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Innovation Solutions of the Safety Means in the Outdoor Switch-Gears

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ABSTRACT: The overhead power lines and open-type switch-gears of 330 and more kV represent one of the main and most powerful sources of electric field generation within electric power systems. 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 found to exist under the wires of A and C phases. These results were verified using programme package COMSOL Multiphysics 3.5. The electric field strength can be diminished to permissible values by shielding. It can be used as a shield comprised of several 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 in the height of at least 2.4 m.

KEYWORDS: Open-type outdoor switch-gear, electric field strength, linear charge density, electric flux density, electric field distribution, protection against electric field.

I.INTRODUCTION

Accordingly to EU Directive 2004/40/EC [11] employees can't be exposed by electric field of industrial frequency 50 Hz with the effective strength value exceeding 10 kV/m. By [9, 12] surroundings of the 330 kV open-type switch-gear include some areas that are hazardous to humans with the electric field values exceeding limits set out in the EU directive. Workplaces in the outdoor switch-gears of 330 kV and higher voltage can be especially dangerous as phase wires are usually suspended at lower heights here. Consequently, it is necessary to take particular safety measures to keep the exposure of electric field for employees working in the surroundings of open-type outdoor switch-gear, below the limit values indicated in the EU directive[2].

This research paper involves analytical, simulative and experimental measurements (using high precision ± 5 % and high long-time stability 3D electric and magnetic fieldmeter ESM-100) of the electric field distribution at the 330 kV outdoor switch-gear, identification of areas hazardous to human operators, and discussion of safety measures used to reduce electric field at the workplace to permissible limit values. Effectiveness of suggested safety measures was examined by means of simulation[1, 5, 6, 7, 14].

II.DISCUSSION OF THE PROBLEM UNDER CONSIDERATION

Our research involved the open-type 330 kV outdoor switch-gear. It is the place in general Lithuanian power-line system where the most powerful electric field can be expected. Twin phase wires and bus-bars represent the source of electric field at this outdoor switch-gear. These current leads are arranged in two different heights. The upper current leads are arranged in height of 15 m at the supports. These wires can sag to 1 m. And the lower current leads are arranged in height of 7.5 m at the supports, and can sag to 6.5 m. The employees operating at this switch-gear are allowed to enter and work in any area of the entire switch-gear territory, i.e., under the conditions of phase current leads carrying high-voltage at the outdoor switch-gear.

In the lower section of outdoor switch-gear where employees can work without switching-off the supply voltage, the strongest electric field is being generated by the set of lower wires. We evaluate the strength of this electric field by means of analytical, simulative and experimental measurements.

As the wires of the power line are caused to sag, the electric field generated by this sag is three-dimensional (3D), thus making its precise analytical calculations extremely difficult. However, maximum values of the electric field strength

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can be evaluated through the straight wire approximation of the power line, arranged at the height of the maximum wire sag. In this case the electric field becomes two-dimensional (2D) and can be calculated analytically.

The speed of variation of industrial-frequency (50 Hz) signals is far and away lower than wave propagation speed, therefore derivative times can be left out of the consideration. Let's now examine the electric field of the 3 phase conductors A, B, C system showed in Fig.1., where the conductor system is comprised of long round cylindrical conductors stretched parallel to the ground surface and having charges with respective linear densities τ_i(i=A, B, C). The potential of the ground surface is equal to 0 V. The radiuses of conductors $r_i << h_i$ are significantly less than the distance from the ground surface area to any of conductors. This is a well-known and common task in a field of electrostatics [13, 15]. We use method of images. The images of charge densities $\tau_i^* = -\tau_i$ (i=A, B, C) are assigned to the points arranged in a negative direction symmetrically to the ground surface and having the same values however opposite signs. Consequently, the electric field strength at the observation point M can be calculated as the sum of electric field strengths generated by those 6 charges.

