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Protection against Electric Field in the Outdoor Switch-Gear Workplaces

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Introduction

Currently, the Hygiene Norm HN110: 2001 "The electromagnetic field of industrial frequency in the workplace" is valid in Lithuania providing that the maximum allowable level of the electric field strength is dependent on the exposure time to this electric field. The exposure to the electric field of industrial frequency with the strength of 5 kV/m for the entire working day is unallowable, whereas the short-time exposure to the electric field with the strength exceeding as much as 20 kV/m is allowed. However, in 2012 the EU Directive 2004/40/EC [1] will come into effect in Lithuania. This Directive prohibits even a short-term exposure to electric field of industrial frequency 50 Hz with the effective strength value exceeding 10 kV/m. According to the research, the findings and results of which have been discussed [2], surroundings of the 330 kV overhead power-line include some areas that are hazardous to humans with the electric field values exceeding limits set out in the EU Directive. The situation in the 330 kV outdoor switch-gear might turn out to be even more hazardous as phase wires are at a lower height here. Consequently, particular safety measures are necessary to keep the electric field exposure to employees working both in the surroundings of the high-voltage transformer and at the 330 kV outdoor switch-gear, below the limit values indicated in the EU directive.

This research paper involves analytical and simulating investigation of the electric field distribution at the 330 kV switch-gear, identification of areas hazardous to humans, discussion of safety measures used to diminish electric field to the permissible limit values, as well as research into their effectiveness.

Sources of electric field at the 330 kv switch-gear

Our research involves the open-type 330 kV outdoor switch-gear. In a power-line system it represents the place where the strongest electric field can be expected. Fig. 1 schematically shows one half of the outdoor switch-gear, whereas another half is a mirror-image of this one. Phase wires represent the source of electric field at the outdoor switch-gear. They are arranged at two different heights. The upper wires are arranged in height of 15 m on the supports. These wires can sag to 13,5 m. The scheme presented in Fig. 1 shows these wires to be arranged along the *y* axis. The lower wires are arranged in height of 7 m on the supports, and can sag to 6,5 m. They are arranged along the *x* axis.

Employees operating at this switch-gear are allowed to enter and work in any area of the entire switch-gear territory. Consequently, it is extremely important to know the strength of the electric field at height of ~2 m in the switch-gear territory.

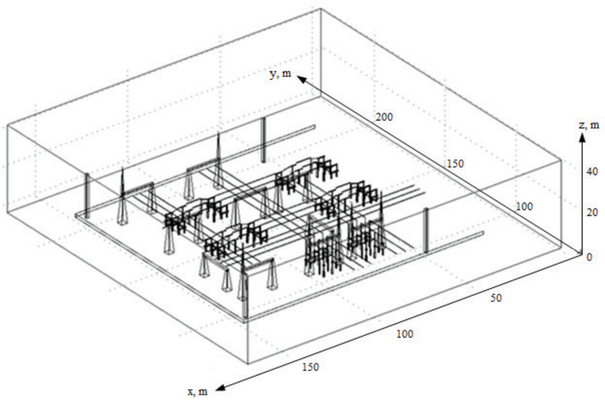

Fig. 1. Image of the part of 330 kV switch-gear

In the lower part of 330 kV switch-gear the strongest electric field is being generated by the set of lower wires. Let's evaluate the strength of this electric field.

Calculations of the electric field under the three phase power line

As the wires of the power line have a sag, the electric field generated by this line is three-dimensional. It is difficult to obtain the precise analytical solution of the field distribution in this case. However, maximum values of the electric field strength can be evaluated through approximation of the power line by the straight wires without a sag, arranged at the height of the maximal wire sag. In this case the field becomes two-dimensional and can be readily calculated.

