

D.G. Koliushko, S.S. Rudenko

## EXPERIMENTAL SUBSTANTIATION OF THE CALCULATION PROCEDURE OF NORMALIZED PARAMETERS OF GROUNDING DEVICE BASED ON THE THREE-LAYER SOIL MODEL

*Purpose.* Experimental substantiation of the possibility of using the calculation procedure of normalized parameters grounding devices on the basis of a three-layer model soil. *Methodology.* The research was based on comparison of the results of experimental measurements for the existing high voltage energy facilities of Ukraine with the results of the calculation. *Results.* Comparison showed that the average error decreased from 18 % for the two-layer model to 10 % for the three-layer model. The analysis of the calculated and experimentally determined values of the touch voltage showed a high degree of coincidence. *Originality.* The adequacy of the calculation procedure of the normalized parameters of the grounding device for model with three-layer soil is substantiated by the results of experimental research on the existing energy objects. *Practical value.* The obtained results allow us to use calculation procedure to create software to determine with increased accuracy the normalized parameters of grounding device located in three-layer soils. References 10, tables 4, figures 3.

*Key words:* grounding device, resistance, touch voltage, three-layer soil model.

*Выполнен анализ возможности применения разработанной методики определения нормируемых параметров заземляющего устройства, расположенного в трехслойном грунте, путем сравнения результатов экспериментальных измерений с расчетными значениями для действующих высоковольтных подстанций Украины. Показано, что средняя погрешность определения значения сопротивления заземляющего устройства снизилась с 18 % для двухслойной модели до менее 10 % для трехслойной модели. Сравнение расчетных и экспериментально определенных значений напряжения прикосновения показало высокую степень их совпадения. Библи. 10, табл. 4, рис. 3.*

*Ключевые слова:* заземляющее устройство, сопротивление, напряжение прикосновения, трехслойная модель грунта.

**Problem definition.** Determination of the values of the normalized parameters (NPs) of the grounding devices (GD) of the operating electric power stations and substations, namely the voltage of the contact, the voltage on the GD and the resistance of the GD [1, 2] experimentally leads, as a rule, to significant difficulties (absence of a free space for removal measuring electrodes at a sufficient distance, communications that go beyond the electrical installation, the impossibility of measuring at a real current of ground fault). Therefore, normative documents [2] provide for the possibility of using experimental and calculation methods [3-7]. The main method of monitoring the state of GD is currently electromagnetic diagnostics (EMD), which includes the experimental and calculation stages, as well as the stage of development of recommendations for bringing the GD in line with the requirements of regulatory documents. In the first stage, the actual layout of the GD, the corrosion state and the section of horizontal groundings (HG) are determined, the vertical electrical sensing (VES) is carried out and the electrical parameters of the GD are measured for further calculation. At the second stage, an interpretation of the results of the VES is carried out to determine the structure and specific electrical resistance (SER) and the thickness of the soil layers, and the calculation of the NP of the GD in the mode of single-phase ground fault is conducted. Currently, the most commonly used to calculate NPs are software that is based on a mathematical model of GD located in a two-layered soil [6].

In [8], based on a statistical database of more than 600 energy objects in Ukraine, it has been shown that in most cases the soil has a three-layer structure (72.7 %), sometimes two-layer (about 8.7 %), or it has more than three layers (about 19 %). Proceeding from this, in order to increase the accuracy of the calculation, the authors

proposed a mathematical model of non-potential GD located in a three-layered soil [9] and a new calculation method is developed on its basis.

However, the developed method for calculating the NP of the GD on the basis of a three-layer soil model has no experimental substantiation which limits its practical application.

**The goal of the work** is experimental substantiation of the method of calculation of normalized parameters of grounding devices on the basis of a three-layer soil model.

**Materials of research.** The verification of the calculation methodology was carried out by comparing the results of experimental studies for existing high voltage power units of Ukraine with the calculated values.

For the implementation of the calculation methodology, a test version of the software package «LiGro» was developed for the determination of the NP of the GD of the existing power stations and substations under the three-layered structure of the soil. From the existing software [3-7] the specified software package is distinguished by:

- taking into account the three-layered structure of the soil with the stored calculation duration at the level of two-layered models;
- the calculation of the electric field occurs on the basis of solving the problem of the potential of the field of a point source of current in a three-layered half-space;
- taking into account non-potential groundings;
- the possibility of arbitrary orientation of the grounding.

