UDC 621.316.9 **doi: 10.20998/2074-272X.2016.5.12**

S.S. Rudenko

REQUIREMENTS FOR DEVICES FOR VERTICAL ELECTRICAL SOUNDING OF SOIL AT DIAGNOSTICS OF GROUNDING DEVICES

Purpose. Creation the scientific requirements for technical characteristics of equipment for vertical electrical sounding based on the electrophysical characteristics of the soil of energy objects with the different voltage classes. Methodology. In work used statistical methods for the analysis database of results the soil sounding and for receiving distribution of largest size of the grounding system. To determine the required range of measurement and permissible value of circuit resistance applied the mathematical description of the electromagnetic field to calculate the apparent resistivity of the soil and the Wenner method of calculating the resistance of a vertical electrode. Also, in work used elements of probability theory to creation the stochastic correlation between device parameters and characteristics object of the research. Results. In the paper found that in the most severe cases (when the depth of sounding is the three maximal diagonal of grounding) at 99% energy objects in Ukraine the lower limit of resistance measurement for the respective classes of voltage must be no more than 1.3 milliohms to 35 kV, 0.6 mOhm to 110 kV, 0.5 milliohms to 150 kV, 0.1 mOhm for ≥ 220 kV. Also it proved that the measurement equipment for vertical electrical sounding when performing electromagnetic diagnostics of grounding system the power facilities Ukraine with 35-750 kV voltage class for all possible values of soil resistivity should be with limit of measurement from 0.1 mOhm to 7.2 kOhm and resistance measuring circuit to 66 kOhm. Originality. For the first time used a statistical approach to evaluate the optimal technical requirements for equipment the soils resistivity when performing diagnostics of grounding systems energy objects of Ukraine. The results obtained in this work, establish the probabilistic dependence of the technical characteristics of measuring equipment from the actual depth of sounding in Wenners configuration (the distance between electrodes) and from the voltage class of object. Practical value. The obtained results allow depending on the specific parameters of the object optimally select the equipment. This technique allows you to create a range of equipments with optimal cost and overall dimensions depending on the region (considering to a significant spread of values of soil resistivity) and on the voltage class of investigated object. References 7, tables 6, figures 5.
Key words: **vertical electrical sounding, grounding device, soil, energy object, technical requirements for equipment.**

На основе анализа статистической базы данных по зондированию грунта и диагностики состояния заземляющего устройства сформулированы требования и созданы рекомендации относительно выбора приборов для проведения вертикального электрического зондирования в зависимости от класса напряжения энергообъекта и доверительной вероятности. Доказана эффективность выбора приборов на основе оптимальных требований. Библ. 7, табл. 6, рис. 5.
Ключевые слова: **вертикальное электрическое зондирование, заземляющее устройство, грунт, энергообъект, технические требования к приборам.**

Problem definition. The purpose of the vertical electrical sounding (VES) is to determine the parameters of the geoelectric structure – the electrophysical characteristics (EPC) of soil: the number of layers, their electrical resistivity (ER) and the power, by injecting an AC generator and measuring the voltage drop on a specific section of the ground surface [1-3]. The value of the spacing of the current and potential electrodes is caused by the type of installation and the required depth sensing. Apparatus, method and interpretation of VES means are well-developed, both theoretically and practically in the framework of the geological survey [4]. Indicated EPC are the initial data for the determination of normalized electrical parameters of the grounding device (GD) as at the design stage as well as during its operation [5]. Therefore, the determination of their maximum reliability is one of the most important tasks.

