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Simulation of electromagnetic processes in the grounding system with a short circuit in the operating high-voltage substation

The aim *of the work is a test of the developed mathematical model of electromagnetic processes of short circuit and approbation of the created software complex «LiGro» on its basis for the existing grounding system located in three-layer soil.* ***Methodology****. To improve the accuracy of calculating the normalized parameters of operating power stations and substations, the authors developed the «LiGro» software package based on the expressions obtained in for calculating the potential of the electric field of a non-equipotential grounding system (GS). To monitor the state and assess the efficiency of the GS of operating power facilities, the electromagnetic diagnostics is used. The topology of the GS was determined with the induction method by complex KNTR-1, the geoelectric structure of the soil was determined by the method of vertical electrical sounding using the Wenner installation, the interpretation of the sounding results was made by the «VEZ-4A» program.* ***The calculation results*** *show that for the selected substation, the model developed in the «LiGro» complex has a deviation δ_2 from the experimental values U_t by an average of 8,2 %, and the model implemented in Grounding 1.0 (IEEE model) δ_1 is 17,2 %.* ***Originality****. The results of the study confirm the adequacy of the developed GS model in the «LiGro» complex based on a three-layer soil model, with the experimental values of the touch voltage obtained by simulating a single-phase ground fault on a real GS in operation. The first time was made approbation of the «LiGro» software package when performing the EMD of the GS of an operating substation with a voltage class of 150 kV.* ***Practical significance.*** *The program software can be used by special measuring's laboratory to determining electrical safety parameters: touch voltage, GS voltage, and GS resistance.* References 17, tables 2, figures 9.

Key words: **grounding system, modeling of the electromagnetic processes, touch voltage, grounding system resistance, grounding system voltage, electromagnetic diagnostics.**

Метою роботи є перевірка розробленої математичної моделі електромагнітних процесів короткого замикання та апробація створеного програмного комплексу «LiGro на її основі для існуючого заземлювального пристрою (ЗП), який розташовано в тришаровому ґрунті. Перевірка практичного застосування була виконана на діючий підстанції класом напруги 150 кВ з використанням вдосконаленої методики електромагнітної діагностики. Топологія ЗП була визначена індукційним методом за допомогою приладу KNTR-1, параметри ґрунту визначені чотириелектродною симетричною установкою за схемою Веннера методом вертикального електричного зондування, інтерпретація результатів зондування виконана спеціалізованою програмою VEZ-4A. Результати порівняння розрахунку показують, що для обраної підстанції модель розроблена в комплексі LiGro має відхилення від експериментальних значень в середньому на 8,2 %, а модель реалізована в Grounding 1.0 (IEEE model) – 17,2 %. Виконано розрахунок нормованих параметрів ЗП в режимі короткого замикання: напругу дотику, опір ЗП та напругу на ЗП. Встановлено, що вони не перевищують допустимого значення. Проаналізовано переваги розрахункового комплексу у порівнянні з аналогами. Отримані результати дозволяють виконати повномасштабне впровадження програмного комплексу в діагностику стану ЗП. Бібл. 17, табл. 2, рис. 9.

Ключові слова: **заземлювальний пристрій, моделювання електромагнітних процесів, напруга дотику, опір заземлювального пристрою, напруга на заземлювальному пристрої, електромагнітна діагностика.**

Problem formulation. To monitor the state and assess the efficiency of the grounding system (GS) of operating power facilities, the electromagnetic diagnostics (EMD) [1, 2] is used, which involves three stages: experimental, calculated, and the stage of issuing recommendations [3]. In the process of research, the topology of the GS is determined, as well as the normalized parameters (NP) of the GS, such as the GS resistance, the voltage across the GS, and the touch and step voltages.

The impossibility of controlling these parameters by direct or even indirect measurements leads to an increase in the urgency of the problem in the field of calculating the GS NP of operating power stations and substations using software [4, 5].