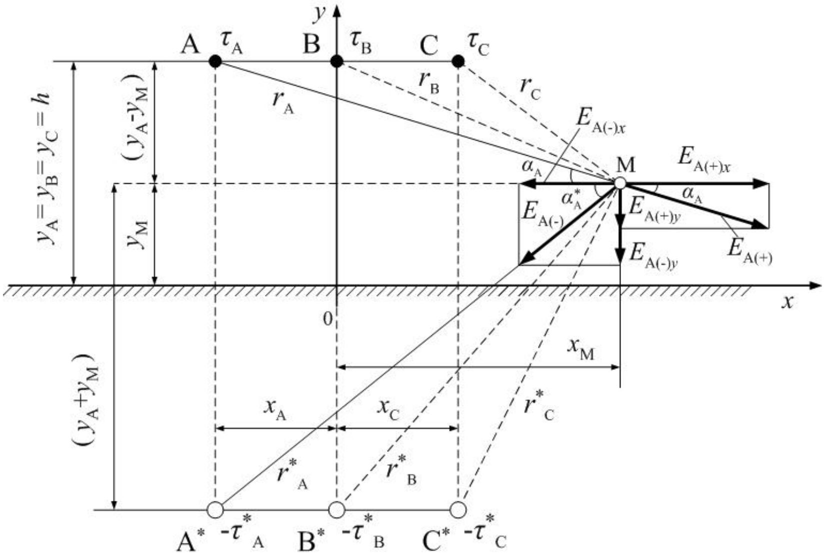


Fig.1. Components of the electric field strength vectors at the observation point M

The charge densities τ_i of phase conductors (i=A, B, C) can be calculated by known values of potentials V_i using Maxwell's equations. Those equations can be expressed in a form of matrix as follows [13, 15]:

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

where β_{kn}(k=1,2,3; n=1,2,3) are capacitive power factors. They are calculated as follows:

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

where Δ_{kn} represents the algebraic complement of the determinant Δ, and α_{ij} (i=1,2,3; j=1,2,3) represent the coefficients of potentials.

The coefficients with the same indices are:

$$\alpha_{11}=\alpha_{22}=\alpha_{33}=\frac{1}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_{0}}\cdot\ln\frac{2\cdot h}{r}; \qquad (3)$$

where r – radius of the conductor, $h=h^{*}=y_{\mathrm{A}}=y_{\mathrm{B}}=y_{\mathrm{C}}$(see Fig.1.),$\varepsilon_0=8.85\cdot10^{-12}$ F/m – dielectric constant,ε_{r} – relative dielectric constant, for air $\varepsilon_{\mathrm{r}}=1$. For the purpose of calculations it was assumed that$h=6.5$ m, $r=0.02$ m.
Whereas coefficients carrying different indices between adjacent wires are found from the following equations:

$$\alpha_{12}=\alpha_{21}=\alpha_{23}=\alpha_{32}=\frac{1}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_{0}}\cdot\ln\frac{b_{\mathrm{g}}^{*}}{a_{\mathrm{g}}}, \qquad (4)$$

Where$a_{\mathrm{g}}=4.5$ m is a distance between two adjacent wires(A and B or B and C phases), and b_{g}^{*} is a distance between one of two wires A or B and the adjacent wire reflection B* or C*. At the outdoor switch-gear under consideration, $a_{\mathrm{g}}=4.5$ m, $b_{\mathrm{g}}^{*}=13.8$ m.
Then, coefficients carrying different indices between the marginal (outer) wires are found from the following equations:

$$\alpha_{13}=\alpha_{31}=\frac{1}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_{0}}\cdot\ln\frac{d_{\mathrm{g}}^{*}}{c_{\mathrm{g}}}, \qquad (5)$$

$c_{\mathrm{g}}=2a_{\mathrm{g}}$ is a distance between the outer wires A and C, and d_{g}^{*} is a distance between wire A and wire reflection C*. At the outdoor switch-gear under consideration, $c_{\mathrm{g}}=9$ m, $d_{\mathrm{g}}^{*}=15.8$ m.
The electric field strength $\boldsymbol{E}_{\mathrm{M}i}$ (i=A, B, C) generated by the charge τ_i (i=A, B, C)andthe electric field strength $\boldsymbol{E}^{*}_{\mathrm{M}i}$ (i= A*, B*, C*), generated by the charge images τ^{*}_{i}(i=A, B, C), at the observation point M, can be calculated using the following equations [13, 15]:

$$\boldsymbol{E}_{\mathrm{M}i}=\boldsymbol{e}_{r\mathrm{M}i}\frac{\tau_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{1}{r_{i\mathrm{M}}},\quad \boldsymbol{E}^{*}_{\mathrm{M}i}=\boldsymbol{e}^{*}_{r\mathrm{M}i}\frac{\tau^{*}_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{1}{r^{*}_{i\mathrm{M}}}; \qquad (6)$$

