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IMPROVED ALGORITHM FOR CALCULATING COMPLEX NON-EQUIPOTENTIAL GROUNDING DEVICES OF ELECTRICAL INSTALLATIONS TAKING INTO ACCOUNT CONDUCTIVITY OF NATURAL GROUNDINGS

Purpose. The method of natural concentrated groundings substitution by the set of electrodes taking them into account in the algorithm of electric characteristics calculation for complicated grounding connections of electric installation is offered. An equivalent model as a set of linear electrodes is chosen in accordance with two criteria: leakage resistance and potentials on the ground surface. Methodology. We have applied induced potential method and methods for computing branched electrical circuits with distributed parameters. Results. We have obtained the algorithm for calculating complex non-equipotential grounding connections, which makes it possible to obtain refined values of the potential distribution in the electric stations and substations with outdoor switchgear. Originality. For the first time, we have taking into account the conductivity of natural concentrated grounds by a set of vertical and horizontal electrodes based on equivalent electrical characteristics applied to a two-layer ground. Practical value. The using of the proposed calculation algorithm in the electric grids of JSC «Kharkivoblenergo» made it possible to determine the values of the potential distribution at short circuit in electrical substation taking into account the influence of the conductivity of natural concentrated groundings. References 9, figures 1.

Key words: **natural concentrated groundings, substitution, induced potential method, the potential distribution, a two-layer ground model.**

Цель. Целью статьи является разработка алгоритма расчета электрических характеристик неэквипотенциальных заземляющих устройств электроустановок с учетом большого числа естественных сосредоточенных заземлителей, а также собственных активных и реактивных сопротивлений горизонтальных заземлителей. Методика. Проведены теоретические исследования с использованием метода наведенных потенциалов, методов конечных разностей для расчета электрического поля простых заземлителей в земле с двухслойной структурой и последовательного применения метода наведенных потенциалов и методов расчета разветвленных электрических цепей с распределенными параметрами. Результаты. Получен алгоритм расчета сложных неэквипотенциальных заземляющих устройств, позволяющий получить уточненные значения распределения потенциала на территории электроустановки. Научная новизна. Новые положения, по сравнению с известными решениями, состоят в учете проводимости естественных сосредоточенных заземлителей совокупностью вертикальных и горизонтальных электродов, обоснованной по равнозначным электрическим характеристикам применительно к двухслойной модели электрической структуры земли. Практическое значение. Использование предложенного алгоритма расчёта в электрических сетях АК «Харьковоблэнерго» позволили определить значения распределения потенциалов при КЗ на электрической подстанции с учетом влияния проводимости естественных сосредоточенных заземлителей. Скорректированные таким образом результаты расчета дадут более точную информацию о величинах нормируемых параметров по заземляющим устройствам действующих электроустановок. С помощью предложенного алгоритма могут быть получены уточненные значения падения напряжений по заземляющим устройствам при КЗ, а, следовательно, рассчитаны напряжения, воздействующие на изоляцию кабелей вторичных цепей, – параметры, нормируемые по условиям электромагнитной совместимости. Библ. 9, рис. 1.

Ключевые слова: **природные сосредоточенные заземлители, электрическая подстанция, метод наведеного потенциала, распределение потенциала, двухслойная модель земли.**

Introduction. The characteristics of grounding devices (GD) of electrical installations with open distribution devices directly determine the electromagnetic situation at power facilities. The natural concentrated groundings, due to the large contact surface with the ground, equalize the potential in the GD nodes and, thereby, unload the horizontal artificial and natural groundings. Therefore, their detailed accounting in solving the problem of calculating the electrical characteristics of complex non-equipotential GD is mandatory, since it affects the level of electromagnetic interference.

The calculation of the electrical characteristics of non-equipotential groundings is based on the consistent application of the induced potential method and methods for calculating branched electrical circuits with distributed electrical parameters. Using the capabilities of this algorithm for calculating complex GD involves the replacement of natural concentrated groundings (reinforced concrete bases and foundations) with a set of vertical and horizontal electrodes whose diameters are taken to be the same as those of the corresponding artificial electrodes. At the same time the uniformity of the calculated forms of all the GD electrodes is achieved.

The method of calculating a complex combined grounding can be based on the condition of its equipotentiality, and on the condition of non-equipotentiality, i.e. taking into account the longitudinal resistance of the horizontal electrodes. Modern computational capabilities make it possible to implement an algorithm for calculating non-equipotential complex combined groundings as a universal one.

