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NUMERICAL EVALUATION OF THE ELECTRIC FIELD IN A COMPACT SWITCHGEAR OF MEDIUM VOLTAGE

ABSTRACT *Numerical evaluation of the electric field distribution in and around electric power devices can significantly facilitate their designing and redesigning processes. Such an approach is here applied to support the redesigning process of a gas insulated switchgear (GIS) of medium voltage. The electric field has been investigated with a professional software package Maxwell (Ansoft) that employs the finite element method (FEM). The obtained results enabled to determine points of the maximum electric field strength in the load-switch compartment of the considered GIS. These results indicate that the apparatus is oversized and its overall dimensions can be reduced.*

Key words: *compact switchgear, electric field, gaseous insulation, finite element method, load switch*

1. INTRODUCTION

In research and development (R&D) sections of many factories, traditional methodologies are still employed in designing processes of compact gas insulated switchgears (GIS). Appropriate distances between energized and earthed elements are indicated in these methodologies. Application of these distances or greater ones in the designed devices guarantees to avoid a breakdown of switchgear gaseous insulation. Nevertheless, such a simplified approach can lead to oversized devices.

Nowadays, the dynamic progress of computer technologies and the advancement of numerical techniques enable the detail computational estimation of the electric field inside of power objects [1–9]. Unfortunately, in the literature, there is a relatively small number of papers (e.g. [1, 5, 8, 9]) concerning the numerical analysis of the electric field in the gas insulated switchgears. Such an analysis can be a useful tool in designing and redesigning processes of GIS under consideration. This approach can help to reduce costs of device prototypes and can limit their indispensable laboratory tests.

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It can also enable to design smaller and more material-saving appliances which are cheaper and more environmental friendly.

In the paper, the numerical assessment of the electric field in a selected compartment of a 24 kV GIS produced by the Polish company ZPUE SA is presented. The analysis has been done using a professional software package Maxwell (Ansys) that employs the finite element method (FEM).

2. SWITCHGEAR DESCRIPTION

The switchgear under consideration (commercial symbol TPM) is a power engineering appliance performing various functions associated with connection to grid, power supply and protection of one or more transformers operating in the ring or radial type municipal power grid. The SF₆ general insulation is applied in this switchgear. A view of the considered switchgear is presented in Figure 1 and its basic technical parameters are shown in Table 1 [10].

Table 1

Basic technical data of the switchgear

Nominal grid voltage	20 kV
Highest apparatus voltage	24 kV
Rated frequency	50 Hz
Rated power frequency withstand voltage	50 kV/60 kV
Rated lightning impulse withstand voltage 1.2/50 μ s	125 kV/145 kV
General insulation	SF ₆
SF ₆ pressure	125 kPa (20°C)
Material of insulators	epoxy resin

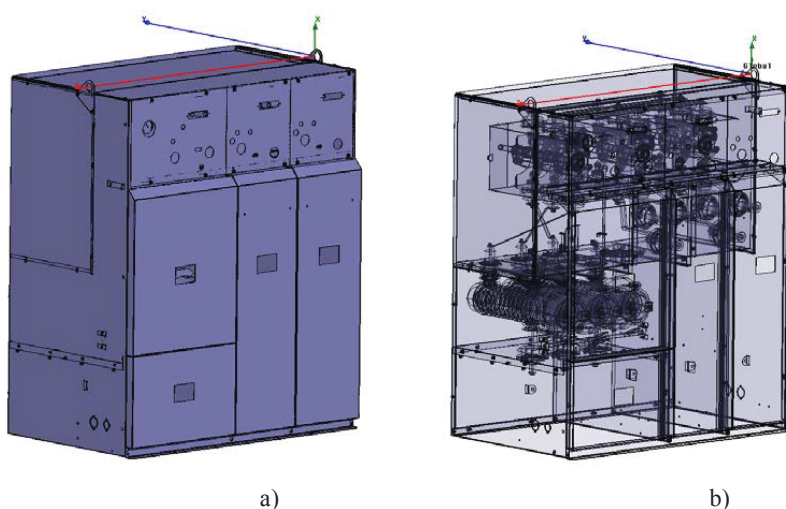


Fig. 1. Switchgear of 24 kV manufactured by ZPUE SA
a) general view, b) equipment of the switchgear

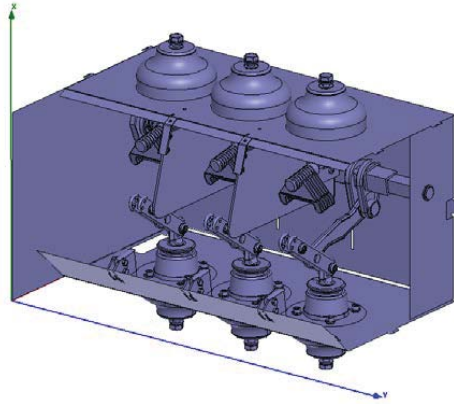


Fig. 2. Load-switch compartment

In the paper, the results of the numerical analysis of the electric field strength in the compartment of a load switch are presented. This compartment is shown in Figure 2.