where $\boldsymbol{e}_{r\mathrm{M}i}$ is a unit vector, pointing towards the point M at the local polar system, having its centre at the point i=A, B or C, and $\boldsymbol{e}^{*}_{r\mathrm{M}i}$ is a unit vector, pointing towards the point M at the local polar system, having its centre at the point i=A*, B* or C*. The total value of the electric field strength vector at the point M, $\boldsymbol{E}_{\mathrm{M}}$, is as follows:

$$\boldsymbol{E}_{\mathrm{M}}=\sum_{i=\mathrm{A,B,C}}\boldsymbol{E}_{\mathrm{M}i}+\sum_{i=\mathrm{A^{*},B^{*},C^{*}}}\boldsymbol{E}^{*}_{\mathrm{M}i}, \qquad (7)$$

The components $E_{\mathrm{M}xi}$, $E_{\mathrm{M}yi}$, $E^{*}_{\mathrm{M}xi}$and $E^{*}_{\mathrm{M}yi}$ of vectors $\boldsymbol{E}_{\mathrm{M}i}$ and $\boldsymbol{E}^{*}_{\mathrm{M}i}$ can be expressed by (Eq. 6) and (Fig. 1.):

$$\begin{aligned}
\boldsymbol{E}_{\mathrm{M}xi}&=\frac{\tau_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{\cos\alpha_i}{r_{\mathrm{M}i}}, & \boldsymbol{E}^{*}_{\mathrm{M}xi}&=\frac{\tau^{*}_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{\cos\alpha^{*}_i}{r^{*}_{\mathrm{M}i}},\\
\boldsymbol{E}_{\mathrm{M}yi}&=\frac{\tau_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{\sin\alpha_i}{r_{\mathrm{M}i}}, & \boldsymbol{E}^{*}_{\mathrm{M}yi}&=\frac{\tau^{*}_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{\sin\alpha^{*}_i}{r^{*}_{\mathrm{M}i}}.
\end{aligned} \qquad (8)$$

We superpose the straight line connecting points B and B* with y axis, and denote the height of wires as $H=6.5$ m the distance of phase wires A and C to the y axis as $q=4.5$ m, and the height of theobservation point as $y=h$. We obtain from (Fig. 1.) for any x:

$$\frac{\cos\alpha_{\mathrm{A}}}{r_{\mathrm{A}}}=\frac{x+q}{(H-h)^2+(x+q)^2},\ \frac{\sin\alpha_{\mathrm{A}}}{r_{\mathrm{A}}}=\frac{H-h}{(H-h)^2+(x+q)^2},$$

$$\frac{\cos\alpha_{\mathrm{B}}}{r_{\mathrm{B}}}=\frac{x}{(H-h)^2+x^2},\ \frac{\sin\alpha_{\mathrm{B}}}{r_{\mathrm{B}}}=\frac{H-h}{(H-h)^2+x^2}, \tag{9}$$

$$\frac{\cos\alpha_{\mathrm{C}}}{r_{\mathrm{C}}}=\frac{x-q}{(H-h)^2+(x-q)^2},\ \frac{\sin\alpha_{\mathrm{C}}}{r_{\mathrm{C}}}=\frac{H-h}{(H-h)^2+(x-q)^2}$$

$$\frac{\cos\alpha_{\mathrm{A}}^*}{r_{\mathrm{A}}^*}=\frac{x+q}{(H+h)^2+(x+q)^2},\ \frac{\sin\alpha_{\mathrm{A}}^*}{r_{\mathrm{A}}^*}=\frac{H+h}{(H+h)^2+(x+q)^2},$$

$$\frac{\cos\alpha_{\mathrm{B}}^*}{r_{\mathrm{B}}^*}=\frac{x}{(H+h)^2+x^2},\ \frac{\sin\alpha_{\mathrm{B}}^*}{r_{\mathrm{B}}}=\frac{H+h}{(H+h)^2+x^2}, \tag{10}$$

$$\frac{\cos\alpha_{\mathrm{C}}^*}{r_{\mathrm{C}}^*}=\frac{x-q}{(H+h)^2+(x-q)^2},\ \frac{\sin\alpha_{\mathrm{C}}^*}{r_{\mathrm{C}}^*}=\frac{H+h}{(H+h)^2+(x-q)^2}.$$