The verification of conformity of the calculation method with the experimental data is performed according to the following criteria:

- comparison of the experimentally determined and calculated resistance value of the GD ( $R_G$ );

- comparison of the experimentally determined and calculated touch voltage value on several selected substation equipment units ( $U_T$ ).

**Analysis of the results of determination of the resistance of the GD.** For the analysis the database on the results of the EMD of the state of the GD of 70 electric substations (SS) of the 35 kV voltage class located in the north of Ukraine was used. The choice of this group of power objects is explained as follows:

- measurements were made in the same weather conditions;
- substations are located in the open area and do not have a galvanic connection with industrial objects (which ensures accuracy of measurements), except for SS No. 12 (see Table 1);

Table 1  
Results of experimental and calculation determination of  $R_G$

SS Number	$R_{Ge}, \Omega$	$R_{G2}, \Omega$	$R_{G3}, \Omega$	SS Number	$R_{Ge}, \Omega$	$R_{G2}, \Omega$	$R_{G3}, \Omega$
1	0.620	0.5953	0.644	36	5.600	6.133	5.527
2	0.700	0.749	0.7349	37	1.170	1.236	1.346
3	1.270	2.084	1.530	38	1.000	0.7291	0.7756
4	0.750	0.7149	0.684	39	0.560	0.5375	0.5917
5	1.160	1.304	1.218	40	1.000	0.8848	0.9036
6	0.990	0.9278	0.9138	41	1.150	1.250	1.227
7	0.955	1.152	1.252	42	9.700	9.000	8.372
8	0.600	0.5419	0.6788	43	1.330	2.428	1.467
9	0.814	0.9386	0.9175	44	2.600	2.918	2.662
10	1.060	1.607	1.396	45	0.760	0.8873	0.898
11	1.120	1.244	1.206	46	0.898	1.29	0.9515
12	0.394	0.6461	0.6448	47	1.790	1.862	1.792
13	2.370	2.318	2.465	48	1.250	1.796	1.491
14	0.960	0.5622	0.764	49	0.500	0.523	0.5225
15	0.710	0.6598	0.5931	50	2.000	2.526	2.524
16	0.870	0.4934	0.7422	51	0.530	0.7412	0.8197
17	0.697	0.6848	0.7046	52	0.622	0.541	0.6842
18	0.873	0.7781	0.828	53	0.990	0.8837	0.8393
19	0.775	0.882	0.849	54	0.670	0.8287	0.9077
20	0.600	0.6185	0.6017	55	1.100	0.8556	0.9265
21	7.200	8.216	7.543	56	0.950	1.575	1.032
22	1.200	1.459	1.316	57	0.630	0.6615	0.63
23	0.840	1.579	0.961	58	0.441	0.5143	0.4982
24	1.088	1.398	1.233	59	3.810	3.969	3.802
25	0.790	0.7408	0.7919	60	2.800	2.840	2.833
26	0.875	1.024	1.111	61	1.740	1.932	1.731
27	0.605	0.5522	0.560	62	10.10	9.591	10.1
28	1.370	1.661	1.372	63	0.680	0.7406	0.694
29	0.900	0.9658	0.9637	64	0.870	0.9517	1.006
30	2.600	2.25	2.746	65	1.060	1.453	1.136
31	0.300	0.3829	0.327	66	2.236	2.171	2.173
32	0.500	0.517	0.4815	59	0.530	0.5849	0.64
33	21.10	17.66	23.66	68	0.986	1.28	1.182
34	0.610	0.6879	0.6903	69	0.610	0.7621	0.7084
35	1.290	1.073	1.220	70	0.560	0.5695	0.5713

- the presence of an area free of underground communications around the objects, which allowed to obtain the curves of the VES with sufficient accuracy of interpretation (the deviation of the estimated curves of the VES from the experimental values did not exceed 10 %);

- ground soils where the objects are located have a wide range of SER values and allow to evaluate all types of soils (for example, the minimum and maximum values

of the SER of the first layer lies in the range from 17  $\Omega \cdot m$  to 5690  $\Omega \cdot m$ ).

In the course of the research, it was compared experimentally measured resistance values of the GD  $R_{Ge}$  with the values  $R_{G2}$  and  $R_{G3}$  calculated by means of the method of determining the NP of the GD located in a two-layered soil (the software complex «Grounding 1.0») [6], and developed by the authors in [9] for the GD located in a three layer soil (software complex «LiGro»). In Table 1, the results of measurements of  $R_{Ge}$ , the calculation by using two-layer  $R_{G2}$  and three-layer model  $R_{G3}$  values, respectively, are presented.

