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Investigation of electric field in the outdoor switch-gear

Abstract. *The distribution of electric field inside of the 330 kV open-type outdoor switch-gear was investigated. The method of images for analytical calculation of electric field created by wires of switch-gear was used. The strongest electric field was found to exist at the phase A and C wires. Shielding represents the most practical way for reduction of the electric field strength to permissible values. For the purpose of shielding several grounded metal bars can be installed in parallel with the phase A and phase C wires above the area to be shielded. It is sufficient to have two shielding bars provided they are raised to the height of at least 2.4 m.*

Streszczenie. *W artykule przedstawiono badania rozkładu pola elektrycznego wewnątrz wyłącznika napięć 330kV. Najsilniejsze pola stwierdzono w sąsiedztwie przewodów faz A i C. Do ekranowania pola zaproponowano wykorzystane kilku uziemionych prętów zainstalowanych równolegle do przewodów faz A i C. (**Badania pola elektrycznego w wyłączniku zewnętrznym**).*

Keywords: 330 kV open-type outdoor switch-gear, electric field strength, electric field distribution, protection against electric field.
Słowa kluczowe: wyłącznik napięcia 330 kV, natężenie i rozkład pola elektrycznego, ochrona przed polem elektrycznym.

Introduction

Recently, issues regarding effect of an industrial electric field on health of operators are being more and more often explored. In the European Union regulating standards exist limiting maximum electric and magnetic field values and indicating threshold values that do not pose risk to human health. According to the directive 2004/40/EC of the European Parliament and of the Council, valid in EU member-states since 29/04/2004, the electric field strength should not exceed 10 kV/m at the workplaces. However, recent studies highlight that even lesser values of the electric field can be harmful for persons working at the powerful electric equipment.

Currently, the Hygiene Norm HN110 : 2001 "The electromagnetic field of industrial frequency in the workplace" is valid in Lithuania since 01/01/2002 providing that the maximum allowable level of the electric field strength is dependent on the occupational exposure time to this electric field. However, in 2012, the EU Directive 2004/40/EC will come into effect in Lithuania. Therefore the human can not work when the effective electric field strength value of frequency 50 Hz exceeds 10 kV/m.

This research paper involves analytical, simulative and experimental investigation of the electric field distribution at the 330 kV outdoor switch-gear, identification of areas hazardous to operators and search of measures enabling to reduce the electric field in the workplaces.

330 kV outdoor switch-gear electric field

The 330 kV open-type outdoor switch-gear is the place in general Lithuanian power-line system where the most powerful electric field can be expected. The source of electric field are the phase wires. They are arranged at two different heights. The upper wires are arranged in height of 15 m at the ground and can sag to 13.5 m. The lower wires are in height of 7 m at the ground, and can sag to 6.5 m. Employees can enter and work in any area of the switch-gear territory. Consequently, it is extremely important to know the strength of the electric field at height of up to 2 m.

The strongest electric field is being generated by the set of lower wires which are arranged horizontally.

Theoretical calculation of electric field at 330 kV outdoor switch-gear

The electric field strength created by the 330 kV (50 Hz) bus-bar system was calculated using some well established methods of electrostatic field investigation.

The electrostatic field methods can be used correctly when the dimensions of the investigated area are considerably lesser than the wave length λ (for f=50 Hz λ=6000 km).

We suppose that the conductor system is comprised of long round cylindrical conductors stretched parallel to the ground surface. The height of the wires is equal to the height of the real wires in the point of maximal sag (6.5 m). In this case the field becomes two-dimensional. The linear charge densities of the wires are τ_i (i=A, B, C). Radiuses of conductors $r_i << h_i$ are significantly less than the distance from the ground to any of conductors. The potential of the ground surface is equal to zero.

Using method of images [3], 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.

The electric field at the point M can be calculated as the sum of fields generated by those 6 charges. The electric field strength E_{Mi} (i=A, B, C, A*, B*, C*) generated by any of the charges with densities τ_i or τ_i^* is calculated using the following equation [3]:

$$E_{\mathrm{M}i}=\frac{\pm\tau_i}{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}\cdot\frac{1}{r_i}. \tag{1}$$

Vector of the electric field strength E_{Mi} is directed by the line connecting point i with the point M.