The components of the electric field vary by the sinus law, too:

$$\begin{aligned} E_{\mathrm{M}x}(t) &= E_{\mathrm{M}x\max}\ \sin(\omega t+\psi_x), \\ E_{\mathrm{M}y}(t) &= E_{\mathrm{M}y\max}\ \sin(\omega t+\psi_y). \end{aligned} \tag{11}$$

Supposing that $E_{\mathrm{M}x}=\sqrt{\frac{1}{T}\sum_{i=1}^{n}E_{\mathrm{M}x\max}{}^2}$, $E_{\mathrm{M}y}=\sqrt{\frac{1}{T}\sum_{i=1}^{n}E_{\mathrm{M}y\max}{}^2}$, the effective electric field strength value E_{M} at the observation point M is calculated as follows:

$$E_{\mathrm{M}}=\sqrt{E_{\mathrm{M}x}^2+E_{\mathrm{M}y}^2}\ . \tag{12}$$

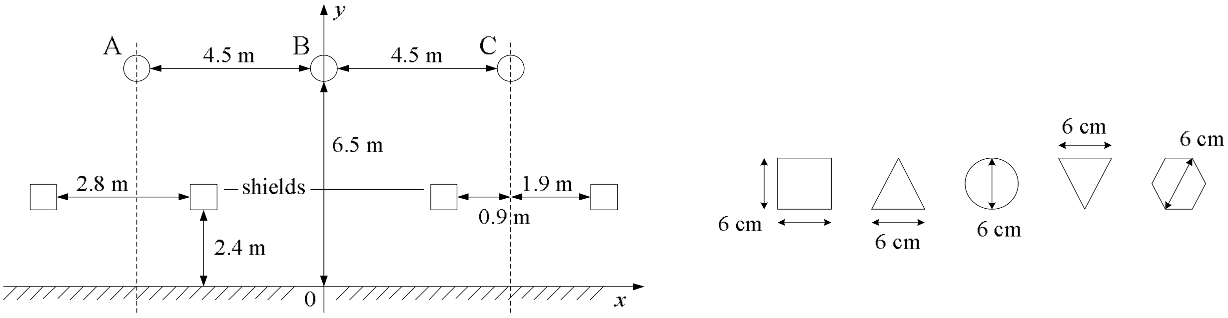
III. SHIELDING DESIGNS AND MITIGATION OF ELECTRIC FIELD IN WORKPLACES AT THE OUTDOOR SWITCH-GEAR

The measurements of the electric field are taken at heights of 0.5 m, 1.0 m, and 1.8 m from the ground surface. Respectively, electric field strength at these heights is not allowed to exceed 10 kV/m.

Employees servicing and operating at the 330 kV outdoor switch-gear are allowed to access any area of the entire switch-gear territory. Moving closer to the flat surface of the ground, the electric field gradually diminishes. However the danger can exist not only overhead, namely at the locations, where wires are too close to the ground surface, but also where the interval of heights [0; 1.8 m] involves sharp-pointed and spiky grounded surfaces. It can be a metal fence, distribution or control panel [9, 12].

The main means of mitigating electric field in the areas where people can work are increasing distances of high-voltage components to the ground surface. However, to raise the installed wires at already established and operating switch-gears it is impossible. In this case shielding of the field is essential.

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. As the electric field must be diminished, it is not necessary to use mesh; it is sufficient to mount only few (or one) grounded metal bars. When two or more shielding bars are used, they must be grounded in such a manner that there were no closed circuits. The research was performed to choose the most appropriate forms of shielding bars. It was found that the optimal and most appropriate form for shielding design is cylindrical metal pipe containing no sharp-pointed edges or spiky surfaces. Fig.3. presents arrangement of electric field shielding, and forms and dimensions used for metal structures.



a) b)

Fig.3. a) arrangement of the electric field shielding, b) forms of metal structures selected for shielding

IV.RESULTS AND DISCUSSION

The methodology described herein allows calculation of the electric field strength at any point M, situated under the 3 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 $h=y_A=y_B=y_C=6.5$ m at the plane perpendicular to wires of the power line. The distance was changed by 1 m steps in x direction. 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 $V_m=U_{fm}\approx 293$ kV. Fig.2. shows research results which suggest that the strongest electric fields are generated under the wires of A and C phases.