Let's now examine the electric field of the three phase conductors A, B, C system shown in Fig. 2, where the conductor system is comprised of the long round cylindrical conductors stretched parallel to the ground surface and charged with linear densities τ_i (i = A, B, C). The potential of the ground surface is equal to zero. Radii of conductors $r_i << h_i$ are significantly less than the distance from the ground surface area to any of the conductors. This is a well-known electrostatic field problem [3]. We use method of images. Charge densities images $\tau_i^* = -\tau_i$ (i = A, B, C), are assigned to the points arranged in a negative direction symmetrically to the ground surface and having the same values as charges τ_i however opposite signs. The electric field strength at the any observation point M is calculated as the sum of electric field strengths generated by these 6 charges.

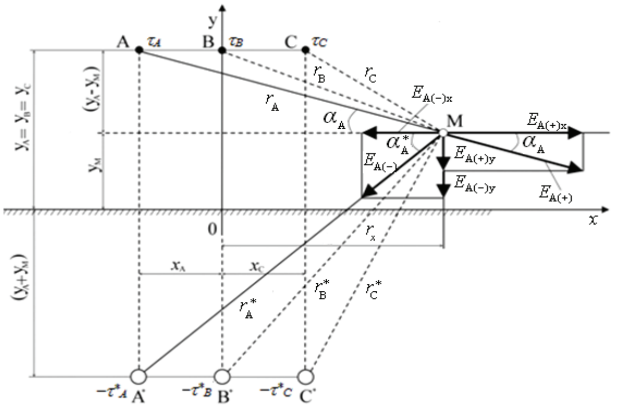

Fig. 2. Components of the electric field strength vectors at the point M

For given potentials of wires V_i (i = A, B, C), charge densities τ_i are calculated using Maxwell's equations [3]:

$$\boldsymbol{\tau}_i = \begin{vmatrix} \beta_{11} & \beta_{12} & \beta_{13} \\ \beta_{21} & \beta_{22} & \beta_{23} \\ \beta_{31} & \beta_{32} & \beta_{33} \end{vmatrix} \cdot \boldsymbol{V}_i, \quad \boldsymbol{\tau}_i = \begin{vmatrix} \tau_A \\ \tau_B \\ \tau_C \end{vmatrix}, \quad \boldsymbol{V}_i = \begin{vmatrix} V_A \\ V_B \\ V_C \end{vmatrix}; \qquad (1)$$

where β_{kn} (k = 1, 2, 3; n = 1, 2, 3) represent Maxwell capacitance coefficients. They are calculated as follows:

$$\beta_{kn} = \frac{\det\alpha_{kn}}{\det\alpha}, \ \det\alpha = \begin{vmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{vmatrix}; \qquad (2)$$

where $\det\alpha_{kn}$ represents the cofactors of the determinant $\det\alpha$, and α_{kn} (k = 1, 2, 3; n = 1, 2, 3) represent Maxwell potential coefficients. The coefficients $\alpha_{11} = \alpha_{22} = \alpha_{33}$ are found from the following equation

$$\alpha_{11} = \frac{1}{2\pi\varepsilon_r\varepsilon_0} \cdot \ln\frac{2 \cdot h}{r}; \qquad (3)$$

where r – radius of the conductor, $h = h^* = y_A = y_B = y_C$ (see Fig. 2), $\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ F/m – dielectric constant, ε_r – relative dielectric constant. For the air $\varepsilon_r = 1$. The coefficients $\alpha_{12} = \alpha_{21} = \alpha_{23} = \alpha_{32}$ are found as follows

$$\alpha_{12} = \frac{1}{2\pi\varepsilon_r\varepsilon_0} \cdot \ln\frac{b_{AB^*}}{a_{AB}}, \qquad (4)$$

where $a_{AB}=a_{BC}$=4,5 m is the distance between the phases wires A and B, whereas $b_{AB}{}^*$ is a distance between the phase A wire and the image B* of the phase B wire (see Fig. 2). The coefficients $\alpha_{13} = \alpha_{31}$ were calculated this way

$$\alpha_{13} = \frac{1}{2\pi\varepsilon_r\varepsilon_0} \cdot \ln\frac{d_{AC^*}}{c_{AC}}, \qquad (5)$$

where $c_{AC}=2a_{AB}$=9 m is the distance between wire phases A and C, whereas $d_{AC}{}^*$ is the distance between the phase A wire and the image C* wire of the phase C.