Devices for VES are characterized by electrical parameters, technological ones (stand-alone or utility power, the ability to connect to a PC, moisture), as well as dimensions and weight parameters. As part of the electromagnetic state diagnostics of the grounding device (EMD GD) during the VES basic parameters of measuring instruments are: accuracy class, measuring range, sensitivity, permissible value of the current and potential resistance circuit, the operating frequency. It is also an important requirement for them is the portability and battery life, as the VES is carried out, as a rule, far away from the mains. The operating frequency is selected close to the industry, but differs from it in order to minimize the influence of electromagnetic field working electrical currents. During the VES in the implementation of EMD GD, the parameters of the instrument requirements (measurement limit, sensitivity, and the permissible value of the measuring circuit resistance), and in general the possibility of using a particular installation of VES are determined by the value of the ER and geometrical dimensions of the GD [1, 5] but in the literature clear requirements to instruments not available. Therefore, the development of technical requirements for appliances for VES depending on the ER of the soil and the required depth sensing is an urgent task. The development of these requirements it is proposed to implement on the basis of the analysis of the database of VES in different regions of Ukraine near the locations of power plants voltage class of 35 – 750 kV [5]. Availability of statistical data on the soil ER and GD sizes allow us to make a probabilistic assessment of the applicability of the instrument in their technical specifications it should be taken into account that the voltage class is crucial for electrical installations' geometrical sizes.

The goal of the paper is the development of science-based requirements for specifications of equipment for VES in the framework of the EMD GD based on the grounds of the EPC of soils of energy objects of Ukraine of different voltage classes.

In the formation of the requirements for appliances for VES at EMD GD it is necessary to solve a number of tasks in the following sequence:

- to perform statistical analysis of ER of layers of soil in order to determine the probability that the value of the resistivity in one of the confidence intervals;
- to assess the required depth sensing;
- to carry put statistical analysis of GD sizes for different voltage classes;
- to determine the allowable values of the lower and upper limits of the measurement device;
- to define the permissible value of the resistance measuring circuit;
- to formulate a generalized technical requirements for devices.

1. Statistical analysis of soil layers ER. For the statistical analysis of the resistivity we used VES results database compiled for 7 years from 2007 to 2014 [6]. These data are shown in Table 1.

Table 1

	ER ratio			Layer ER ρ_i, Ω·m			ER power	
	ρ_1/ρ_2	ρ_2/ρ_3	ρ_1/ρ_3	ρ_1	ρ_2	ρ_3	h_1, m	h_2, m
Average	5.12	6.03	12.11	183.9	136.93	67.63	0.79	5.46
Median	2.75	2.29	4.31	75	29	18	0.45	4
Mode	5	0.5	2	200	15	30	0.2	10
Minimum	0.017	0.004	0.018	3.0	1.2	0.3	0.02	0.01
Maximum	83.3	416.7	625	8700	7000	9000	10	35
Sample	612	592	592	612	612	592	612	592

Analysis of the data presented in Table 1 [6] the minimum and maximum values of ER of various layers showed that VES devices for the diagnosis of the state of the memory must be capable of measuring the ER of 0.3 to 9000 Ω·m.

Such a wide range of measurements, taking into account the large spread required probing depth (it varies from a few dozen to several hundred meters, depending on the GD size of the object), leads to an increase in the unit cost and large overall dimensions, as well as to the need for close venue VES network or mobile power source (e.g., a diesel generator). However, it should be noted that these values are the limit and cover 100 % of the soil and substations of all voltage classes of Ukraine. In order to assess the optimal requirements, use the histogram distribution EPC values given in Table 1 from [6]. Their analysis showed that when considering ER values as a single set of data and calculating a relative particular, are within $\rho \in [3; 9000]$ Ω·m covers 99 % of the cases, $\rho \in [3; 2000]$ Ω·m – 98% of cases, and $\rho \in [5.5; 2000]$ Ω·m – 97 % which may allow to significantly reduce the required range of measured values. Common power (99 % of cases) lies within $h_1 \in [0.1; 7.5]$ m and $h_2 \in [0.5; 30]$ m.