The consecution of calculation is as follows [2]:
1) the x and y components of vectors E_{Mxi} and E_{Myi} (i=A, B, C, A*, B*, C*) by expressions $E_{Mxi}=E_{Mi}\cos\alpha_i$ and $E_{Myi}=E_{Mi}\sin\alpha_i$ (α_i is the angle between the direction r_i and x axis) are calculated;
2) the total values of components E_{Mx} and E_{My} are calculated by the expressions:

$$\begin{cases} E_{\mathrm{M}x}=\sum\limits_{i=\mathrm{A,B,C}}E_{\mathrm{M}xi}+\sum\limits_{i=\mathrm{A^*,B^*,C^*}}E^*_{\mathrm{M}xi}, \\ E_{\mathrm{M}y}=\sum\limits_{i=\mathrm{A,B,C}}E_{\mathrm{M}yi}+\sum\limits_{i=\mathrm{A^*,B^*,C^*}}E^*_{\mathrm{M}yi}. \end{cases} \tag{2}$$

3) the total electric field strength is calculated as follows:

$$E_{\mathrm{M}}=\sqrt{E^2_{\mathrm{M}x}+E^2_{\mathrm{M}y}}. \tag{3}$$

The obtained analytical results were also verified through simulation by the Finite Element Method (FEM) using the software package COMSOL Multiphysics 3.5. Simulation took into consideration potentials of not only lower but also of upper wires. Analytical calculations and simulations were performed by the values: x_A=-4.5 m, x_C=4.5 m, y_A=y_B=y_C=6.5 m (the wire height in the plane of the maximal sag). The height of the observation point M was y_M=1.8 m. The calculation and simulation was performed for 19 values of the point M *x* coordinate with distance 1 m between the neighbouring values (see Fig. 1).

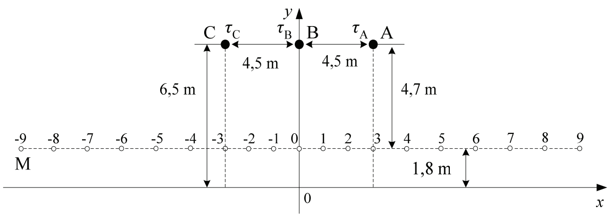

Fig.1. Positions of the observation point M

The amplitude value V_m of potentials V_A, V_B, and V_C was equal to the phase voltage amplitude V_m=U_{fm}≈293 kV. Fig. 2 shows that the strongest electric field is created under the wires of A and C phases.

Table 1 presents results of the simulation. They are very close the analytical results. The maximal values of the electric field strength are obtained at points M_{-4} and M_4, arranged near phases A and C. The minimal value is in the point M_0 is located under phase B [3].

Table 1. Simulation values of the electric field strength

l, m	-9	-8	-7	-6	-5	-4	-3
E_s, kV/m	9.0	10.7	12.6	14.6	16.3	17.3	17.0
l, m	-2	-1	0	1	2	3	4
E_s, kV/m	14.2	10.9	8.8	10.9	14.2	17.1	17.2
l, m	5	6	7	8	9		
E_s, kV/m	16.3	14.6	12.6	10.7	9.0		

Analytical results and simulation findings were also verified through experimental measurements of the electric field strength. Measurements were performed in the perpendicular to the line plane *xy*, in which the sag is maximal using 3D electric-magnetic field-meter ESM-100.

30 experimental measurements were taken at each position of the observation point M_i. The mean value of experimental results was calculated for each position of the observation point M_i:

$$\overline{E}_i = \frac{1}{n}\sum_{k=1}^{n} E_k; \quad (4)$$

where *n* – number of measurements at the any point M_i (*n*=30), E_k – current measurement value (in kV/m).

Table 2 presents the mean experimental electric field strength values in the same points M_i in which were obtained the results of the calculation and simulation.

Table 2. Measurement values of the electric field strength

l, m	-9	-8	-7	-6	-5	-4	-3
E_e, kV/m	8.73	10.4	12.4	14.2	15.8	16.4	15.7
l, m	-2	-1	0	1	2	3	4
E_e, kV/m	12.9	10.1	7.4	9.93	12.9	15.6	16.1
l, m	5	6	7	8	9		
E_e, kV/m	15.9	14.2	12.5	10.6	8.64		

Table 2 suggests that maximal values of the electric field strength are at points M_{-4} and M_4. These points are arranged near phases A and C of the 3 phase conductor system. The minimal electric field strength value is at the point M_0 located under the phase wire B. Moreover, results of experimental measurements are very close to analytical findings.

