the sounding depth required does not exceed the maximum size of the EA ($D$): these are substations at those EAs $D \geq$ 50 m (according to Fig. 1 their 61 %) for $p_{EA}$ = 0.95.

Taking into account the statistics (see Fig. 1, 2), the probability of finding such a substation $p_{LD}$ is:

$$p_{LD} = 61\ \%\cdot 0.95/100\ \% = 0.58.$$

Taking into account the above, the following algorithm of determination of $H_{VES}$ is proposed when conducting VES in the framework of electromagnetic diagnostics of the state of the EAs of operating substations of 35 kV class (provided there is no prior information about the soil structure):

1) to determine the maximum size of the EA using the induction method (for example, $D$ = 50 m);

2) to consider that the soil has a relative SER value in the range $\rho^* \in [0.05; 2]$ (see P.1 in Fig. 4: $K_{VES} = 1$, hence $H_{VES} = D$);

3) the soil is sounded by means of the Wenner installation [3-5] at a maximum inter-electrode distance equal to $D$;

4) approximate interpretation of VES results is performed;

5) depending on the obtained value of SER in item 4 the following options are possible:

- if $0.05 \le \rho^* \le 2$, then we believe that the sounding depth is sufficient;
- if $2 < \rho^* \le 5$ or $\rho^* > 5$, then to determine the required sounding depth according to the corresponding curve of Fig. 5 and expression (1), to increase the inter-electrode distance and to carry out additional measurements (for example, if $\rho^*$ = 4.5, then the required sounding depth has increased to $2D$ – see P.2 in Fig. 4);

6) if necessary, the results of the VES are re-interpreted and the value of $\rho^*$ obtained is evaluated.

**Conclusions.**

1. On the basis of the analysis of statistical data on the results of electromagnetic diagnostics of substations with a voltage of 35 kV, the probabilistic dependence of the required depth of sounding on the ratio of specific resistances of the soil and the size of the EA was determined.

2. It is found that there are soil ratios and sizes of the EAs for which the required depth of sounding does not exceed the maximum size of the EA. Taking into account statistics, the probability of finding such substations is 0.58.

3. An algorithm for determining the minimum required depth of sounding depending on the size of the diagonal of the EA of the substation and the ratio of SER of soil layers is developed.

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