The calculations was performed assuming that h=6,5 m, r = 0,04 m. The following values of the potential coefficients and the capacitance coefficients were obtained for the problem presented in Fig. 2:

$$\begin{cases} \boldsymbol{\alpha} = \dfrac{1}{2\pi\varepsilon_0} \begin{vmatrix} 5{,}78 & 1{,}12 & 0{,}56 \\ 1{,}12 & 5{,}78 & 1{,}12 \\ 0{,}56 & 1{,}12 & 5{,}78 \end{vmatrix}, \\ \boldsymbol{\beta} = 2\pi\varepsilon_0 \begin{vmatrix} 0{,}180 & -0{,}033 & -0{,}011 \\ -0{,}033 & 0{,}186 & -0{,}033 \\ -0{,}011 & -0{,}033 & 0{,}180 \end{vmatrix}. \end{cases} \qquad (6)$$

The electric field strength E_{Mi} (i=A, B, C) generated by the charge with density τ_i at the observation point M can be calculated using the equation as follows [3]

$$E_{Mi} = \frac{\pm\tau_i}{2\pi\varepsilon_0} \cdot \frac{1}{r_i}. \qquad (7)$$

The total value of the electric field strength E_M at any point M in the field can be obtained through calculating the x and y components of the electric field strength, i.e., E_{Mx} and E_{My}. For this purpose, first let's calculate angles α_i between the straight lines AM, BM, CM and x axis as well as angles α_i^* between the straight lines A*M, B*M, C*M and x axis. Using equation (7), strengths of electric fields E_i (i = A, B, C, A*, B*, C*) generated by charges existent at these points are calculated. Components x and y of these field strengths are calculated as follows:

$$\begin{cases} E_{Mx} = \sum\limits_{i=A,B,C} E_{Mxi} + \sum\limits_{i=A^*,B^*,C^*} E^*_{Mxi}, \\ E_{My} = \sum\limits_{i=A,B,C} E_{Myi} + \sum\limits_{i=A^*,B^*,C^*} E^*_{Myi}. \end{cases} \qquad (8)$$

Components E_{Mxi}, E_{Myi}, E^*_{Mxi}, and E^*_{Myi} in the expressions (8) are found from the matrix equations:

$$\boldsymbol{E}_{xi} = \frac{\boldsymbol{\beta} \cdot \boldsymbol{d}_{xi}}{2\pi\varepsilon_0}, \quad \boldsymbol{E}_{xi} = \begin{vmatrix} E_{MxA} \\ E_{MxB} \\ E_{MxC} \end{vmatrix}, \boldsymbol{d}_{xi} = \begin{vmatrix} V_A \cos\alpha_A / r_A \\ V_B \cos\alpha_B / r_B \\ V_C \cos\alpha_C / r_C \end{vmatrix}, \qquad (9)$$

$$\boldsymbol{E}_{yi} = \frac{\boldsymbol{\beta} \cdot \boldsymbol{d}_{yi}}{2\pi\varepsilon_0}, \quad \boldsymbol{E}_{yi} = \begin{vmatrix} E_{MyA} \\ E_{MyB} \\ E_{MyC} \end{vmatrix}, \boldsymbol{d}_{yi} = \begin{vmatrix} V_A \sin\alpha_A / r_A \\ V_B \sin\alpha_B / r_B \\ V_C \sin\alpha_C / r_C \end{vmatrix}, \qquad (10)$$