2. Estimation of the required depth of sounding. In [1, 7] that the memory size actually defines the required depth sensing. However, as the literature review, carried out in [6], a clear correlation between the size of the memory and the required depth sensing is absent, and the dependence of the current electrodes separation was obtained by S.I. Kostruba only for installation of Burgsdorf in 1983:

$$L_C = K_{VES}\sqrt{S}, \quad (1)$$

where L_C is the distance between current electrodes, m; K_{VES} is the geometrical size ratio between the substation and the electrode spacing varying from 1 to 3 depending on the GD area (S), m^2.

However, the literature has not shown a similar or some other relationship to other VES systems (in particular for the most common installation of Wenner).

In [1, 7] presented some data on the required depth sensing obtained by studying the dependence of the resistance of the GD of its area. From the analysis of these works should be concluded on the need to determine the structure of the soil, at least, at a depth of about $\sqrt{S}$ at the ER decrease with increasing depth, while increasing the ER of the underlying layers – need information about the structure of the soil at a depth of a few $\sqrt{S}$.

In addition, an important practical issue is the depth of the installation, i.e. dependence of the depth sensing the magnitude of a particular installation spacing current (or potential) electrodes. Probing depth different settings VES studied more than eighty years since the 30s of the last century, and the matter has undergone three major stages of development: in the 30s they engaged K. Schlumberger, in 1970 – Roy and Apparo and the last stage of the research which began in the late 80s from the work by Barker and lasting until now [3]. The main methods of estimating the depth at the moment are: the dependence of the current density on the depth of the derivative of the current density on the depth Merrick function and the use of formulas by Dar-Zarrouk. This current density is taken to decrease its value up to 50-80 %, and their extremes are taken according to the derivative of the current density on the depth and Merrick function. According to the data given in the works of geophysical prospecting depth for installation of Schlumberger (Wenner installation is actually a special case) in a fraction of the spacing of current electrodes varies from 1/10 L_C to 1/2.5 L_C while in the literature [3] there are cases where the depth is reduced to 1/200 L_C under the influence and relations of macroanisotropy of ER layers.

So, in works devoted to carrying out VES for the design or diagnose memory, there are ambiguous information about the desired depth sensing which should be determined by the GD size and soil ER. In the frame of this work will take the assumption, the traditional practice of VES for the design and GD diagnostic: the probing depth setting Wenner is one-third the value of the current spacing of the electrodes (ie, inter-electrode distance between the two nearest electrodes L_e). Given that the issue required depth sensing still does not have a unique solution, and in the practice of EMD GD for storage of measurement and touch voltage resistance is used the distance (1.5 – 3) D, where the D is the longest diagonal of the GD then consider the required probing depth of between one and three D. Therefore, is fair to the Wenner installation expression is fair:

$$L_e = K_{VES} D, \quad (2)$$

where K_{VES} ranges from 1 to 3.

Here, the expression (1) to determine the distance between the current electrodes, respectively, will be:

$$L_C = 3 K_{VES} D. \quad (3)$$

3. Statistical analysis of GD sizes for different voltage classes. The size of the memory, as indicated earlier, defines the required depth sensing EMD during EMD GD. Fig. 1 shows a histogram of the percentage distribution f of the greatest diagonal D to 963 electrical substations, diagnostics of memory which was conducted between 1999 and 2015.

From the analysis of Fig. 1 shows that 58 % of the highest value storage diagonal lies within 10-100 m, i.e. spacing value in the application of current electrodes Wenner installation according to (3) is 90 – 900 m (with the coefficient of spacing K_{VES} = 3) and can be realized in practice.

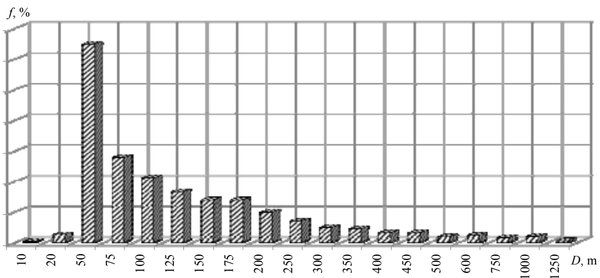

Fig. 1. The probability density of the largest diagonal values in the GD of energy objects of Ukraine

Fig. 2 – 5 shows the histograms of the percentage distribution of the length of the largest diagonal f for different voltage classes.