Literature analysis. Several works [4–12] are devoted to the issues of modeling electromagnetic processes that occur in the GS during the flow of emergency currents. In most cases, a mathematical model of the GS located in two-layer soil is used (in particular, with the help of [7], more than 1000 power facilities of Ukraine with voltage classes of 35-750 kV were calculated, and the software package [9, 10] based on it is one of the most commercial versions popular in the world).

The calculation of the GS is usually carried out in two modes: a single-phase ground fault on the territory of the power facility and outside it. The following calculation methods are used to determine the touch voltage:

- finite element method in the time domain (so-called FDTD method);
- method of integro-differential equations;
- method of optical analogy.

Each of these methods has a similar algorithm [13]: geometric and electrical data are entered into the initial data block (GS dimensions, location, depth, and cross-section of groundings, short-circuit current, electrophysical characteristics of the soil, electrical resistivity of the grounding material, etc.). This is followed by the calculation of longitudinal active and inductive resistances of connections, and the coefficients of the system of linear algebraic equations are determined for calculating the density of currents flowing from the ground electrode. Because of the complex dependence of the resistance of the electrode material on the magnitude of the current flowing through them, the solution of the problem is found by the method of successive approximations.

The method of integro-differential equations is based on the analytical solution of the problem of the electric field potential of a point current source [6, 7, 9–13]. Programs based on this method with a two-layer electric soil structure are used to carry out calculations by the world's leading scientific research institutions and following the international standards IEEE Std. 80 and 81 [13, 14].

In Ukraine, for power facilities, the number of GS located in two-layer soil is only 10 % [6]. In other cases, it is necessary to apply equivalence techniques with the reduction of a multilayer structure to a two-layer calculation model, which can give a significant methodological error (from 20 % to 100 %).

The use of a mathematical model of GS [6], located in a three-layer soil, allows to directly (without equivalentization) perform a calculation for 80 % of the existing energy facilities in Ukraine and determine the resistance of GS with an error of up to 10 % (confirmed according to the calculation data of more than 50 substations with a voltage class 35 kV). Comparison with the experimental value of the contact voltage showed more than 90 % falling into the calculated range for the GS of three test substations [3].

To improve the accuracy of calculating the NP of operating power stations and substations, the authors developed the «LiGro» software package based on the expressions obtained in [6] for calculating the potential of the electric field of a non-equipotential GS.

From the existing world analogues [7–12] for determining the NP of GS of operating power stations and substations when the GS is located in three-layer soil, this software package is distinguished by:

- the calculation of the electric field is based on the analytical solution of the problem of the electric field potential of a point current source in a three-layer half-space;
- the possibility of the arbitrary orientation of the grounding in space;
- the consideration of non-equipotentiality of the groundings;
- saving the duration of the calculation at the level of two-layer models.

The assessment of the adequacy of the developed mathematical model and the created software package was carried out by comparing the results of experimental studies for operating high-voltage power facilities in Ukraine with the calculation results, and is given in [3].

The calculation of the GS NP can be divided into three stages:

- the preparation of initial data for modeling;
- the calculation of the experiment to assess the adequacy of the constructed GS model to the real GS according to the method given in [15];
- the calculation of the GS NP in the short circuit mode.

The aim of the work is a test of the developed mathematical model of electromagnetic processes of short circuit and approbation of the created software complex «LiGro on its basis for the existing grounding system located in three-layer soil.

Research materials.

1. Initial data. To carry out the research, the substation with a voltage class of 150 kV, located in the central part of Ukraine, was taken as operating.

The initial data for the simulation are the characteristics of the substation (short circuit current, outflow current in the neutral, protection response time), the topology of the GS, and the geoelectric structure of the soil.

Using the induction method, within the first stage of EMD of GS (see Fig. 1), using complex KNTR-1 [15], the topology of the GS was determined, it is shown in Fig. 2.