It should be noted that for a fairly significant number of substations (28.5 %) a four-layered soil was characteristic and for calculations the equivalence technique had to be applied with bringing the existing structure of soil to the calculated two- and three-layer models. In particular, this is true for substations No. 7-10, 24-28, 37, 52-61 (see Table 1). The GD of the substation No. 50 is located in five-layer soil. For all other energy objects, a three-layered soil structure is characteristic, so when calculating with the help of «LiGro» the initial soil structure was used, and in the case of «Grounding 1.0» simulation, in all cases an equivalence technique was used.

As can be seen from the results presented in Table 1, for most cases (71 %), the calculation error using a three-layered structure of the soil by the software complex «LiGro»  $\delta_3$  is less than the error  $\delta_2$  (calculation using the two-layer model «Grounding 1.0»). In addition, it should be noted that for a three-layer model (about 74 %), the error is a positive value. This is due to the fact that the simulation did not take into account the presence of natural groundings (the foundations of equipment and cable lightning rods, the connection of the GD to the outer metal fence, etc.).

However, for three substations, a significant error ( $\delta_3 > 35\%$ ) is recorded in the calculation of the resistance of the GD. Therefore, in order to check the results of the determination of the resistance of the GD (namely, the error value module  $\delta_3$ ) for the presence of random differences in the sample, the Grubbs criterion [10] was used. At the same time, the level of statistical significance for determining the table value of the criterion was 0.05.

As a result of the analysis, the results of determination of the resistance of the GD for substations No. 12, 51, 54 were excluded in stages from the sample volume.

From a physical point of view, a significant deviation of the calculated and experimental data for substation No. 54 is due to the influence of the methodological error that arose when using the equivalence technique to bring the four-layer soil structure to the calculated three-layer. And in two other cases due to the removal of potential outside the power plant: for the substation No. 12 by cables, and for the substation No. 51 by two cable lightning rods which in turn are connected to the metal supports of overhead lines with a voltage class of 35 kV and are natural additional groundings.

The analysis results for a sample of 67 objects (excluding switched off substations) are presented in Table 2.

As can be seen from Table 2, the technique of calculating a non-potential GD located in a three layer soil realized in the form of the software complex “LiGro” has a significantly lower average error (1.8 times) for the determining resistance of the GD in comparison with the two-layer model [6].

Table 2  
Comparison of the accuracy of determining the resistance of the GD for 67 substations

Model type	Average error $\delta$ , %	Number of substations that fall into the range of error			
		$\pm 5\%$	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$
Two-layer “Grounding 1.0”	18.22	14	28	41	47
Three-layer “LiGro”	9.91	22	40	50	59

Also, for the developed method of calculating the NP of the GD located in the three-layer soil, a greater number of falls of the experimentally determined values in the permissible error ranges (by an average of 31 %) is recorded. This is especially true for ranges of  $\pm 5\%$  and  $\pm 10\%$  where the number of such falls increased by 57 % and 42 % respectively.

**Analysis of the results of determining the touch voltage.** The test was based on a comparison of the touch voltage on several selected substation equipment units when simulating a single-phase ground fault. The analysis was carried out on three substations with voltage class 110 (150) kV. In this case, the traditional method of the set of experimental data was used to assess the adequacy of the mathematical models of the GD which is presented in [6]. The substations were selected in such a way that each of them had one of the most common types of soil: Q, H and K which make up more than 99 % of all three-layered soils of Ukraine in the locations of power facilities. Type A soil was not considered, since it occurs in less than 1 % of cases [8].

Fig. 1-3 show the layouts of the GD locations for the specified substations. The horizontal groundings are marked with a thick black line, the grounding conductors connecting the equipment with grounding are marked by points, and the name of the equipment QS-1–QS-6 on which the measurements have been carried out as well as the power transformers 1T and 2T are shown.

The result of the calculation is the maximum and minimum value of the touch voltage within a radius of 0.8 m around the point of study.

