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Determination of the electric field strength of high-voltage substations

The electric field strength is one of the main factors influencing sensitive microprocessor equipment and personnel on power stations and substations, power lines. Determining its level is an important applied task for ensuring the safe operation of electrical installations. ***The aim*** *is to develop calculation relationships for determining the electric field strength created by the busbar of high-voltage substations in the working areas of personnel. The solution of the problem was based on the use of the method of equivalent charges to determine the strength of the electric field created by the complex busbar of high-voltage substations.* ***Methodology.*** *The development was based on solving the problem of the potential of the electric field of a point charge located in a dielectric half-space for a cylindrical coordinate system. By representing the electrode in the form of a set of point charges and subsequent integration, an expression for calculating the potential is obtained, created by a busbar of arbitrary orientation of finite length in an analytical form. Using the principle of superposition of fields and the definition of the derivative, expressions were obtained for calculating the vertical component of the electric field strength at given heights.* ***Results.*** *Based on the obtained expressions, using Visual Basic, the simulation of the distribution of the electric field strength under a three-phase power line with a voltage of 150 kV was performed. Comparison with the known calculation results obtained on the basis of analytical expressions for infinitely long conductors showed that the obtained expressions have an error of no more than 7%.* ***The scientific novelty*** *lies in the fact that for the first time expressions were obtained for determining the electric field strength created by a system of electrodes of finite length, based on the analytical method for solving differential equations.* ***Practical significance.*** *The proposed technique is implemented as a test module of the LiGro specialized software package, which allows modeling complex busbar systems typical for power stations and substations and power lines. A test calculation was carried out for an operating substation of regional electric networks with a voltage class of 110 kV. By comparing the duration of the calculation of switchgears with a diagonal of about 500 m, it was found that the calculation time in the LiGro complex based on the analytical method is several tens of times less than the calculation based on the finite element method. In addition, a more powerful computer was used for the end element simulation.* References 14, tables 1, figures 5.

Key words: **substation, power line, electric field, method of equivalent charges.**

В електричних станціях та підстанціях, лініях електропередачі напруженість електричного поля є одним з головних факторів впливу на чутливе мікропроцесорне обладнання та персонал. Визначення її рівня є важливою прикладною задачею для забезпечення безпечної експлуатації електроустановок. ***Мета роботи*** *– розробка розрахункових співвідношень для визначення напруженості електричного поля, що створюється ошиновкою високовольтних підстанцій в робочих зонах персоналу. Розв'язання задачі базувалося на використанні методу еквівалентних зарядів для визначення напруженості електричного поля, створюваного складною ошиновкою високовольтних підстанцій.* ***Методика.*** *В основу розробки покладено розв'язання задачі про потенціал електричного поля точкового заряду, розташованого в діелектричному напівпросторі, для циліндричної системи координат. Шляхом представлення електроду у вигляді множини точкових зарядів та подальшого інтегрування отримано вираз для розрахунку потенціалу, що створений ошиновкою довільної орієнтації кінцевої довжини в аналітичному вигляді. Використовуючи принцип суперпозиції полів і визначення похідної, отримано вирази для розрахунку вертикальної складової напруженості електричного поля на заданих висотах.* ***Результати.*** *На основі отриманих виразів за допомогою Visual Basic виконано моделювання розподілу напруженості електричного поля під трифазною лінією електропередачі напругою 150 кВ. Порівняння з відомими результатами розрахунків, отриманими на основі аналітичних виразів для нескінченно довгих провідників, показало, що отримані вирази мають похибку не більше 7%.* ***Наукова новизна*** *полягає в тому, що вперше отримано вирази для визначення напруженості електричного поля, створюваного системою електродів скінченної довжини, на основі аналітичного методу розв'язування диференціальних рівнянь.* ***Практична значимість.*** *Запропонований спосіб реалізовано у вигляді тестового модулю спеціалізованого програмного комплексу LiGro, що дозволяє виконувати моделювання складних систем ошиновок, характерних для електричних станцій та підстанцій і ліній електропередачі. Виконано тестовий розрахунок для діючої підстанції регіональних електричних мереж класом напруги 110 кВ. Шляхом порівняння тривалості розрахунку розподільчих пристроїв з діагоналлю близько 500 м встановлено, що час розрахунку в комплексі LiGro на основі аналітичного методу в декілька десятків разів менший, ніж розрахунок на основі методу кінцевих елементів. Крім того, для моделювання методом кінцевих елементів використовувався комп'ютер з більш потужними характеристиками.* Бібл. 14, табл. 1, рис. 5.