$$\boldsymbol{E}^*_{yi} = \frac{\boldsymbol{\beta} \cdot \boldsymbol{d}^*_{xi}}{2\pi\varepsilon_0}, \quad \boldsymbol{E}_{xi} = \begin{vmatrix} E_{\mathrm{M}x\mathrm{A}} \\ E_{\mathrm{M}x\mathrm{B}} \\ E_{\mathrm{M}x\mathrm{C}} \end{vmatrix}, \boldsymbol{d}^*_{xi} = \begin{vmatrix} V_\mathrm{A} \cos \alpha_\mathrm{A} / r^*_\mathrm{A} \\ V_\mathrm{B} \cos \alpha_\mathrm{B} / r^*_\mathrm{B} \\ V_\mathrm{C} \cos \alpha_\mathrm{C} / r^*_\mathrm{C} \end{vmatrix}, \quad (11)$$

$$\boldsymbol{E}^*_{yi} = \frac{\boldsymbol{\beta} \cdot \boldsymbol{d}^*_{yi}}{2\pi\varepsilon_0}, \quad \boldsymbol{E}_{xi} = \begin{vmatrix} E_{\mathrm{M}y\mathrm{A}} \\ E_{\mathrm{M}y\mathrm{B}} \\ E_{\mathrm{M}y\mathrm{C}} \end{vmatrix}, \boldsymbol{d}^*_{yi} = \begin{vmatrix} V_\mathrm{A} \sin \alpha_\mathrm{A} / r^*_\mathrm{A} \\ V_\mathrm{B} \sin \alpha_\mathrm{B} / r^*_\mathrm{B} \\ V_\mathrm{C} \sin \alpha_\mathrm{C} / r^*_\mathrm{C} \end{vmatrix}. \quad (12)$$

The equations from (1) to (12) are also applicable to the industrial-frequency sinusoidal signals, too, [4]. Taking into consideration that:

$$\begin{cases} u_\mathrm{A} = U_\mathrm{m} \sin \omega t, \\ u_\mathrm{B} = U_\mathrm{m} \sin\left(\omega t - 120^\mathrm{o}\right), \\ u_\mathrm{C} = U_\mathrm{m} \sin\left(\omega t + 120^\mathrm{o}\right), \end{cases} \quad (13)$$

the components of the electric field at the observation point M can be expressed this way:

$$\begin{aligned} E_{\mathrm{M}x}(t) &= E_{\mathrm{M}x\,\max} \sin(\omega t + \psi_x), \\ E_{\mathrm{M}y}(t) &= E_{\mathrm{M}y\,\max} \sin(\omega t + \psi_y). \end{aligned} \quad (14)$$

Supposing that $E_{\mathrm{M}x} = E_{\mathrm{M}x\max}/\sqrt{2}, E_{\mathrm{M}y} = E_{\mathrm{M}y\max}/\sqrt{2}$, the effective electric field strength value E_M at the observation point M is calculated as follows

$$E_\mathrm{M} = \sqrt{E^2_{\mathrm{M}x} + E^2_{\mathrm{M}y}}. \quad (15)$$

The methodology described herein allows calculation of the electric field strength at any point under the three phase overhead power line. Based on this particular methodology, the effective electric field strength value was calculated at 1,8 m height under the lower power line while supposing that the height of wires $h = y_\mathrm{A} = y_\mathrm{B} = y_\mathrm{C} = 6{,}5$ m at the plane perpendicular to wires of the power line, while changing the distance by 1 m steps. Calculations were made assuming that amplitude value V_m of potentials V_A, V_B, and V_C is equal to amplitude value of the phase voltage $V_\mathrm{m} = U_\mathrm{fm} \approx 293$ kV. Fig. 3 shows analytical results (the lower line) which suggest that the strongest electric fields are generated near the wires of A and C phases.