Based on the histograms shown in Fig. 2–4, in Table 2 presents data on the maximum size of the GD diagonals for the confidence interval with a confidence level γ equal to 50 %, 80 %, 90 % and 99 % of the patients of power corresponding to the voltage class. For example, this means that 80% of substations voltage class U = 110 kV have maximum diagonal GD length $D \leq 160$ m and $D \leq 250$ m for 99% of the specified voltage class substations.

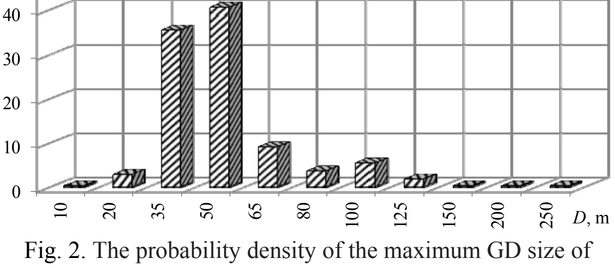

Fig. 2. The probability density of the maximum GD size of substation 35 kV

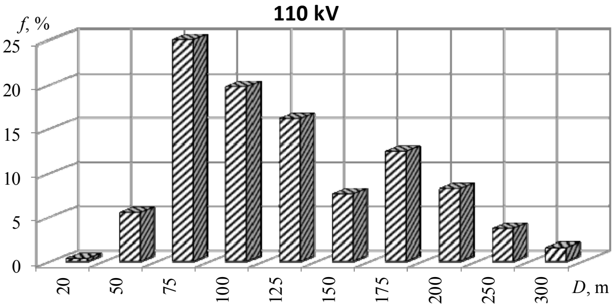

Fig. 3. The probability density of the maximum GD size of substation 110 kV

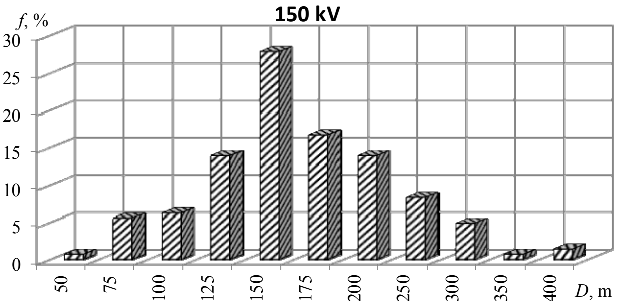

Fig 4. The probability density of the maximum GD size of substation 150 kV

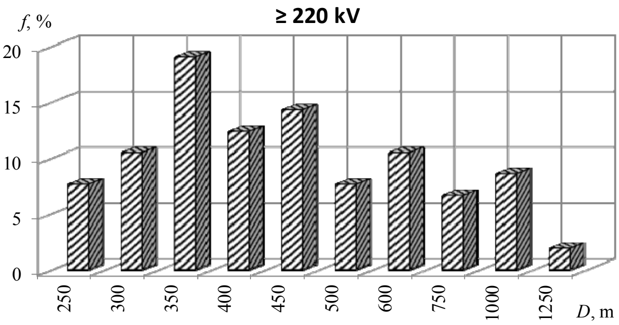

Fig. 5. The probability density of the maximum GD size of substation 220 kV and more

Table 2

Voltage class U, kV	Maximal GD size D, m			
	γ = 50 %	γ = 80 %	γ = 90 %	γ = 99 %
35	40	50	80	125
110	100	160	185	250
150	140	180	220	350
≥220	400	600	800	1250

So, these values indicate a large variation of maximum GD diagonal of power to different voltage class but at the same time allow us to estimate the permissible value of the lower limit of measurement at the level of trust to the appropriate voltage class.