The evaluation of the results of the calculation was as follows: the experimentally measured value of the touch voltage  $U_t$  should be in the interval between the minimum and maximum calculated values for the corresponding point. Table 3 shows the results of comparison of  $U_t$  for disconnectors of substations SS No. 1, 2, 3. Resistance of the base (plate)  $R_o$  is the experimentally determined value according to [6] which is necessary for calculation and is an own characteristic for each point:

$$U_t = \left| \varphi_{k0} - \varphi_{0.8} \right| \frac{R_{body}}{R_{body} + R_o}, \quad (1)$$

where  $\varphi_{k0}$  is the potential on the  $k$ -th equipment unit,  $\varphi_{0.8}$  is the potential on the soil surface determined by the

results of calculations, within a radius of 0.8 m around the  $k$ -th equipment unit;  $R_{body}$  is the resistance of the human body of 1 k $\Omega$  [6].

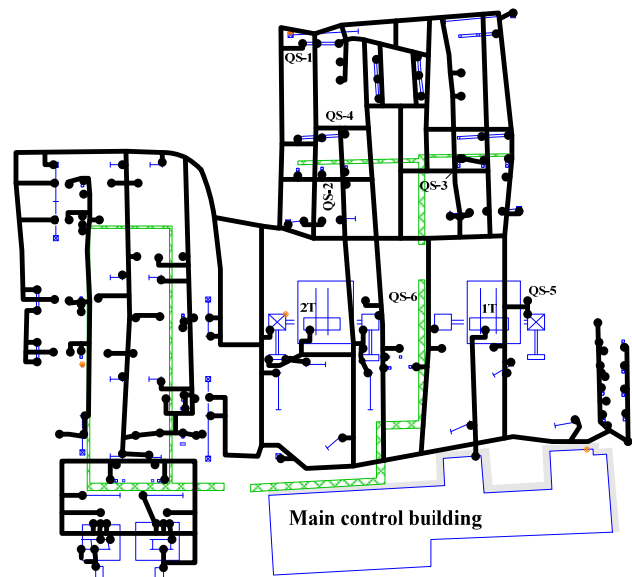


Fig. 1. Schematic diagram of the operating substation SS No. 1 of the voltage class 150 kV in the central part of Ukraine

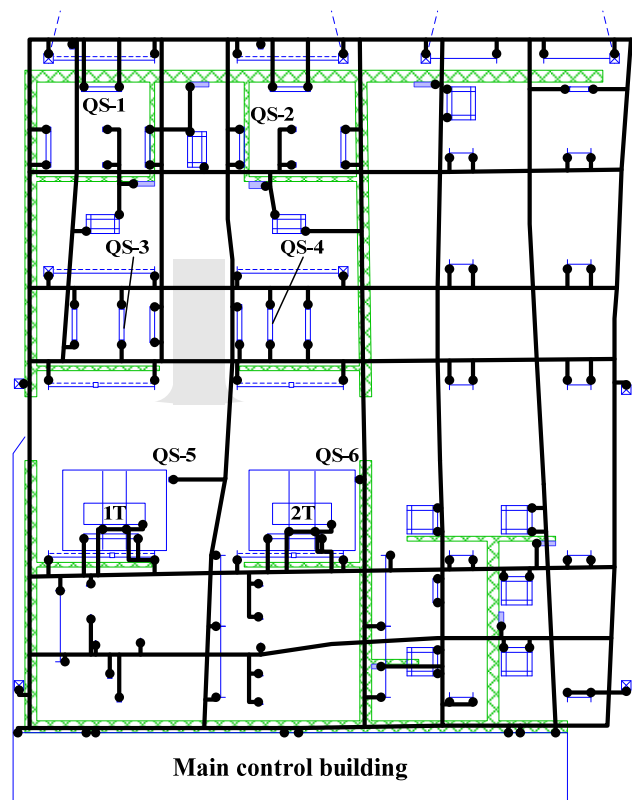


Fig. 2. Schematic diagram of the operating substation SS No. 2 of the voltage class 110 kV in the central part of Ukraine

Input data for the calculation (grounding parameters, specific electrical resistance of soil layers  $\rho$  and their thicknesses  $h$ , and the value of the measuring current) are given in Table 4.

For SS No. 1 and SS No. 3, the experimentally determined value of the touch voltage for all points (that is, in 100 % of cases) lies in the calculated range.

For SS No. 2, the experimentally determined value of the touch voltage for 5 points of 6 (i.e. 83.3 % of cases) lies in the calculated range, and for the QS-4 equipment, the deviation of the nearest calculated value from  $U_t$  is 20.8 %. For specified point such a deviation can be explained by the difference in the cross section of the local grounding, its corrosion wear, or the difficult path of the grounding trail (the depth of bedding is variable, and the grounding itself has not a straight line, but an arbitrary shape at a distance of less than 0.2 m which can not be determined).