Fig. 2 presents all the results graphically. Curves in the graphic presented in Fig. 2 suggest that electric field strength proportionally reduces when moving away from phases A and C of the 3 phase conductor system. Along the distance of 5 m in the both directions at axis *y*, however, the electric field strength still exceeds 10 kV/m.

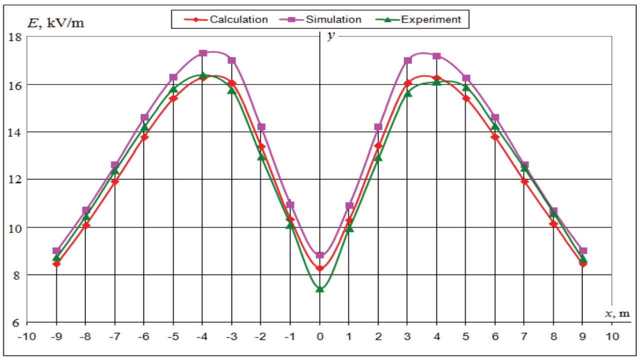

Fig.2. Distribution of the effective values of electric field strength in the plane perpendicular to the power line

Assessment of findings and obtained results leads to the following suggestions:

1) the mean difference between analytical and simulation results is below 6%;
2) the mean difference between experimental and simulation results is below 5.5 %;
3) the mean difference between experimental and analytical results is below 4 %.

The experimental measurements show that real metal installations and other conditions which were not evaluated by calculation and simulation have not appreciable influence to the electric field strength.

Moreover, electric field strength values obtained using any of research methods, exceed limit values indicated in EU Directive 2004/40/EC.

Investigation of electric field along the 330 kV overhead power line

The real wires have some sag. Investigation of the line with the sag was performed for evaluation the sag influence to results (see Fig. 3.).

Now the electric field was investigated in the plane *yz* for *x*=4.5 m, where the maximal field strength values were obtained. The point of observation M remains at height of 1.8 m 7 points with different sags were selected at each side. At the central point of observation, M=0, wires are at height of 6.5 m. Respectively, at the point M=7, wires are at height of 7.0 m above the ground surface.

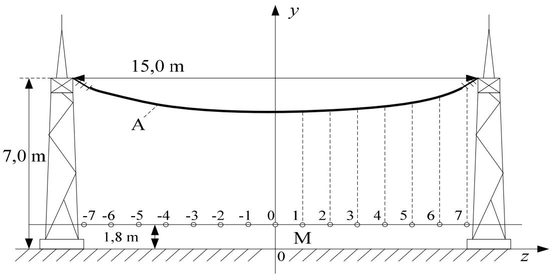

Fig.3. Positions of the observation point M

The 15 different positions for the observation point M were selected at the 1 m distance from each other (see Fig. 3).
Table 3 shows different heights of the wire above the ground surface at each respective observation point M_i.

Table 3. Height to the conductor at each respective point M_i

M_i	0	1	2	3	4	5	6	7
H, m	6.5	6.54	6.58	6.6	6.7	6.8	6.9	7.0

The two-dimensional electric field in any perpendicular to the line plane was calculated. These results were verified through simulation and measurement. The technique of the simulation and measurement is the same as early.

Table 4 presents the results of the calculation, simulation and measurement. E_c are analytical results E_s are simulation results, and E_e are experimental results.

The maximal values of the electric field strength are obtained at the point M_0, located at the wire lowest sag.

Table 4. Values of the electric field strength

l, m	-7	-6	-5	-4	-3
E_c, kV/m	14.48	14.89	15.32	15.74	16.15
E_s, kV/m	15.09	15.51	15.93	16.36	16.68
E_e, kV/m	14.59	15.01	15.43	15.86	16.28
l, m	-2	-1	0	1	2
E_c, kV/m	16.24	16.41	16.57	16.39	16.26
E_s, kV/m	16.86	17.03	17.2	17.04	16.86
E_e, kV/m	16.36	16.53	16.7	16.55	16.34
l, m	3	4	5	6	7
E_c, kV/m	16.13	15.76	15.29	14.92	14.46
E_s, kV/m	16.67	16.35	15.92	15.5	15.07
E_e, kV/m	16.26	15.88	15.41	15.03	14.57

During the experimental measurements, not only potentials of upper and lower wires were measured but effects of other metal installations, and weather conditions were taken into consideration, too.

All the results are represented graphically in Fig. 4.