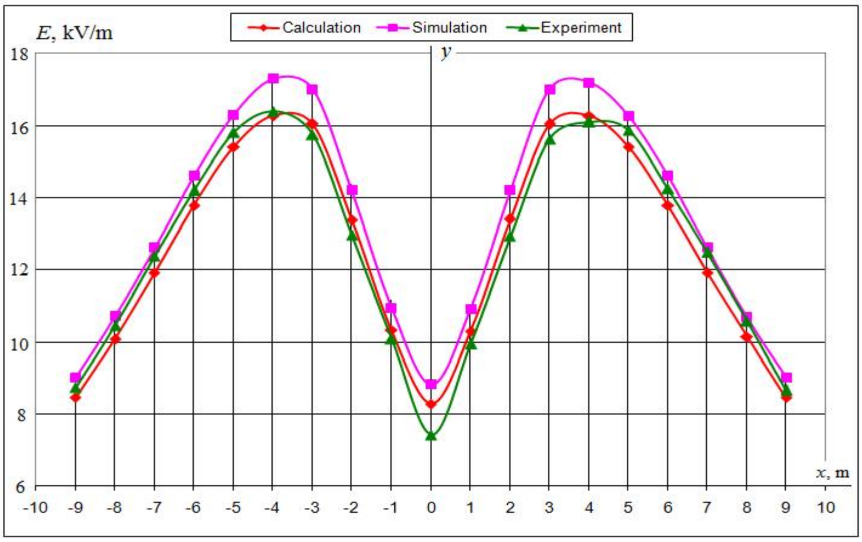


Fig.2. Distribution of the effective values of electric field strength in the plane perpendicular to the power line

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, as well as the wire sag. Measurements were also taken experimentally by the fieldmeter ESM-100. Experimental measurements and results of simulation were found to be very close to the analytical results, consequently the proposed methodology can be used for examination of maximum values of electric field strength near the electric power line with any voltage.

Table 1 shows results obtained for forms of metal structures used for shielding against the electric field through 3D simulation using a software package COMSOL Multiphysics 3.5 with the height of shield being $H=2.4$ m and distance between the outer bars $l=2.8$ m.

Table 1. The electric field strength under the shields of different form at 1.8 m height

Form	■	▲	●	▼	⬣
$E_{m1.8}$, [kV/m]	9.4	9.5	9.2	9.4	9.3

As (Fig.2.)shows, the most hazardous zones occur under the wires of A and C phases. These are the areas where the shielding against electric field must be installed. The simulation was performed for shielding designs comprised of n parallel grounded metal bars mounted at height H=2.4 m, where n=1, 2, 3, and 4. Shields were made of 6 cm diameter pipes. For the shielding of two or three bars, the distance between the marginal bars, l, was varied. The electric field under the shielding gradually diminishes moving closer to the ground surface. Consequently, electric field strength was measured at 1.8 m height. Table 2 presents maximum values of the electric field strength measured in this particular height, $E_{m1.8}$. In this Table 2, n represents number of bars used for shielding, and l represents distance between the marginal bars of the shielding.

Table 2. 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
$E_{m1.8}$, [kV/m]	11	12.5	9.3	9	8.5	7

In case the shielding 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 [9, 12]. As electric field strength reaches hazardous values at the vertical metal support-bars, it is desirable to mount shielding to the grounded structures available at the switch-gear or use insulated materials.

Obtained results suggest that with the increasing height of shielding the electric field strength diminishes at a workplace. In case the shielding is mounted in a height of at least 2.5 m, it is sufficient to have the shielding comprised of two shielding bars under each phase A or C wire in order to protect the entire area for interest of us from the excessive exposure of the electric field.

V.CONCLUSIONS

Distribution of the electric field strength at the high-voltage outdoor switch-gear can be calculated as the electrostatic field.

The electric field can be reduced to the permissible limit values by using metal grounded bars as a means of shielding raised above the area to be shielded. For the 330 kV open switch - gear it is sufficient to mount two metal bars raised to the height of 2.4 m parallel to wires of A and C phases which are at the height of 6.5 m in order to ensure safe work and operation under these wires.

The proposed models can be used for monitoring of other hazardous workplaces.

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