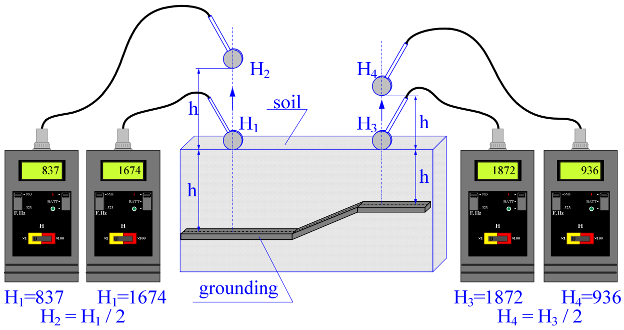

Fig. 1. Determination of GS topology

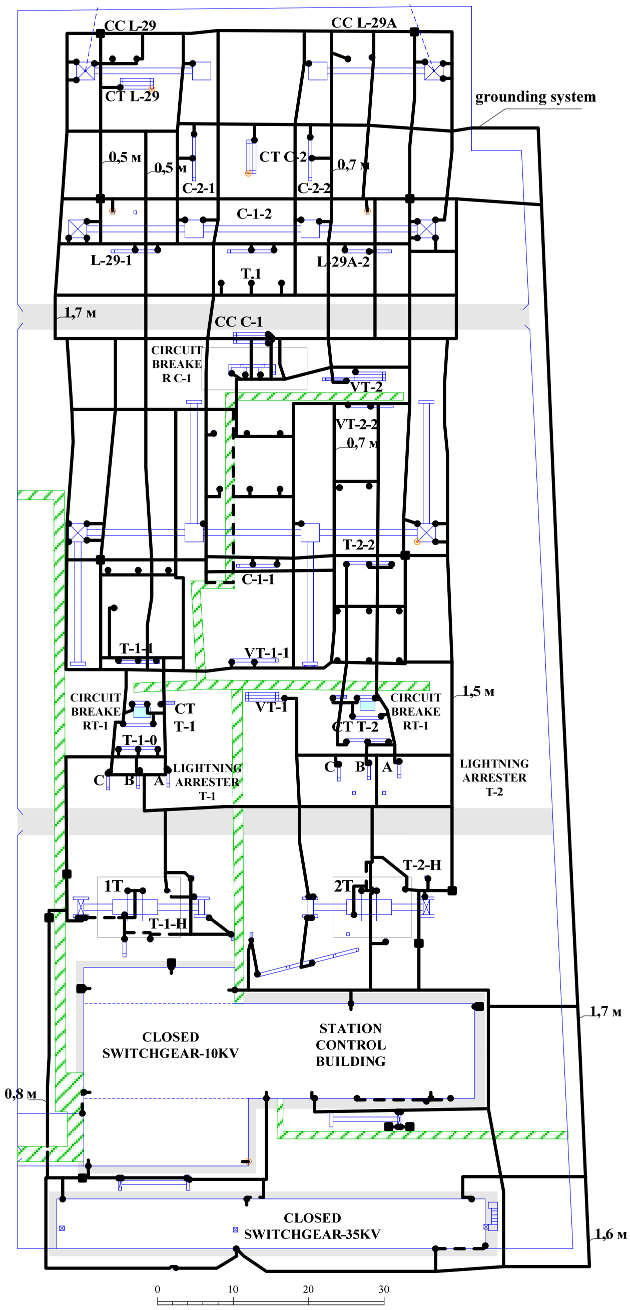

Fig. 2. GS topology of investigated substation 150 kV

It was found that the GS of the substation is a branched grid of horizontal groundings and vertical electrodes, with dimensions of 65 m × 164 m. Horizontal groundings are made of a steel staff of 4 mm × 40 mm and hot-rolled steel with a diameter of ∅14 mm, vertical electrodes are made of rolled steel of 16 mm and 3 m long.