Analysis of recent investigations and publications. The mathematical model of the non-equipotential GD of a substation located in a two-layer soil proposed in work [1] is based on the main provisions of the joint representation of the GD in the general case as a complex electric circuit and creating a steady electric field in the ground. Additionally into account the change in the current density flowing from the horizontal electrodes, linearly and their arbitrary arrangement is taken into account. However, the impact on the formation of electrical characteristics of the GD of electrical installations, which can have natural concentrated groundings is not taken into account in this work not taken into account.

The calculation algorithm based on a unified mathematical model and simultaneously taking into account both the non-uniformity of the potential distribution with respect to the object's GD and the process of current flow from the grounding to the ground are realized in the form of the «Contour» software package [2]. The proposed mathematical model, judging from the construction of the algorithm, does not take into account the nonlinear dependence of the distributed parameters of the horizontal electrodes on the current flowing through them.

In work [3] various methods of calculation of resistance of various groundings in homogeneous and two-layer models of electric structure of the earth are considered. The obtained results are compared with the corresponding formulas of the finite element method, which are considered as reference ones. In work [3] it was noted the need to find the best approximations in the course of calculating the resistance of a complex GD, especially for the case of a multilayer ground model.

The main idea of the method [4] consists in a joint consideration of the GD in the general case as a complex electric circuit and creating a steady electric field in the ground. According to this method, vertical elements are represented by lumped parameters, and horizontal ones are represented by distributed parameters that are nonlinearly dependent on the current flowing through them.

An analysis of the expressions given in [4] shows that they do not cover all possible variants of arrangement of elements of complex GD with respect to a two-layer soil model. The form of the representations of these expressions reflects those limitations in the geometry part of the computational model of GD that are adopted in the algorithm that implements the expressions. According to [4], in the design of complex GD structures, reinforcing skeletons of reinforced concrete bases (natural concentrated groundings) should be replaced by a combination of vertical and horizontal electrodes, taking into account the capabilities of known algorithms for the calculation of groundings. It should, however, be noted that the calculated set of replacement electrodes in this case is not based on equivalent electrical characteristics.

The goal of the work is the improvement of the algorithm that implements a mathematical model based on joint consideration of the GD as a complex electric circuit and creating steady electric field of current in the ground, by taking detailed account of the natural concentrated groundings of the open distribution devices of high voltage electrical installations.

A method of complex GD calculation. The basis for the algorithm for calculating complex non-equipotential GD of electrical installations taking into account the conductivity of natural groundings is the method of calculating GD taking into account the longitudinal resistance of horizontal elements [4]. This method is developed for the case when the GD contains, along with horizontal and vertical elements. Under horizontal elements, the longitudinal resistance of which is taken into account, the parts of the grounding, enclosed between two adjacent nodal points (the points at which two or more elements intersect and converge) are understood and which are constructively the electrodes of the grounding grid. As a node, you can take any point located on the horizontal part of the grounding [4]. When replacing reinforced concrete pedestals and racks with a combination of vertical and horizontal linear electrodes, the longitudinal resistance of the last elements is not taken into account.

The initial model of a complex earth electrode is determined by the assumptions in accordance with [4]:

1) within a given complex grounding plane, those horizontal elements whose longitudinal resistance is taken into account have homogeneous (within the element) distributed specific parameters, i.e. per unit length: longitudinal active resistances, inductance and transverse conductance of current spreading;

2) the values of the transverse conductivity of the elements also depend on their longitudinal parameters, which in turn, when using elements of steel, are a nonlinear function of the current passing through them;

3) there is no effect on the distributed parameters of the grounding of the electromagnetic field of the single-phase grounding fault current passing through the air lines;

4) vertical elements and those horizontal elements whose longitudinal resistance is not taken into account are ideal lumped;

5) there may be several «setting» points within the grounding, i.e. points directly electrically connected to the external electrical circuit (the «setting» is the nodal points of the grounding directly connected to the neutral transformers or autotransformers, and the point at which the phase of the power line is closed in the design emergency mode);

6) with the design single-phase closure through the setting node points, the driving currents (steady-state values of the single-phase ground fault current and the

currents «returning» to the system through neutral transformers and autotransformers) pass.

In accordance with the requirements for the straightness of the grounding electrodes, the following method for taking into account the natural conductivity of the current spreading from the reinforcement of reinforced concrete groundings is proposed to realize the capabilities of this calculation algorithm. Let's imagine a natural concentrated grounding as an equivalent set of linear electrodes, for example, so that these electrodes are located on the outline of a natural grounding. In particular, the reinforcing frame of the footrests is replaced by a set of vertical electrodes, the dimensions and location of which is determined by the corresponding geometric characteristics of the pedestal stand, and the set of horizontal electrodes – in accordance with the geometric characteristics of its plate. The set of replacement electrodes is located in the ground with a layer-by-layer homogeneous electrical structure, as well as a simulated natural concentrated grounding. Further to the indicated set of electrodes, one can apply the induced potential method [4] to solve the electric field problem as a complex GD and determine the values of the flow resistance and the potentials of points on the surface of the ground.