Ключові слова: **підстанція, лінія електропередачі, електричне поле, метод еквівалентних зарядів.**

Analysis of the problem. Ensuring the resistance of technical objects to the action of powerful electromagnetic fields of natural and artificial origin is an important technical problem, without solving which the reliable and safe use of modern equipment, objects of military equipment and critical infrastructure is impossible.

Distribution devices of electrical stations and substations represent a complex technical system that combines power and measuring equipment of various voltage classes, control and telemechanics devices, including those based on microprocessor technology, cable products and busbars, as well as grounding and lightning protection devices. In such systems, the electric field strength $\boldsymbol{E}$ is one of the main factors affecting sensitive microprocessor equipment and personnel. Therefore, its permissible value is regulated in a number of normative documents [1–3]. For personnel, this is 5 kV/m for the vertical component of the electric field strength at height of 1.8 m above ground level. If this value is exceeded, the duration of staff stay at the workplace is limited. For example, in electric field with strength of 20 to 25 kV/m, the working time should not exceed 10 minutes, and at 25 kV/m and above, special personal protective equipment should be used. The boundaries of sanitary protection zones for active power transmission lines are determined at the level of 1 kV/m.

Limitations regarding the value of the electric field strength for microprocessor equipment are regulated in the relevant documentation regarding the conditions of its operation.

Determination of the electric field strength level is carried out experimentally [4, 5] and/or by calculation [4–10].

Experimental determination is performed with the help of electric field strength meters, unidirectional or tridirectional. The specified devices when used at power stations and substations should have a wide range of measurements (approximately from 1 to 50 kV/m), not distort the field lines, be insensitive to electromagnetic interference, be resistant to vibration and shocks and be able to work in difficult weather conditions, etc. This leads to a significant complication of the design and an increase in the cost of the specified devices. In addition, measurement in the field is quite time-consuming and does not allow to build detailed plans of strength zones on the territory of switchgear. In addition, there are zones in which it is practically impossible to carry out measurements (the presence of an internal fence, proximity to current-carrying parts, etc.).

In the conditions of targeted strikes by the Russian army on energy facilities of Ukraine and the prompt restoration of critical infrastructure, including by installing new power transmission line supports, the express assessment of field strength and boundaries of sanitary protection zones becomes even more relevant. Operationally, such an assessment can be performed only with the help of calculation methods. Here, it is enough to know the voltage class of the line and its geometric parameters.

The listed factors increase the relevance of the calculation way of determining the electric field strength for both planned and operating electrical stations and substations. As a rule, calculations for electric power facilities with a voltage class of 35–1000 kV are performed using numerical methods, among which the finite volume method has become the most common [9, 10]. By finite we mean a small volume around each grid mesh. In this method, volume integrals that contain expressions with divergence are transformed into surface integrals using the Ostrogradsky formula. Finite difference and finite element methods are also used [4–6]. The application of such methods is quite complicated, requires significant computing resources and is characterized by a long calculation time for large objects, which is explained by the iterative process and the size of the mesh cell. The calculation step should be comparable to the diameter of the busbar, which is tens of millimeters with object sizes up to several hundreds of meters. Thus, with a uniform mesh step, we have a large number of calculation points. Reducing their number is possible thanks to the use of special algorithms for irregular dividing of the computational volume [9, 10], which significantly complicates the modelling of objects with arbitrary orientation of busbars. In addition, in [11] it is stated that these methods are highly dependent on «human experience and trial and error.»