4. Determination of permissible values of the lower and upper limits of the measurement of the device. The value of the apparent ER will always be in the range between the minimum and the maximum value of resistivity geoelectric layer structure, so to determine the technical requirements for appliances for VES by Wenner installation and their probabilistic estimation of use defined previously [6] statistics data of EPC. From the expression for apparent ER of the Wenner installation and the distance between the electrodes, as measured by the limit value of R_{lim} resistance can be written as:

$$R_{\lim} = \frac{\rho}{2\pi L_e}, \qquad (4)$$

where ρ is the apparent ER value.

To determine the lower limit of measurement using the minimum value of the ER of the first layer taken from Table 1 and the electrode spacing L_e calculated by the formula (2), where the length of the largest GD diagonal D from the Table 2 with the appropriate level of trust.

Table 3 shows the values of the lower limit of measurement device $R_{l.lim}$ at K_{VES} = 1-3. The values obtained show that, for example, during the VES on probing depth equal to one diagonal of a energy object (K_{VES} = 1) for 90 % of energy objects of lass of 110 kV the device must have the lower measuring limit of no more than 2.6 mΩ.

So, these data allow us to estimate the applicability of the instrument for carrying out VES on its lower measuring limit of energy object for different voltage classes based on three variables taken electrode spacing.

Table 3

Confidence level γ, %	Electrode spacing L_e	Lower measuring limit of the device $R_{l.lim}$, mΩ for classes of voltage:			
		U =35 kV	U = 110 kV	U = 150 kV	$U \geq$ 220 kV
50 %	3D	4	1.6	1.1	0.4
	2D	6	2.4	1.7	0.6
	D	11.9	4.8	3.4	1.2
80 %	3D	3.2	1	0.9	0.3
	2D	4.8	1.5	1.3	0.4
	D	9.5	3	2.7	0.8
90 %	3D	2	0.9	0.7	0.2
	2D	3	1.3	1.1	0.3
	D	6	2.6	2.2	0.6
99 %	3D	1.3	0.6	0.5	0.1
	2D	1.9	1	0.7	0.2
	D	3.8	1.9	1.4	0.4

To determine the upper limit of measurement and resistance measurement electrodes specify multiple confidence levels (95%, 99.9% and 100%) and consider the corresponding values of the resistivity of the first layer:

- 600 Ω·m (confidence interval covers up to 95% ρ_1 values);
- 2000 Ω·m (confidence interval covers up to 99.9 % ρ_1 values);
- 9000 Ω·m (confidence interval covers 100% ρ_1 values)

To determine the upper limit of measurement should consider the lowest value of distance between electrodes L_e, which is determined by the condition $L_e \geq 3t$ and $L_e \geq 6r_0$, where t and r_0 are the immersion depth and radius of the electrode, respectively. Generally, in the practice of EMD GD $L_{\min}$ is 0.2 m. The results of calculation using (2), with the ER value and the specified confidence levels are shown in Table 4.

Obtained results establish a probabilistic dependence for the upper and lower limits of the measuring devices for VES at EMD GD energy objects of Ukraine, and a substantial increase shown in Table 3, 4 limits (that are usually associated with a significant increase in capacity and device cost) in most cases can be not justified.

Table 4

Soil ER $\rho_{\max}$, Ω·m	Confidence level γ, %	Lower limit of the measurement of the device $R_{up.lim}$, Ω
600	95.0	480
2000	99.9	1600
9000	100.0	7170

5. Determination of the permissible resistance value measuring device circuit. When finding an acceptable resistance to current and potential circuits consider the electrode radius r_0 plunged vertically into the soil to depth t. Since the limit value is the maximum possible resistance of the electrode, the assessment should be performed for the maximum value of the ER of a homogeneous soil, wherein the electrode is known [7] has a resistance of:

$$R_e = \frac{\rho}{2\pi t} \ln \frac{2t}{r_0}, \qquad (5)$$

In carrying out VES in the frame of EMD GD by the author together with employees of the Scientific-&-Research Planning-&-Design Institute «Lightning» NTU «KhPI» electrodes are used on a radius of 4 mm to 10 mm, which are clogged in the measuring process to a depth of 50 to 500 mm.