Replacement of natural concentrated groundings. The polyfunctionality of the GD of electrical installations with voltages above 1 kV of a network with a solidly grounded or effectively grounded neutral has led to the necessity of rationing several parameters of the GD - or touch voltage or resistance of the GD [5]. In this regard, we accept two criteria for the equivalence of the replacement circuit for natural concentrated GD by a set of linear electrodes: the approximation in resistance and the approximation of the potentials of points on the surface of the earth. In this case, as initial data for estimating the sufficiency of the approximation, we take the results of solving the boundary-value problem for the Laplace equation with reference to the model of a natural concentrated grounding in a limited volume of the ground. The sufficiency of the approximation achieved in the process of building up replacing linear electrodes is estimated as follows:
by resistance

$$\xi_R = \left| \frac{R_{s,e} - R_{p,\mathrm{m}}}{R_{p,\mathrm{m}}} \right| \le \xi_{R,\mathrm{lim}} ; \qquad (1)$$

by potentials of points

$$\xi_\varphi = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\varphi_{i,s,\mathrm{e}} - \varphi_{i,p,\mathrm{m}}}{\varphi_{i,p,\mathrm{m}}} \right| \le \xi_{\varphi,\mathrm{lim}} , \qquad (2)$$

where $R_{s,e}$, $R_{p,m}$ are the resistance to the spreading of the set of electrodes and the approved model, respectively; $\varphi_{i,s,e}$, $\varphi_{i,s,e}$ are the potential on the earth's surface of a set of electrodes and the approved model, respectively; n is the number of points on the earth's surface.

Variants of substitution of natural concentrated groundings (reinforced concrete racks and footrests) with the calculated set of linear electrodes were obtained by the method described earlier using ξ_R- и ξ_φ-criteria, and presented in [6, 7].

Calculation expressions for mutual and intrinsic resistances. The proposed method of taking into account the natural conductivity of current spreading from the reinforcement of reinforced concrete natural groundings may require the use of expressions for mutual and intrinsic resistances with respect to horizontal electrodes located in the lower layer of a two-layer earth model. Necessity in these expressions will appear when the reinforcing frame of the footrunners is replaced, the slab of which is located at a depth of about 3 m, a set of vertical and horizontal electrodes.

The calculation expressions for the mutual and intrinsic resistances are derived from the general formula for the mutual resistance R_{qg} between two electrodes with the indices g and q located in the conducting half-space with respect to the electrodes whose cross-sectional dimensions are hundreds of times smaller than their length [4], i.e .

$$R_{qg} = \frac{1}{l_q l_g} \int_{(l_q)} \int_{(l_g)} f'_{0q}(Q) f'_{0g}(G) \Psi_{QG} dl_Q dl_G , \qquad (3)$$

where l_q and l_g is the length of electrodes; $f'_{0q}(Q)$ and $f'_{0g}(G)$ is function of the non-uniformity of the linear current density along the electrode length; Ψ_{QG} is the proportionality function between the current flowing out into the conducting half-space from the vicinity of the point G, and the potential induced by this current at the point Q.

As a result of the derivation according to (3), the following expressions are obtained: the mutual resistance of two horizontal electrodes located in the lower layer and parallel to each other; mutual resistance of two horizontal electrodes located in the lower layer and perpendicular to each other; the mutual resistance of two horizontal electrodes, in the case where one electrode is located in the upper layer, the second - in the lower layer; mutual resistance of two horizontal crossed at right angles electrodes located in the upper and lower layer; the mutual resistance of the horizontal electrode located in the lower layer, and the vertical electrode crossing the interface of the layers.

The correctness of the expressions is confirmed by comparing the results of the test calculations by them and the expressions given in [4] for the location conditions of the horizontal electrode(s) in the upper layer and the initial data corresponding to the position of the electrode(s) at the interface of the layers. The calculated expressions for the mutual and intrinsic resistances of the electrodes were published in [8] and, together with previously published ones, encompass all possible combinations of the arrangement of the electrodes in the calculation of complex GD with allowance for natural concentrated groundings.