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 on which the measurements have been carried out as well as the power transformers 1T and 2T are shown (see Fig. 2).

The geoelectric structure of the soil was determined by the method of vertical electrical sounding using the Wenner installation (see Fig. 3) [16].

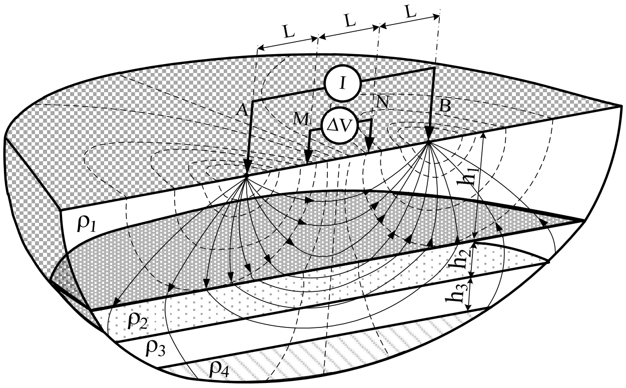

Fig. 3. Soil sounding by using the Wenner installation

Using the «VEZ-4A» program (see Fig. 4), which is created by authors and built into the «LiGro» complex, it was found that the soil is a three-layer geoelectric structure, and the interpretation of the sounding results showed that the resistivity is equal to:

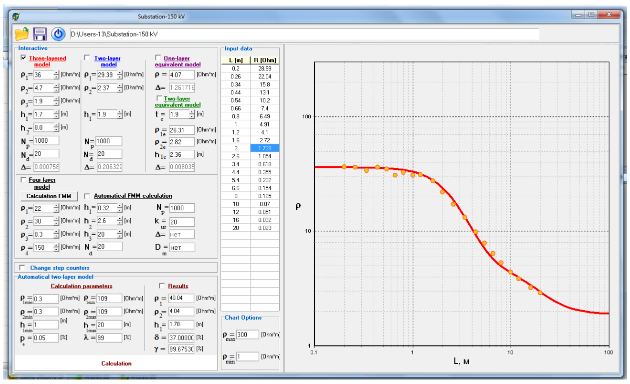

Fig. 4. A working window of the software for multi-layer soils interpretation «VEZ-4A»

- for the first layer at a depth of up to 1,6 m – 34,5 Ω×m;
- for the second layer at a depth from 1,6 m to 8,1 m – 5,5 Ω×m;
- for the third layer at a depth from 8,1 m – 1,85 Ω×m.

To compare the calculation results with two-layer models, in particular, the IEEE model, the three-layer soil structure was reduced to an equivalent two-layer model:

- for the first layer at a depth of up to 1,9 m – 29,39 Ω×m;
- for the second layer at a depth from 1,9 m – 2,37 Ω×m.

The given initial data were entered into the «LiGro» software package, and a model of the GS of the studied substation was created. Fig. 5 shows the GS scheme, where the blue color indicates groundings located underground at the same depth, the green color – groundings at varying depths, the purple/red color – buildings and structures, and the metal construction of the substation equipment.

To create a calculation model the «LiGro» complex, in contrast to [7–12], has ample opportunities and allows to:

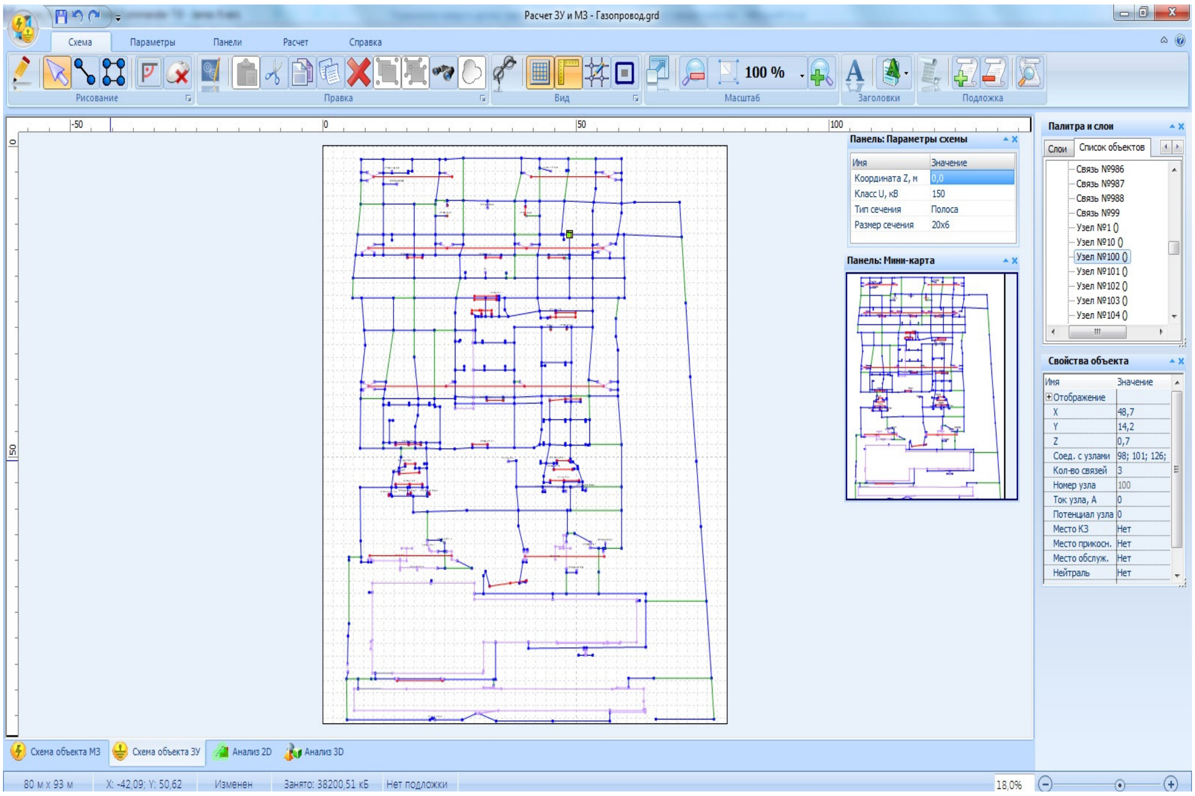

Fig. 5. Model of the GS of investigated substation 150 kV by software «LiGro»

• set in any node (see Fig. 6) its individual properties (voltage class, short circuit location, touch point, service point, experiment measurement point, neutral with setting the current in the neutral for each voltage class, base resistance, initial current in the node);

• build a grounding system on a scale with an arbitrary configuration (directions of groundings location and their cross-section);

• carry out both group and individual editing of properties (coordinates, parameters, etc.) of objects (nodes and links);

• copy individual elements of GS, create palettes of standard elements, automatically build grounding grids with specified parameters, perform quick navigation through the scheme.

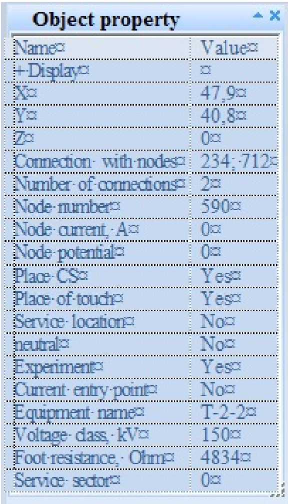

Fig. 6 Property of the node-object GS of investigated substation 150 kV by software «LiGro»

2. Calculation of the experiment to assess the adequacy of the constructed model. 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 six equipment of substations with voltage class 150 kV. In this case, the traditional method of the set of experimental data was used to assess the adequacy of the mathematical model of the GS which is presented in [3] (see Fig. 7) with measuring current – 5,13 A. Figures 2 and 5 show the layouts of the GS locations for the specified substation.