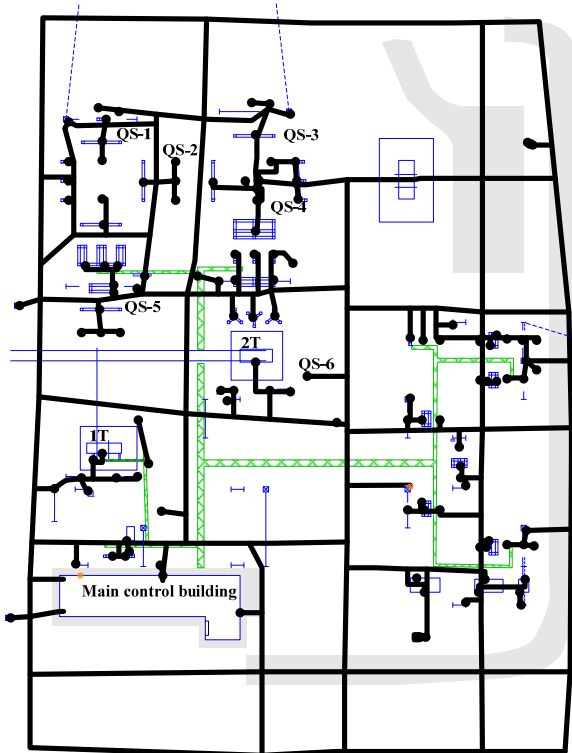


Fig. 3. Schematic diagram of the operating substation SS No. 3 of the voltage class 150 kV in the south of Ukraine

Table 4

Input data to calculate the touch voltage			
Parameter:	SS No. 1	SS No. 2	SS No. 3
HG cross section, mm	band 20×6	band 40×4	bar Ø16
$\rho_1, \Omega\cdot\text{m}$	92.5	42	150
$\rho_2, \Omega\cdot\text{m}$	61	3,3	43
$\rho_3, \Omega\cdot\text{m}$	13	22	12
$h_1, \text{m}$	0.9	0.3	0.3
$h_2, \text{m}$	3.2	5.3	9.8
Measuring current $I_f, \text{A}$	4.76	4.76	4.76

In order to take into account this, it is necessary to carry out additional research with the introduction of the corresponding results into the calculation model. However, the proximity of the experimental value to the calculated one for this point and the fall into the calculated range for other points makes it possible to conclude that the model for the GD of this substation is adequate.

Thus, the total fall in the calculated range is observed in 17 points of 18, which is 94.4 %.

The results of the performed research confirm the adequacy of the developed method of calculating the GD based on the three-layer soil model, the experimental value of the touch voltage obtained at simulating a single-phase ground fault on the real GDs that are in service.

#### Conclusions.

1. The adequacy of the method of calculation of the normalized parameters of the grounding device based on the three-layer soil model is substantiated by comparing the results of experimental research for the operating high-voltage power facilities of Ukraine with the calculation results.

2. It is shown that the developed method of calculation allows to improve the accuracy of the determination of normalized parameters of grounding devices. In this case, the average error of determining the resistance of grounding devices does not exceed 10 %, and when determining the touch voltage, the fall in the calculated range is recorded for 94 % of the experimental points.

3. The obtained results allow to use the developed method of calculation for the creation of software tools for determining the normalized parameters of grounding devices of arbitrary configuration located in a three layer soil.

#### REFERENCES

- IEEE Standard 81-2012. IEEE Guide for measuring Earth resistivity, ground impedance, and Earth surface potentials of a grounding system. [Amended by 2012-12-28]. New York: IEEE, 2012. 86 p. doi: 10.1109/ieeestd.2012.6392181.
- Natsional'nyy standart Ukrayiny. SOU 31.2-21677681-19:2009. Viprobuвання та контроль' пристоїв заземлення електростановок. Типова інструкція. [National Standard of Ukraine SOU 31.2-21677681-19:2009. Test and control devices, electrical grounding. Standard instruction]. Kyiv, Minenergougillya Ukrayiny Publ., 2010. 54 p. (Ukr).
- Tabatabaei N.M., Mortezaei S.R. Design of grounding systems in substations by ETAP intelligent software. *International Journal on «Technical and Physical Problems of Engineering» (IJTPE)*, 2010, iss.2, vol.2, no.1, pp. 45-49.
- Turri R., Andolfato R., Cuccarollo D. A numerical simulation tool for cathodic protection and electromagnetic