Algorithm for calculating a complex non-equipotential GD. The obtained models of natural concentrated groundings in the form of a set of linear vertical and horizontal electrodes are introduced into the algorithm for calculating a complex non-equipotential GD, which we take as the initial one. These elements, along with artificial linear earth conductors, participate in the current distribution of the GD. In this case, the longitudinal resistance of the horizontal electrodes, replacing the natural groundings, is not taken into account. At an industrial frequency, the electric field of the current leaving the earth electrode into the ground can be considered as stationary. In this case, the current distribution between the equipotential bond elements is determined by a system of linear algebraic equations (SLAE) [4]:

$$\varphi_G = \sum_{p=1}^{n} \alpha_{mp} I_p , \quad \text{at } m = \overline{1,n} \qquad (4)$$

where n is the number of grounding elements; α_{mp} is the mutual resistance of GD elements with indices m and p (at $m \neq p$) and the intrinsic resistance of elements with identical indices; I_p is current flowing into the ground from the p-th element; φ_G is the potential of the grounding (equipotential).

In this case we have SLAE (5) analogous to SLAE with proper and mutual potential coefficients in the system of charged bodies [9].

According to [4], in the case of a non-equipotential grounding, the SLAE in matrix form has the form:

$$AI_0 = U , \qquad (5)$$

where A is the matrix of mutual and intrinsic resistances of elements; I_0 is the matrix-column of complex values of currents flowing from the elements of a complex grounding to the earth; U is the matrix-column of complex values of the voltages of elements (for horizontal elements, the average of the values of the voltage at the beginning and the end of the element is taken, and for the vertical elements, the voltage of the node point with which it is connected).

The complex values of the voltages of the GD elements are related to the values of the driving currents and to the parameters of a complex nonlinear electrical circuit simulating the original GD, without taking into account the natural groundings. We express this connection by the method of nodal voltages in matrix form (all nodes starting from the reference one, which we take as the «ground» – zone of the zero potential, are numbered from zero to q) [4]:

$$YU_{nodal} = I_{set} , \qquad (6)$$

where Y is the square matrix of total conductivity of circuits; U_{nodal} is the matrix-column of nodal voltages; I_{set} is the matrix-column of setting currents.

In accordance with [4], the calculation of a complex electric circuit replacing a multielement GD is reduced to joint solution of two matrix equations (5) and (6). Taking into account the fact that the parameters of horizontal elements are nonlinearly dependent on the current flowing through them, equation (6) is nonlinear. Vertical elements of the GD are replaced by concentrated conductances on the ground; also those horizontal elements are replaced whose longitudinal resistance is not taken into account.

At the next stage of the calculation algorithm, the horizontal elements whose longitudinal resistance is taken into account are replaced by equivalent U-shaped circuits with lumped parameters (Fig. 1).

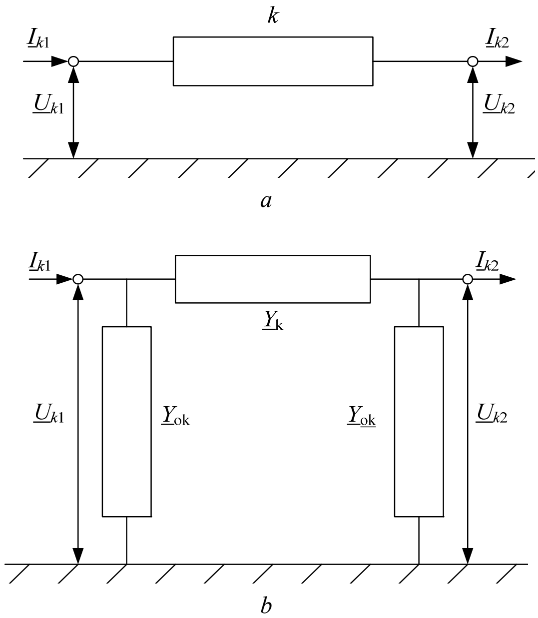

Fig. 1. Horizontal k-th element with distributed parameters r, L, g (a) and its equivalent U-shaped equivalent circuit (b)

The relationship of the lumped parameters of the U-shaped equivalent circuit of the k-th horizontal element ($\underline{Y}_k$ and $\underline{Y}_{0k}$) with its distributed parameters is known [6]:

$$\begin{aligned} \underline{Y}_k &= 1/\underline{Z}_{wk}\,\mathrm{sh}\underline{\gamma}_k l_k ; \\ \underline{Y}_{0k} &= \left(\mathrm{ch}\underline{\gamma}_k l_k - 1\right)/\underline{Z}_{wk}\,\mathrm{sh}\underline{\gamma}_k l_k , \end{aligned} \qquad (7)$$

where $\underline{Z}_{wk}$ is the wave impedance; $\underline{\gamma}_k$ is the propagation coefficient.