Calculation results of the measurement electrode resistance for ER and confidence intervals from Table 4 are shown in Table 5.

Table 5

Soil ER, ρ, Ω·m	Confidence level γ, %	Electrode immersion depth t, m	Measuring electrode resistance R_e, Ω:	
			at r_0 = 4 mm	at r_0 = 10 mm
600	95.0	0.05	6150	4400
		0.1	3740	2870
		0.2	2200	1770
		0.3	1600	1310
		0.5	1060	880
2000	99.9	0.05	20500	14660
		0.1	12460	9540
		0.2	7330	5880
		0.3	5320	4350
		0.5	3520	2940
9000	100.0	0.05	92220	65970
		0.1	56040	42920
		0.2	32990	26420
		0.3	23930	19550
		0.5	15820	13200

The data obtained allow to formulate the requirements for permissible resistance measuring circuit devices for VES, as well as take into account the diameter of the measuring electrodes and the depth of their dives.

7. The formulation of generalized technical requirements for devices. Assessing the characteristics of the device, it is possible to draw a conclusion about the applicability of it with a certain probability based on the longest diagonal of the memory and the voltage of a power class. To do this, move on to the confidence level γ confidence probability P (the male probability). P is obtained based on the properties of the probability of the occurrence of three independent events, and is determined according to the expression (6):

$$P = P_{l.\lim} \cdot P_{up.\lim} \cdot P_C, \qquad (6)$$

where $P_{l.lim}$ is the confidence level based on the Table 3; $P_{up.lim}$ is the confidence level based on the Table 4; P_C is the confidence level based on the Table 5.

Table 6 shows the generalized probabilistic requirements for device performance for VES. When this is taken into account that in practice during VES measuring electrodes immersion depth t on average is 0.2 m and the resistance R_c of the measuring circuit is equal to twice the resistance R_e of the electrode from Table 5.

Table 6

Voltage class U, kV	R_c, kΩ	$R_{up.lim}$, kΩ	$R_{l.lim}$, mΩ $L_e = D$	$L_e = 2D$	$L_e = 3D$
At confidence probability P = 0.791					
35	15	1.6	9.5	4.8	3.2
110			3.0	1.5	1.0
150			2.7	1.3	0.9
≥220			0.8	0.4	0.3
At confidence probability P = 0.899					
35	66	6.4	6.0	3.0	1.3
110			2.6	1.3	0.6
150			2.2	1.1	0.5
≥220			0.6	0.3	0.1
At confidence probability P = 0.99					
35	66	7.2	3.8	1.9	1.3
110			1.9	1.0	0.6
150			1.4	0.7	0.5
≥220			0.4	0.2	0.1

Consider the example of the use of Table 6 in selecting the device for carrying out VES for substation of the voltage class:

1) U = 35 kV. As initial data we set:

- the value of the electrode distance equal to three GD diagonals ($L_e = 3D$);
- confidence level P = 0.99.

Consequently, for the substations of 35 kV voltage class with the given parameters of the instrument must have a measuring range from 1.3 mΩ to 7.2 kΩ and allow the resistance of current and potential circuits up to 66 kΩ.

2) U = 150 kV. As initial data we set:

- the value of the electrode distance equal to two GD diagonals ($L_e = 2D$);
- confidence level P = 0.899.

Consequently, for the substations of 150 kV voltage class with the given parameters of the instrument must have a measuring range from 1.1 mΩ to 6.4 kΩ and allow the resistance of current and potential circuits up to 66 kΩ.

Conclusions.

In the paper for the first time a statistical approach for estimating the optimal specifications for devices for the purpose of VES EMD GD of energy objects of Ukraine is used. Obtained earlier statistics on soil resistivity allowed to divide the significant range resistivity values into the range of confidence intervals characterized by a confidence level of engulfing.