Fig. 4 shows that total electric field strength at phase A of the 3 phase conductor system, diminishes proportionally with the observation point M=0 (see Fig. 3.) moving to the right along axis *z*. And total electric field strength diminishes with the increasing height H_i from the ground surface to the conductor, however still exceeds 10 kV/m.

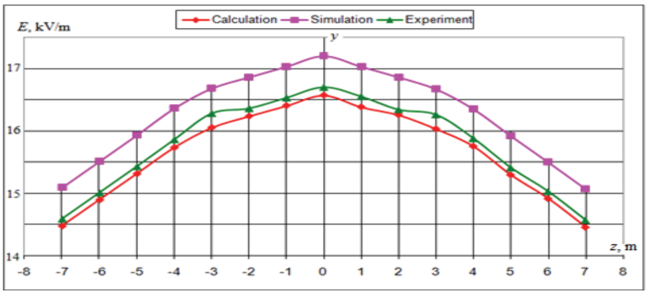

Fig.4. Distribution of the effective values of electric field strength in the *yz* plane

Electric field mitigation in switch-gear workplaces

A well-known technique of shielding against electrostatic fields is Faraday cage or Faraday shield: a space to be shielded is covered with the grounded metal cage. It is sufficient to mount only few (or one) grounded metal bars parallel to the phase wires [3]. When two or more shielding bars are used, they must be grounded without the closed circuits in connecting structures.

For the purpose of selecting an optimal shield design, the simulation using COMSOL was performed.

According to Fig. 2 the most hazardous zones occur under the phase A and phase C wires. These are the areas where the shields must be installed. Simulation included shielding designs comprised of *N* parallel grounded metal round bars mounted at height *H*=2.4 m where *N*=1, 2. Bars were made of 6 cm diameter metal pipes. In any case under simulation, the electric field present below the shielding gradually diminishes when moving closer to the ground surface. Consequently, electric field strength was measured at 1.8 m height. Maximum values of the electric field strength measured at this height were:

1) 11.4 kV/m, when the shield was comprised of one bar;
2) 9.3 kV/m, when the shield was comprised of two parallel bars with the distance between it is equal to 2.5 m.

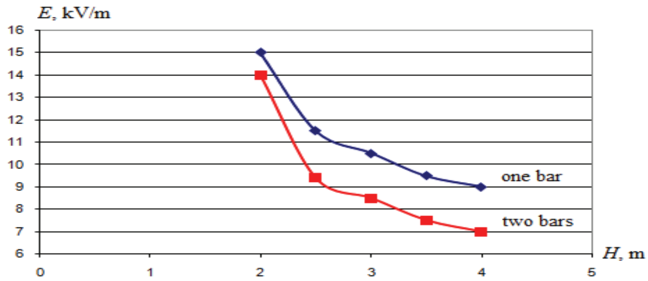

Fig.5. Dependence of the electric field strength at 1.8 m at the height of shielding

In the case when the shield is comprised of only one bar, it is mounted in the plane perpendicular to the ground surface, passing under the phase A or C wire. In the case when he shielding is comprised of two bars, these bars are arranged symmetrically to this plane.

Simulation also involved investigation of variation in digital values of electric field strength under the shielding comprised of one and two bars, depending on the height of shielding from the ground surface. Fig. 5 presents findings of this investigation.

Conclusions

1. Distribution of the electric field strength at the high-voltage outdoor switch-gear was investigated analytically, by the simulating and experimentally. The difference was less than 10% among the results of the calculation, simulation and measurement.

2. It was found that at workplaces on the ground level in the 330 kV outdoor switch-gear, electric field strength exceeds maximum limit values indicated in the EU directive 2004/40/EC, and must be reduced.

3. The electric field can be reduced by using metal grounded bars as a means of shielding raised above the area to be shielded. 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 under these wires.

4. The technique of the calculation or the simulation of the electric field strength generated by the phase wires in the 330 kV outdoor switch-gear can be used for monitoring of determination and identification of hazardous workplaces.

REFERENCES

[1] Crowley J. M. Fundamentals of applied electrostatics. – New York: Laplacian Press, 1999. – 272p.
[2] R. Deltuva, J. A. Virbalis, S. Žebrauskas. Analysis of Electric Field in 330 kV Overhead Transmission Line // Electrical and Control Technologies. – Kaunas: Technologija, 2011. ISSN 1822-5934. – P. 255-259.
[3] R. Deltuva, J. A. Virbalis. Protection against Electric Field of the Outdoor Switch-Gear Workplaces // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 6 (112). – P. 11-14.

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