Analytical formulas for determining the electric field strength are given in a number of works, in particular in [6, 8]. They are, as a rule, easier to use, the mathematical expression shows the dependence of the field on all parameters of the line [6], they do not require significant computer resources. Traditionally, in such calculations, the busbar is replaced by a charged axle, and the method of equivalent charges is used to take into account the diameter. However, the main drawback of the existing expressions is that they consider infinitely long conductors (busbars). This leads to the limitation of the use of analytical formulas only for the simplest cases of the location of busbars of power transmission line supports. Here, expressions for determining the equivalent bus radius are usually used to take into account phase splitting. Taking into account that in the distribution devices of electrical stations and substations, the busbar is arbitrarily oriented in space, there are several voltage classes, split phases of different diameters, etc., the use of existing analytical expressions for them is practically impossible. In [4, 11], the implementation of the charge simulation method is proposed, which is actually a combination of numerical and analytical solutions for modelling the field of a substation with a voltage class of 500/220 kV, but in these works it is noted that the given method has similar disadvantages to numerical calculation methods.

Taking into account the perspective of using analytical expressions, their potentially higher accuracy and acceleration of calculation for complex objects of the electric power industry, the solution of the problem of the electric field of an arbitrarily oriented conductor of finite size (electrode) located above the earth's surface is relevant.

The goal of the work is to develop calculation relationships for determining the electric field strength created by the busbar of high-voltage substations in the working areas of the personnel.

Research materials. When using analytical methods to calculate the electric field strength of energy objects, the following assumptions are accepted [9, 10]:

- the electric field of the power frequency is quasi-static, which is explained by the propagation speed of the electromagnetic field in the air of $3 \cdot 10^8$ m/s at frequency of 50 Hz, so the expressions for the instantaneous value of the electric potential or strength will be valid for lines of size << 6000 km;
- busbars are long cylinders, the charge of which is regularly distributed along their axes;
- the voltage on the busbar changes according to the sinusoidal law with constant power frequency;
- the time shift between the busbar voltage phases is 120°;
- the earth's surface is flat, and it is an infinite electrical conductor compared to air and, accordingly, has zero potential;
- the air-ground separation boundary is plane-parallel;
- the influence of buildings and structures of electric stations and substations is not taken into account;
- the relative dielectric permittivity of air is assumed to be $\varepsilon_r = 1$.

Taking into account the above assumptions for solving the problem of the electric field strength of an arbitrarily oriented electrode, consider the electric field of a point charge located above a conductive surface.

The electric field of a point charge has axial symmetry. Therefore, it is advisable to use a curvilinear orthogonal cylindrical coordinate system (r, z, ψ) with an axis perpendicular to the boundary of the half-space with dielectric permittivity ε and passing through the point charge itself (see Fig. 1).

The formulation of the problem under consideration consists of the Laplace equation and additional conditions. The potential does not depend on the coordinate ψ, so the Laplace equation takes the form [12]:

$$\frac{\partial^2\varphi}{\partial r^2}+\frac{1}{r}\frac{\partial\varphi}{\partial r}+\frac{\partial^2\varphi}{\partial z^2}=0\,. \qquad (1)$$

Additional conditions are as follows:

- the condition at the air-ground boundary looks like this:

$$\varphi\big|_{z=0}=0\,; \qquad (2)$$

- when the coordinate z increases, the potential φ goes to zero:

$$\varphi_{\to\infty}=0\,. \qquad (3)$$

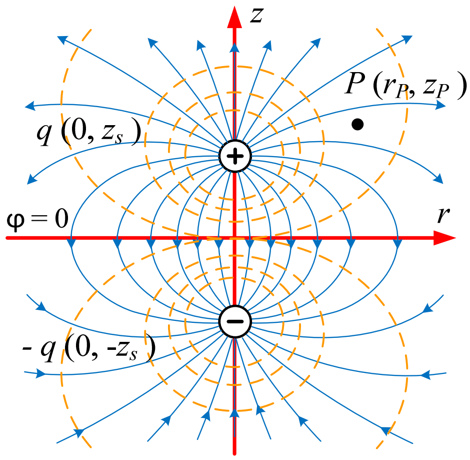


Fig. 1. A point charge located in the dielectric half-space

The solution of such a problem for the observation point $P(r_P, z_P)$ according to the method of mirror images and the principle of superposition is the sum of potentials from an electric dipole [6]:

$$\varphi(r,z)=\frac{q}{4\pi\varepsilon}\left[\frac{1}{\sqrt{r_P^2+(z_P-z_s)^2}}-\frac{1}{\sqrt{r_P^2+(z_P+z_s)^2}}\right], \qquad (4)$$

where z_s is the coordinate of the point charge along the axis z; ε is the static dielectric permittivity, which is equal to $\varepsilon=\varepsilon_r\varepsilon_0=8.8541878176\cdot10^{-12}$ F/m.

We denote the two fractions in the brackets of expression (4) as α_1 and α_2, respectively.

To obtain relationships for calculating the total potential of a system of arbitrary configuration, consider a separated electrode, uniformly charged with length L_i, in the form of a set of point charges located along its axis (Fig. 2). In fact, the electrode is an infinitely thin rod. Here, the linear charge density of such a source, located on the axis of the i-th electrode, has the form:

$$\tau_i=\sum_{l_i=0}^{L_i}q_{si}\Big/L_i\,. \qquad (5)$$

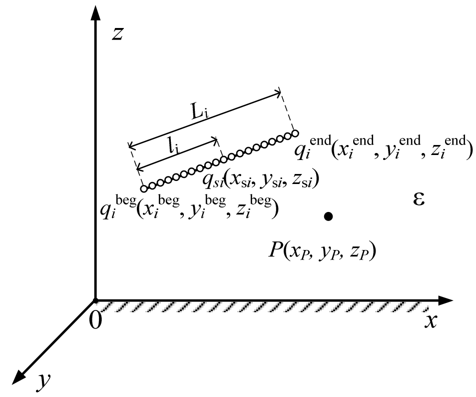


Fig. 2. An electrode in the form of a set of point charges located in a dielectric half-space

When moving from the cylindrical to the Cartesian coordinate system, the distance between the point charge located on the axis of the electrode and the observation point P can be rewritten as:

$$r_i=\sqrt{(x_{si}-x_P)^2+(y_{si}-y_P)^2}\,, \qquad (6)$$

where x_P, y_P are the Cartesian coordinates of the observation point P; x_{si}, y_{si}, z_{si} are the Cartesian coordinates of the point charge of the i-th electrode.

In turn, the coordinates of a point charge (Fig. 2) can be given in the form:

$$x_{si}=x_i^{\text{beg}}+\left(x_i^{\text{end}}-x_i^{\text{beg}}\right)\frac{l_i}{L_i}\,,$$
$$y_{si}=y_i^{\text{beg}}+\left(y_i^{\text{end}}-y_i^{\text{beg}}\right)\frac{l_i}{L_i}\,, \qquad (7)$$
$$z_{si}=z_i^{\text{beg}}+\left(z_i^{\text{end}}-z_i^{\text{beg}}\right)\frac{l_i}{L_i}\,,$$

where x_i^{beg}, y_i^{beg}, z_i^{beg} and x_i^{end}, y_i^{end}, z_i^{end} are the Cartesian coordinates of the beginning and end nodes of the i-th electrode, respectively; l_i is the current distance of the point charge from the beginning of the electrode.