To estimate the required depth of sounding, in the paper the statistical distribution of length of the largest GD diagonal by voltage classes is analyzed. Dependencies of lower limit value on the voltage class of devices and the level of confidence desired value are determined based on the required depth of sounding and statistics on the largest GD diagonal of existing energy objects of Ukraine, and the upper limit value – based on the statistical distribution of the ER for the appropriate level of confidence.

The results obtained in this work establish a probabilistic link between the technical characteristics of the device, the actual depth of sounding by Wenner installation (interelectrode distance) and the voltage class of the object. This allows the device to select optimally the device depending on the particular characteristics of the object, as an incorrect choice of device leads to the impossibility of full measurement or a significant increase in cost and weight and size characteristics of the device. It is found that the device for VES in the frame of EMD GD state of energy objects of Ukraine to encompass all classes of voltage and the possible values of soil ER should have the limit of measurement from 0.1 mΩ to 7.2 kΩ and allow the resistance of the measurement circuit to 66 kΩ.

REFERENCES

1. Averbukh M.A. Zabusov V.V., Panteleev V.I. *Sistemnyi podkhod k otsenke zazemliaiushchikh setei elektroustanovok severnykh promyshlennykh kompleksov* [The systematic approach to the evaluation of grounding grids electrical installations of northern industrial complexes]. Krasnoyarsk, Siberian Federal University Publ., 2009. 164 p. (Rus).

2. Hördt A. *Praktikumsunterlagen Angewandte Geophysik und Geoelektrik*. Technische Universität Braunschweig Institut für Geophysik und extraterrestrische Physik, 2006. 11 p. (Ger).

3. Shevnin V.A., Kolesnikov W.P. Rating depth VES for the uniform and layered medium. *Electronic Journal «GEORazrez»*, 2011, no.1(8), pp. 1-9. Available at: http://www.georazrez.ru/download/2011/08/Shevnin-Otcenka_glubinnosti_VEZ.pdf (Accessed 10 November 2013). (Rus).

4. Kolesnikov V.P. *Osnovy interpretatsii elektricheskikh zondirovanii* [Fundamentals of electrical sounding interpretation]. Moscow, Nauchnyi mir Publ., 2007. 248 p. (Rus).

5. Koliushko G.M., Koliushko D.G., Rudenko S.S. On the problem of increasing computation accuracy for rated parameters of active electrical installation ground grids. *Electrical engineering & electromechanics*, 2014, no.4, pp. 65-70. (Rus). **doi: 10.20998/2074-272X.2014.4.13.**
6. Koliushko D.G., Rudenko S.S., Koliushko G.M. Analysis of electrophysical characteristics of grounds in the vicinity electrical substation of Ukraine. *Electrical engineering & electromechanics*, 2015, no.3, pp. 67-72. (Rus). **doi: 10.20998/2074-272X.2015.3.10.**
7. Borisov R.K., Gorshkov A.V., Zharkov Y.V. *Zazemliaiushchie ustroistva elektroustanovok (trebovaniia normativnykh dokumentov, raschet, proektirovanie, konstruktsii, sooruzhenie): spravochnik* [The grounding system of electrical installations (regulatory requirements, calculation, design, construction: Handbook]. Moscow, Publishing House MEI, 2013. 360 p. (Rus).

Received 02.09.2016

S.S. Rudenko, Postgraduate Student, Research Associate,
National Technical University «Kharkiv Polytechnic Institute»,
21, Kyrpychova Str., Kharkiv, 61002, Ukraine.
e-mail: nio5_molniya@ukr.net

How to cite this article:
Rudenko S.S. Requirements for devices for vertical electrical sounding of soil at diagnostics of grounding devices. *Electrical engineering & electromechanics*, 2016, no.5, pp. 68-73. doi: 10.20998/2074-272X.2016.5.12.