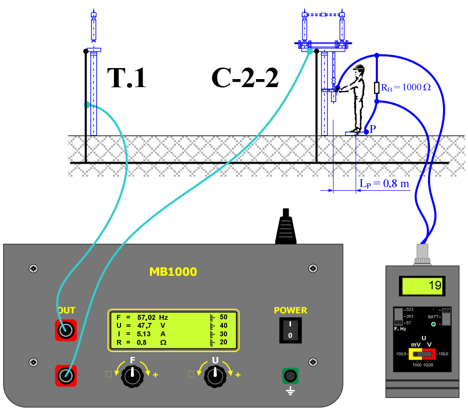

Fig. 7. Method of the set of experimental data to assess the adequacy of the mathematical model of the GS

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 1 shows the results of the comparison of U_t for disconnectors of substations. Table 1 shows the calculated (U_{t1} and U_{t2}) and experimental values of the voltage U_t obtained, respectively, by mathematical modeling and simulating a single-phase short circuit on the territory of the substation with the return of the entire short circuit current to the grounding conductor of the supporting insulator (point T.1, see Fig. 2). When comparing, the calculated current was taken equal to the measuring one, foot resistance (R_O) was determined experimentally at each measuring point.

Table 1

Results of the comparison of touch voltage

Name of the equipment	Experimental results		Calculated results			
			IEEE model		LiGro	
	U_t, mV	R_O, Ω	U_{t1}, mV	δ_1, %	U_{t2}, mV	δ_2, %
C-2-2	19	1146	19,87	4,6	18,8	1,1
C-2-1	38	565	32,22	15,2	34,4	9,5
L-29-1	16	425	16,95	5,9	15,9	0,6
C-1-1	20	399	23,39	17,0	22,0	10,0
VT-2-2	37	472	22,09	33,4	30,9	16,5
T-2-2	6	4834	3,58	27,3	5,3	11,7

The calculation results show that for the selected substation, the model developed in the «LiGro» complex has a deviation δ_2 from the experimental values U_t by an average of 8,2 %, and the model implemented in Grounding 1.0 (IEEE model) δ_1 is 17,2 %. Thus, the results of the study confirm the adequacy of the developed GS model in the «LiGro» complex based on a three-layer soil model, with the experimental values of the touch voltage obtained by simulating a single-phase ground fault on a real GS in operation. In addition, the three-layer model showed higher accuracy than the one reduced to the two-layer model.

3. Calculation of GS NP in short circuit mode. Following the requirements of regulatory documents, when determining the allowable value of the touch voltage, the sum of the protection time at the substation and the total time of the circuit breaker off should be taken as the estimated duration of the operation.

According to the data of the operating organization: the voltage class is 150 kV, short-circuit current value is 14,156 kA, operating mode of transformer neutrals – grounded. When carrying out the calculations, allowable contact voltage was assumed to be equal to 213,3 V for all equipment, based on the protection duration of 0,48 s [17].

With the help of the «LiGro» complex, it was determined:

• touch voltage (see Fig. 8) on each unit of equipment in all modes of a single-phase short circuit to earth, taking into account the current in the grounded neutrals of transformers and additional galvanic connections (pipelines, cables, portals);

- GS voltage;
- GS resistance;
- the value of the electric field potential in each node and the current in each grounding (see Fig. 9).