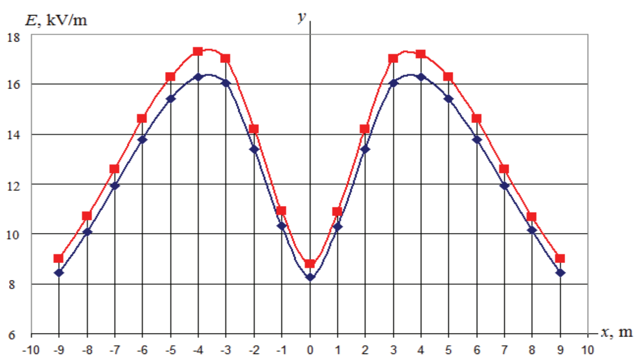

Fig. 3. Distribution of the effective values of electric field strength in the plain perpendicular to the power line at the height $h = 1{,}8$ m, obtained through calculation and simulation (values of the simulation curve is higher —■—)

The obtained analytical results were also verified through simulation using a software package COMSOL Multiphysics 3.5. Simulation took into consideration potentials of not only lower but also of upper wires. Results of simulation (see upper curve of the Fig. 3) were found to be close to the analytical results, consequently the proposed methodology can be used for investigation the electric field which the three phase line creates.

Attenuation of Electric Field in the Outdoor Switch-Gear Workplaces

With reference to the currently valid hygiene norms, measurements of the electric field are taken at heights of 0,5 m, 1,0 m, and 1,8 m. Respectively, electric field strength at these heights is not allowed to exceed 10 kV/m.

Employees operating at the outdoor switch-gear are allowed to enter and work in any area of the entire switch-gear territory. Moving closer to the flat surface of the ground, the electric field gradually diminishes. But the electric field strength values can be exceed the permissible values in surroundings of sufficiently sharp-pointed and spiky grounded surfaces, such as, for example, metal fence. The modelling results presented in [2] show that the electric field is significantly increased around the top of the metal fence while exceeding allowed limit values.

A well-known technique of shielding against electrostatic fields is Faraday cage or Faraday shield: a space is shielded by covering it with the metal grounded mesh. Such a shielding can be successfully used for attenuation of the 50 Hz frequency electric field. As the electric field must not be cancelled but only diminished, it is not necessary to use cage; it is sufficient to mount only a few (or one) metal bars. When two or more shielding bars are used they must be grounded in such a manner that there were no closed circuits.

For the purpose of selecting an optimal shield design, the simulation was performed using a software package COMSOL Multiphysics 3.5.

According to Fig. 3 the most hazardous zones occur under the wires of A and C phases. These are the areas where electric field shields must be installed. Simulation included shielding designs comprised of N parallel grounded metal bars mounted at height $H = 2{,}4$ m where $N = 1, 2, 3$, and 4. Metal bars were made of 8 cm diameter pipes. For the shielding of two or three bars, the distance between the marginal bars, l, was varied. In Fig. 4 different designs of the shields are showen. In any case under simulation, the electric field under the shield gradually diminishes moving to the ground surface. The electric field strength was measured at 1,8 m height. In table 1 there are presented maximum values of the electric field strength measured in this height, $E_{\mathrm{m}1{,}8}$. In the table 1 N represents number of bars used for shielding, and l represents distance between the marginal bars of the shield.

Table 1. The electric field strength under the shields at 1,8 m height (the shields are mounted in the height $H = 2{,}4$ m)

N	1	2	2	3	3	4
l, m	-	6	2,5	4	2,5	6
$E_{\mathrm{m}1{,}8}$, kV/m	11	12,5	9,3	9	8,5	7

In the case when the shield is comprised of only one bar, it is in the plane perpendicular to the ground surface stretching under the phase A or C wire. In case the shielding is comprised of more than one bar, these bars are arranged symmetrically to this plane (see Fig. 4.). As electric field values reach hazardous limits at the vertical metal support-bars, it is desirable to mount shielding to the grounded structures available at the switch-gear or use bars made of insulated materials.