Taking into account (6) and (7), the two fractions in expression (4) can be represented in the general form:

$$\alpha_{ki}=\frac{1}{\sqrt{\frac{A_i}{L_i^2}l^2+\frac{B_{ki}}{L_i}l_i+C_{ki}}}; \qquad (8)$$

where k = 1 or 2 to account for positive or negative charge (Fig. 1)

$$A_i=\left(x_i^{end}-x_i^{beg}\right)^2+\left(y_i^{end}-y_i^{beg}\right)^2+\left(z_i^{beg}-z_i^{end}\right)^2;$$
$$B_{1i}=2\Big[\left(x_i^{beg}-x_p\right)\left(x_i^{end}-x_i^{beg}\right)+\left(y_i^{beg}-y_p\right)\times$$
$$\times\left(y_i^{end}-y_i^{beg}\right)+\left(z_i^{beg}-z_p\right)\left(z_i^{end}-z_i^{beg}\right)\Big];$$
$$C_{1i}=\left(x_i^{beg}-x_p\right)^2+\left(y_i^{beg}-y_p\right)^2+\left(z_i^{beg}-z_p\right)^2;$$
$$B_{2i}=2\Big[\left(x_i^{beg}-x_p\right)\left(x_i^{end}-x_i^{beg}\right)+\left(y_i^{beg}-y_p\right)\times$$
$$\times\left(y_i^{end}-y_i^{beg}\right)+\left(z_i^{beg}+z_p\right)\left(z_i^{end}-z_i^{beg}\right)\Big];$$
$$C_{2i}=\left(x_i^{beg}-x_p\right)^2+\left(y_i^{beg}-y_p\right)^2+\left(z_i^{beg}+z_p\right)^2.$$

When integrating (4) along the electrode and taking into account the transition to the cylindrical coordinate system, we obtain:

$$\varphi_i = \tau_i \frac{1}{4\pi\varepsilon}\left(G_{1i} - G_{2i}\right), \qquad (9)$$

where

$$G_{ki} = \int_0^{L_i} \frac{d\ell_i}{\sqrt{\frac{A_i}{L_i^2}\ell_i^2 + \frac{B_{ki}}{L_i}\ell_i + C_{ki}}} =$$

$$= \left(\ln\left| \frac{2A_i + B_{ki}}{2\sqrt{A_i}} + \sqrt{A_i + B_{ki} + C_{ki}} \right| - \ln\left| \frac{B_{ki}}{2\sqrt{A_i}} + \sqrt{C_{ki}} \right| \right).$$

With a known value of the voltage on the electrode, we can determine the value of the linear density of the i-th electrode using the principle of «replacing the electrode surface with an equipotential» (method of equivalent charges):

$$\tau_i = \frac{4\pi\varepsilon\varphi_i}{\left(G_{1i} - G_{2i}\right)}. \qquad (10)$$

Here, the observation point P is located on the surface of the electrode in the middle of its length.

The total potential from the system of electrodes (busbars) is determined by the principle of superposition of fields:

$$\varphi = \sum_{i=1}^{Q_{con}} \varphi_i , \qquad (11)$$

where Q_{con} is the number of electrodes in busbar system.

The electric field strength is a vector equal to the gradient of the electric field potential with a minus sign. When determining the distribution of the electric field strength, the vertical component of the vector is used to control its impact on the personnel, i.e. the projection of $\boldsymbol{E}$ on the z axis, which is numerically equal to the derivative of the potential along the applicate axis. According to the definition of the derivative, this can be represented as a limit:

$$E_z = \left| \frac{\partial \varphi}{\partial z} \right| = \left| \lim_{\Delta z \to 0} \frac{\Delta\varphi}{\Delta z} \right|. \qquad (12)$$

Thus, having set the calculation step along the applicate axis $\Delta z << z_P$, we can determine the modulus of the vertical component of the electric field strength at the height z_P.

The obtained expressions (9)–(12) allow to calculate the electric field strength of busbar systems when they are replaced by electrodes of arbitrary orientation in space.