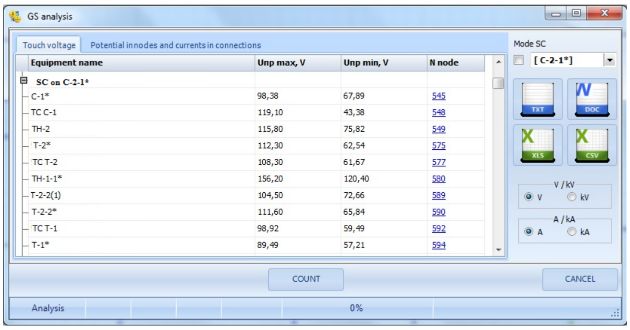

Fig. 8. Calculation results of touch voltage of the investigated substation 150 kV by software «LiGro»

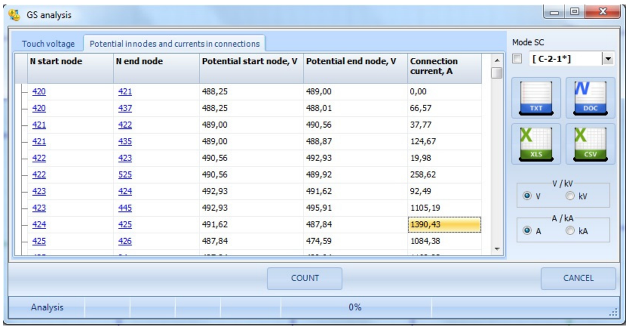

Fig. 9. Calculation results of potential and current in the GS of the investigated substation 150 kV by software «LiGro»

It should be noted that the derivation of the voltage value in the nodes helps to determine the places for laying additional groundings to equalize the potential on the soil surface and to reduce the touch voltage.

As the calculation results showed, during a short circuit on the territory of the 150 kV substation, the touch voltage on all equipment does not exceed the allowable value (see Table 2).

The maximum value of the voltage on the substation GS in the case of a short circuit is 616 V.

The calculated value of the substation GS resistance, taking into account only artificial groundings, was 0,0454 Ω, which does not exceed the allowable value of 0,5 Ω.

Conclusions.

1. The adequacy of the developed mathematical model of the existing substation was confirmed by comparing the calculated and experimental measurements of the touch voltage by the simulation of the short - circuit current. It is shown that the average error in determining the touch voltage of the specified substation is 8,2 %.

2. Approbation of the created «LiGro» software package was carried out when performing the electromagnetic diagnostics of the grounding system of an existing substation with a voltage class of 150 kV in terms of determining electrical safety indicators: touch voltage, grounding voltage, and grounding system resistance. The authors was to the developed LiGro software package, as well as the VEZ-4A, received the copyright certificate.

Table 2

Calculation results of the touch voltage on equipment

Name of the equipment	$U_{t\max}$, V	$U_{t\min}$, V
CIRCUIT BREAKER C-1	130,9	94,21
CT T-1	139,6	50,46
VT-2	120,7	78,66
CIRCUIT BREAKER T-2	164,4	98,01
CT T-2	141,3	78,01
TH-1-1	222,1	173,6
T-2-2	133,4	93,91
CT T-1	125,8	74,19
CIRCUIT BREAKER T-1	135,9	93,87
T-1-0	159,2	81,57
T-2-0	154,1	86,14
T-2-H	208,7	90,99
C-1-1	158,4	130,3
VT-2-2	163,9	105,9
L-29-1	181,7	121,3
C-1-2	193,7	152,1
L-29A-2	177,7	116,3
C-2-1	237,6	124,9
C-2-2	217,2	141,1
T-1-1	115,7	79,61
CC-L-29	154,5	97,95
CC-L-29A	196,6	97,85
TC L-29	189,1	82,42
TC C-2	194,5	127,2
TN-1	184,4	99,82
2T	266,1	247,6
1T	368,4	362,8

3. It was confirmed that the advantages of the complex in its practical application are:

- the presence of a module for interpreting the results of soil sounding;
- calculation of the GS located in three-layer soil, which allows covering 90 % of energy facilities in Ukraine;
- taking into account all the design parameters of the GS;
- the presence of the analysis module with the display of currents in the connections, potentials in the nodes, the output of the maximum values of the touch voltage for the corresponding short circuit mode or for all points in all modes.

Conflict of interest. The authors declare no conflict of interest.

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