The quantities included in the formulas for the wave impedance $\underline{Z}_{wk}$ and the propagation coefficient $\underline{\gamma}_k$ are the specific impedance of the element and the specific total transverse conductivity g_k. The specific total longitudinal resistance of the horizontal electrode is determined by the active resistance and inductance, the latter having two components: the external L_{ext}, caused by the magnetic field outside the electrode, and the internal L_{int}, connected with the magnetic field inside the electrode. The internal inductance L_{int} is calculated as a function of the magnetic permeability of the electrode steel μ_k which is determined from the main magnetization curve at a given effective value of the magnetic field strength at the electrode surface. The magnetic permeability of the steel of the element μ_k depends nonlinearly on the current I_k passing through the k-th element. The external inductance of L_{ext} is determined on the basis of the well-known Pollachek formula. Conductivity

$$g_k = G_k l_k^{-1},$$

and G_k is determined by the method of the induced potential.

For the first approximation or the first iteration [4], the grounding is assumed to be equipotential and the numerical values of the solution vector of the matrix equation (4) are found. Further, the transverse conductivities G of all horizontal and vertical elements of the grounding are determined; at the first iteration, we assume that all the conductivities under consideration are of an active nature.

Further, given a certain initial value of the magnetic permeability of the electrode steel μ, we determine the distributed longitudinal parameters of the horizontal elements of the grounding grid and the parameters of their equivalent U-shaped replacement circuits. The solution of the matrix equation (6) for given reference currents makes it possible to obtain numerical values of the node voltages and calculate the currents in all branches of the equivalent circuit for the complex GD.

At the second approximation [4], the voltages in the nodes and currents in the branches of the grounding's equivalent circuit calculated in the first approximation are used as additional initial data, namely, the grounding is represented as non-equipotential - the SLAE has the form (5), and the above current values allow to clarify the magnetic permeability of the electrode steel μ. For this refinement, the values of μ we use the mean between the current values at the beginning and at the end of each horizontal element with distributed longitudinal parameters. The solution of system (3) with respect to currents in complex form allows us to further determine the values of the total transverse conductivities of all elements; these conductivities have reactive components which is formally connected with the presence of phase shifts with respect to each other at the node voltages at the first iteration. Further by using μ and G, the distributed longitudinal parameters of those horizontal elements of the grounding, whose longitudinal resistance is taken into account, are determined, etc.

In the part of determining the voltage before touching the given points on the ground and the input resistance of the GD, the calculation is performed in a known manner [4].

The obtained solution of currents in all branches of the equivalent circuit of the complex GD gives values of the currents flowing along the horizontal elements of the GD as average between the current values at the beginning and at the end of each horizontal element with distributed longitudinal parameters. As a result of this is adding to the algorithm for calculating complex non-equipotential GD of electrical installations the solution of the problem of determining the level of electromagnetic compatibility.

The sufficiency of the approximation achieved is estimated by the ξ-criterion:

$$\xi = \frac{1}{q}\sum_{j=1}^{q}\left|\frac{U_{jo}^{(n-1)} - U_{jo}^{(n)}}{U_{jo}^{(n)}}\right| \le \xi_{\lim}, \qquad (8)$$

where (n) is the upper index indicating the number of last iteration; q is the number of nodes of the grounding's equivalent circuit; U_{jo} is the voltage module of the j-th node with respect to the reference one.

Conclusions.

The necessity of taking into account the influence of natural concentrated groundings during the formation of electrical characteristics of complex non-equipotential GD of electrical installations by means of their equivalence by a set of vertical and horizontal electrodes is justified.

The calculation expressions for the mutual and intrinsic resistances of horizontal electrodes of complex non-equipotential GD located in the lower layer of the two-layer ground model that encompass all possible combinations of their location and provide for the calculation of natural concentrated groundings are obtained.

The use of the proposed algorithm for calculating the potential distribution at short-circuit at the substation in the electric networks of JSC «Kharkivoblenergo» taking into account the influence of the conductivity of natural concentrated groundings, made it possible to ensure the optimal normalization of the parameters of the operating electric installations due to more accurate determination of the touching voltage.

Expressions for calculating the values of voltage drops on the GD at short circuit are determined, which allow to estimate the level of voltages affecting the insulation of secondary circuit cables, which is necessary for normalizing their parameters according to the electromagnetic compatibility conditions.

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