To determine the electric field strength, which is created by a three-phase bus system, the equivalent linear charge density of one of the phases is calculated according to (10), and for the other two, it is taken according to the sinusoidal distribution of the instantaneous value of the voltage at a fixed moment in time. For example, for phases B and C it is assumed that $\tau_{B,C} = \pm 0.5\tau_A$ at the time corresponding to 210°.

On the basis of the obtained expressions (9) – (12) in the MS Excel software product using the Visual Basic application, the busbar of a three-phase power transmission line was modelled with the following parameters: busbar suspension height 10 m, length 1000 m, radius 0.04 m, voltage class 150 kV, interphase distance 6.2 m. The calculation was performed along an axis perpendicular to the busbar at distance of 500 m from the beginning of the span. The analysis was carried out at height of 1 m and 3 m, respectively (see Fig. 3,*a*,*b*).

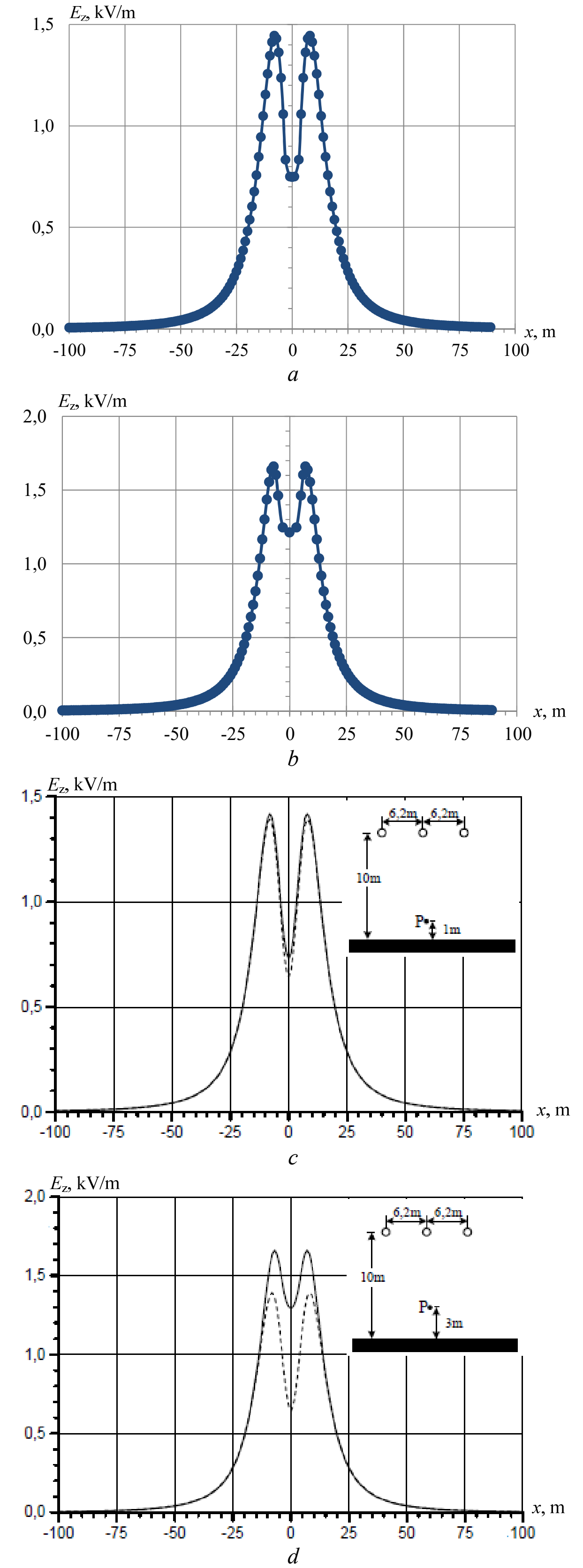


Fig. 3. Comparison of the results of calculating the field strength under the busbar of the power transmission line portal according (9)–(12) for height: *a* – 1 m; *b* – 3 m and according to [6] for height: *c* – 1 m; *d* – 3 m

The use of the presented initial data allows to compare the calculation results with the known ones [6], which were obtained for a three-phase line based on analytical expressions for infinitely long conductors (see Fig. 3,*c*,*d*).