Table 3  
Comparison of experimental and calculated value of the touch voltage

Object name	Conditional name of the equipment	Experimental results		Calculated results		Fall into the definition range $U_t$
		$U_t, \text{mV}$	$R_o, \Omega$	$U_{t \max}, \text{mV}$	$U_{t \min}, \text{mV}$	
SS No. 1	QS-1	20	273	21.40	16.10	+
	QS-2	19	92	21.40	18.40	+
	QS-3	30	130	30.50	25.40	+
	QS-4	18	213	19.90	14.00	+
	QS-5	35	162	51.35	32.50	+
	QS-6	42	114	58.00	41.90	+
SS No. 2	QS-1	33	38	34.6	19.5	+
	QS-2	17	42	24.0	16.2	+
	QS-3	16	61	20.3	15.2	+
	QS-4	13	87	21.5	15.7	-
	QS-5	24	123	31.1	23.1	+
	QS-6	38	116	61.4	36.5	+
SS No. 3	QS-1	95	266	97.5	78.13	+
	QS-2	117	239	120.1	85.20	+
	QS-3	99	315	99.3	65.60	+
	QS-4	190	252	238.4	129.70	+
	QS-5	60	298	70.8	56.60	+
	QS-6	107	1169	259.0	106.80	+

interference analysis. *NACE Milano Italia Section – Conference & Expo 2016 «A European event for the Corrosion Prevention of Oil&Gas industry»*. 17 p. Available at: [https://www.researchgate.net/publication/303685228\\_A\\_NUMERICAL\\_SIMULATION\\_TOOL\\_FOR\\_CATHODIC\\_PROTECTION\\_AND\\_ELECTROMAGNETIC\\_INTERFERENCE\\_ANALYSIS](https://www.researchgate.net/publication/303685228_A_NUMERICAL_SIMULATION_TOOL_FOR_CATHODIC_PROTECTION_AND_ELECTROMAGNETIC_INTERFERENCE_ANALYSIS) (accessed 22 September 2016).

5. Zubov K.N. *Sovershenstvovanie raschetnykh metodov molniezashchity i zazemliayushchikh ustroystv v neodnorodnykh gruntakh*. Diss. cand. techn. nauk [Improved computational methods for lightning protection and grounding devices in heterogeneous soil. Cand. tech. sci. diss.]. Vologda, 2011. 158 p. (Rus).

6. Koliushko D.G. *Sovershenstvovanie diagnostiki zazemliayushchikh ustroystv elektroenergoob'ektov*. Diss. cand. techn. nauk [Improving the diagnosis of grounding devices for electric power objects. Cand. tech. sci. diss.]. Kharkov, 2003. 172 p. (Rus).

7. Unde M.G., Kushare B.E. Grounding grid performance of substation in two layer soil – a parametric analysis. *International Journal of Engineering Sciences & Emerging Technologies*, 2012, vol.1, no.2, pp. 69-76. doi: **10.7323/ijeset/v1\_i2\_8**.

#### How to cite this article:

Koliushko D.G., Rudenko S.S. Experimental substantiation of the calculation procedure of normalized parameters of grounding device based on the three-layer soil model. *Electrical engineering & electromechanics*, 2018, no.1, pp. 66-70. doi: **10.20998/2074-272X.2018.1.11**.

8. 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**.

9. Koliushko D.G., Rudenko S.S. Mathematical model of grounding connection of a power plant with under layer. *Electronic modeling*, 2014, vol.36, no.2, pp. 89-97. (Rus).

10. International Organization for Standardization. ISO 5725-2: 1994: Accuracy (Trueness and Precision) of Measurement Methods and Results-Part 2: Methods for the Determination of Repeatability and Reproducibility. International Organization for Standardization, 1994.

Received 10.12.2017

D.G. Koliushko<sup>1</sup>, Candidate of Technical Science, Senior Research Associate,

S.S. Rudenko<sup>1</sup>, Research Associate,

<sup>1</sup>National Technical University «Kharkiv Polytechnic Institute»,

2, Kyrpychova Str., Kharkiv, 61002, Ukraine,

e-mail: nio5\_molniya@ukr.net