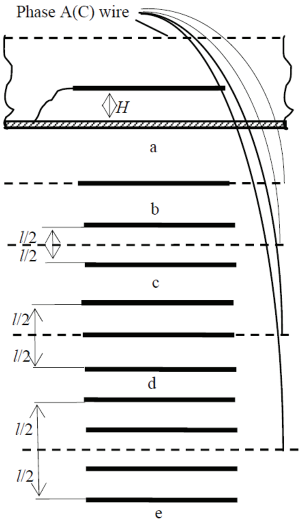

Fig. 4. The designs of simulated shielding: a) front-view; b-e) top-view when shielding is comprised of 1, 2, 3, and 4 bars, respectively

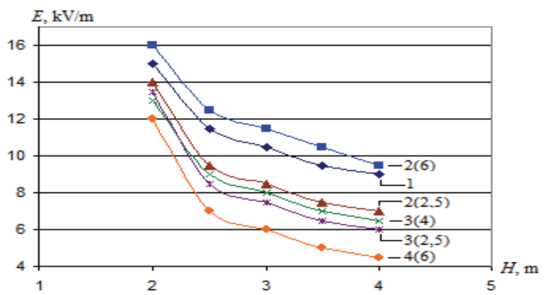

Fig. 5. Dependence of the electric field strength at 1,8 m on the height of shielding. The schield variant is pointed by *N(l)* there *N*-number of bars, *l*- the distance between the marginal bars

Simulation also involved investigation of variation in values of electric field strength under the shield comprised of 1, 2, 3 and 4 bars, depending on the height of the shield from the ground surface. Findings of this investigation are presented in the Fig. 5.

These results suggest that with the increasing height of the shield the electric field strength diminishes at a workplace. When the shield is mounted in a height at least 2,4 m it is sufficient to have the shield comprised of two shielding bars under each phase A or C wire in order to protect the entire area from the unacceptable exposure of the electric field.

Conclusions

1. Distribution of the electric field strength at the high-voltage outdoor switch-gear can be calculated using methods of the electrostatic field investigation.
2. There are potential employee exposure areas in the 330 kV outdoor switch-gear where electric field strength exceeds maximum limit values indicated in the EU directive 2004/40/EC.
3. The electric field can be attenuated to the permissible limit values by using metal grounded bars as a means of shielding mounted above the area to be shielded.
4. When the height of the 330 kV line wires is not less than 6,5 m it is sufficient to mount two shields composed of two metal bars situated under the wires of A and C phases in the height of 2,4 m in order to ensure safe work and operation under these line.

References

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The technique of the electric field distribution analysis in the 330 kV outdoor switch-gear is proposed. There are the zones in which electric field strength is greater than maximum permissible values by European Directive 2004/40/EU. The peak values of electric field strength are under the wires of A and C phases. These results are confirmed using programme package COMSOL. The electric field strength can be diminished to permissible values by shielding. It can be used as a shield comprised of some metal bars mounted parallel to wires of A and C phases over the shielding place. For the purpose of shielding it is sufficient to mount two bars provided they are mounted in the height of at least 2,4 m. Ill. 5, bibl. 4, tabl. 1 (in English; abstracts in English and Lithuanian).

R. Deltuva, J. A. Virbalis. Aukštosios įtampos skirstyklos darbo vietų apsauga nuo elektrinio lauko // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 6(112). – P. 11–14.

Pasiūlyta, kaip apskaičiuoti elektrinio lauko stiprio pasiskirstymą 330 kV aukštosios įtampos skirstykloje. Nustatyta, kad joje yra zonų, kuriose elektrinio lauko stipris viršija leistinas vertes. Stipriausias laukas yra šalia A ir C fazinių laidų. Šie rezultatai patvirtinti naudojant modeliavimo programą COMSOL. Elektrinio lauko stiprį sumažinti iki leistinų verčių patogiausia ekranuojant. Ekranavimui galima naudoti kelis įžemintus strypus, įrengiant juos lygiagrečiai su A ir C fazių laidais virš ekranuojamo ploto. Jeigu ekranavimo strypai įrengiami ne žemiau kaip 2,4 m, vienam ekranui pakanka dviejų strypų. Il. 5, bibl. 4, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).