Figures 3,*c*,*d* show the curves according to the calculation data [6]: the dashed line is for the approximate expression, and the solid line is for the exact expression. To assess the correspondence of the results obtained by the authors Table 1 summarizes the characteristic values of the vertical component of the electric field strength E_z at the given heights of the analysis z_P and the relative error of the calculation δ.

Table 1

Data for comparative calculation analysis

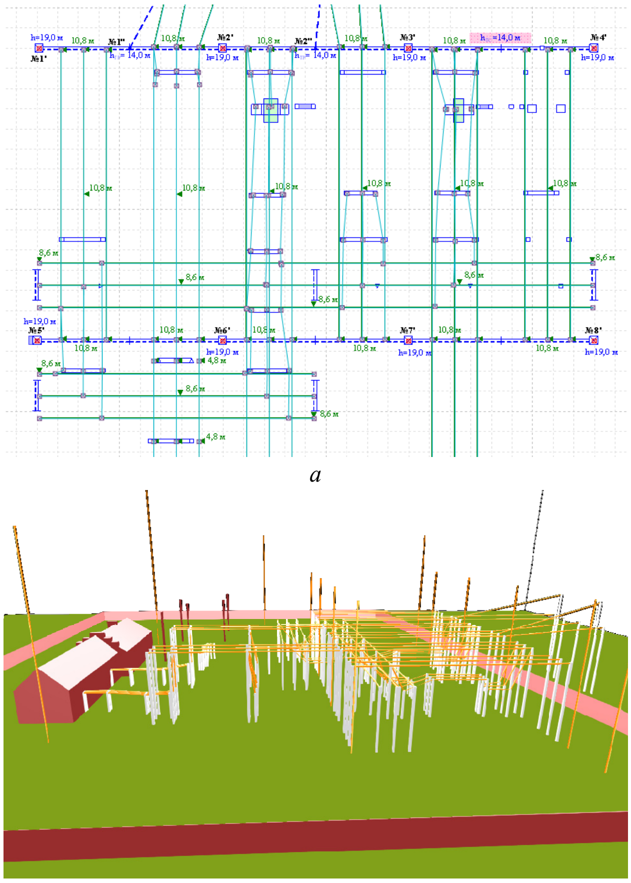
x, m	E_z, kV/m					
	z_P = 1 m			z_P = 3 m		
	developed	exact [6]	δ, %	developed	exact [6]	δ, %
0	0,7481132	0,7461	0,3	1,2135346	1,2913	6,0
5	1,2347961	1,1997	2,9	1,4629176	1,5576	6,1
6,2	1,4413401	1,4195	1,5	1,6597963	1,6518	0,5
10	1,3458512	1,3254	1,5	1,4358176	1,4423	0,4
15	0,8472474	0,8584	1,3	0,8140060	0,8733	6,8
20	0,4807888	0,4853	0,9	0,4532538	0,4823	6,0
25	0,2822402	0,2901	2,7	0,2679740	0,2833	5,4
30	0,1756019	0,1778	1,2	0,1684291	0,1785	5,6
40	0,0794274	0,0789	0,7	0,0773403	0,0822	6,0
50	0,0419541	0,0426	1,4	0,0412079	0,0441	6,6

Comparisons with the results obtained by the authors show that the shape of the curves is practically identical, the maximum is observed in all cases under the extreme phases of the busbar at distance of ±6.2 m. The maximum deviation at height of 1 m is 2.9%, and at height of 3 m is 6.8%.

The increase in error when approaching the busbar can be explained by the effect of the geometric size of the conductor (the authors assumed 0.04 m, but it was not specified in [6]). Thus, the validity of the obtained expressions compared to the known calculation results was confirmed.

The proposed calculation method was implemented as a test module for the LiGro software complex [13]. The choice of the specified complex is due to the availability of the necessary palette of modelled objects (busbars, portals, supports, equipment, buildings and communications of arbitrary location and complexity, etc.), as well as 2D and 3D visualization modules. For the convenience of displaying the calculation results, a gradient form of representation is used.

Figure 4 shows fragments of 2D and 3D models of an operating distribution device of the 110/6 kV voltage class of a substation of one of the regional energy companies in the east of Ukraine. The substation plan, heights and geometric parameters of the busbar, which were determined during the diagnosis of the lightning protection system according to the method [14], were used as initial data. The voltage class of each bus system and phasing, set in the parameters of each electrode (busbar) separately, were also taken into account. This allows to take into account all voltage classes that are present on the object.



a

b

Fig. 4. Fragments of 2D (*a*) and 3D (*b*) models of a functioning substation of voltage class 110/6 kV in the LiGro complex

The simulation results for an operating distribution device with voltage class of 110/6 kV are shown in Fig. 5. The calculation was carried out at standardized height of 1.8 m, with a mesh with a step of 0.1 m. The calculation did not take into account the sagging of the busbar. But, if necessary, this can be solved by dividing it into parts at the appropriate angle of inclination.

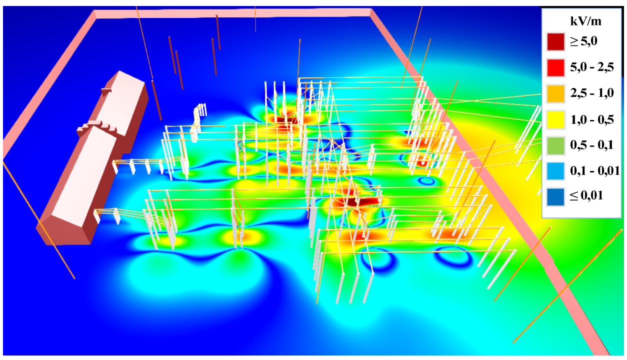


Fig. 5. Distribution of the electric field strength for an operating electric power facility of voltage class of 110/6 kV, obtained in the LiGro software complex

The calculation results show that there are areas at the substation where the field strength exceeds the permissible value of 5 kV/m, and the presence of personnel in these areas should be limited. In addition, it can be noted that the quality of the display of calculation results corresponds to the world level, namely to such software as [4, 5]. Here, in [5], where the simulation was performed on the basis of the finite element method using ANSYS and SolidWorks codes, the calculation time for a substation with voltage class of 1000 kV with a diagonal of approximately 500 m was 7 hours when using a powerful computer with the following parameters: an Intel processor Xeon 8×2.50 GHz and 32 GB RAM. For comparison, the calculation time in the LiGro complex of a similar distribution device with a diagonal of 540 m and voltage class of 750 kV of one of the nuclear power plants of Ukraine with a calculation mesh step of 0.2 m was only 6 minutes when using a computer with significantly worse parameters: an Intel processor Pentium G2020 2×2.90 GHz and 4 GB RAM. Therefore, the model developed by the authors based on the analytical method allows to significantly reduce the time spent and technical requirements for the computer when modeling the electric field strength of complex objects.

Conclusions.

1. On the basis of the method of equivalent charges, for the first time calculation relationships were developed for determining the intensity of the electric field created by the complex busbar of high-voltage substations in the working areas of the personnel.

2. The developed calculation relationships were used to create a computer code that allows to calculate the electric field strength at high-voltage substations and other high-voltage energy facilities taking into account the voltage class of each bus system, and at the design stage of these facilities to determine safe working areas for personnel by electric field.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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