3. SF₆ GASEOUS INSULATION

In the considered switchgear, SF₆ is used not only as a general insulation of the device but also as an arc-quenching medium for the load switch. It gives to the appliance a great simplicity, compactness, reliability and safety.

SF₆ does not contribute to the ozone layer depletion, because it does not contain chlorine; nevertheless, the Kyoto Protocol [11] treats SF₆ as a greenhouse gas.

The application of SF₆ is not forbidden by the European Union (EU); however, accordingly to the mentioned Kyoto Protocol, the EU imposed specific conditions on manufacturers and operators of electric switchgears. These special conditions help to limit the SF₆ emission to the atmosphere [12].

SF₆ is an exceptionally effective electrical insulator and its responsible use ensures the safe and reliable performance of modern switchgears. These switchgears can be smaller and owing to this more material-saving, cheaper and simultaneously more environmental friendly.

The electric withstand of SF₆ is about 3 times greater than the withstand of air [13, 14] and is about 60 kV/cm (rms) in normal atmospheric conditions. Obviously, this value is greater for the increased gas pressure [13] that is equal to 125 kPa in the switchgear under consideration [10]. Therefore, 75 kV/cm [13] can be assumed (for this pressure) as the electric field strength of the sparkover for the homogeneous field condition. In the case of strongly inhomogeneous field the above value (of the electric field strength) should be treated only as an inception value for the partial discharges [13, 15]. In such a situation the sparkover does not ensue.

The electric field is strongly inhomogeneous in the surroundings of bare energized elements of the considered GIS, therefore, if the electric field strength is lower than 75 kV/cm around these elements, the sparkover and partial discharges should not supervene.

4. BOUNDARY-VALUE PROBLEM AND NUMERICAL TECHNIQUE

Computational analysis of the electric field inside of the considered GIS compartment is a very complicated task because of a complex 3D geometry of the problem. The mentioned field (produced by energized elements) is affected by many metal earthed elements (e.g. casing, supporting elements, screws, nuts, bolts, rivets, etc.) that considerably change field distribution. Such an issue can be solved only by the use of numerical techniques.

The finite element method (FEM) [16] and the boundary element method (BEM) [17, 18] are the numerical techniques that are most frequently applied to the analysis of the electric and magnetic fields in electric power devices. In this paper, the FEM has been employed for this purpose.

The considered problem is described by 3D Laplace's partial differential equation (expressed in terms of the scalar electric potential):

$$\nabla^2 \varphi = 0 \quad (1)$$

with appropriate boundary conditions that are described below. On the surfaces Γ of conducting elements on which the electric potential $\bar{\varphi}$ is known, Dirichlet's boundary condition is applied:

$$\varphi \Big|_{\Gamma} = \bar{\varphi} \quad (2)$$

On the other hand, on the surfaces of conducting elements Γ_c where the electric potential is of an unknown value, the following boundary condition is introduced:

$$\varphi \Big|_{\Gamma_c} = C \quad (3)$$

where C is a constant value. Such a condition appears on the boundary of the conducting element that is entirely surrounded by a dielectric environment. Because the constant C is of the unknown value, an additional equation has to be introduced to obtain the unique solution of the boundary-value problem. This equation results from Gauss's law and has the following form:

$$\iint_{\Gamma_c} \varepsilon \frac{\partial \varphi}{\partial n} d\Gamma = 0 \quad (4)$$

where ε is the electric permittivity of the surrounding dielectric.

The continuity condition on the interface Γ_i between dielectrics of different electric permittivities (e.g. the surface of epoxy-resin element that is immersed in the gas) has to be taken into account as well. The above condition is given below:

$$\varepsilon^+ \frac{\partial \varphi}{\partial n} \Big|_{\Gamma_i^+} - \varepsilon^- \frac{\partial \varphi}{\partial n} \Big|_{\Gamma_i^-} = 0 \tag{5}$$

where ε^+ and ε^- are the electric permittivities of the adherent dielectric elements. After the solution of the boundary-value problem, the electric field strength is computed using the well-known formula:

$$\mathbf{E} = -\nabla \varphi \tag{6}$$

5. NUMERICAL APPROXIMATION OF THE PROBLEM

The electric field analysis inside of the load-switch compartment for the case of closed switch contacts (Fig. 3) is presented in the paper. The maximum value of the electric field strength is attained for this contact position.

Computations have been performed for the rated power frequency withstand voltage that is equal to 50 kV for the switchgear under consideration. The energized elements of the load switch are indicated in Figure 3a.

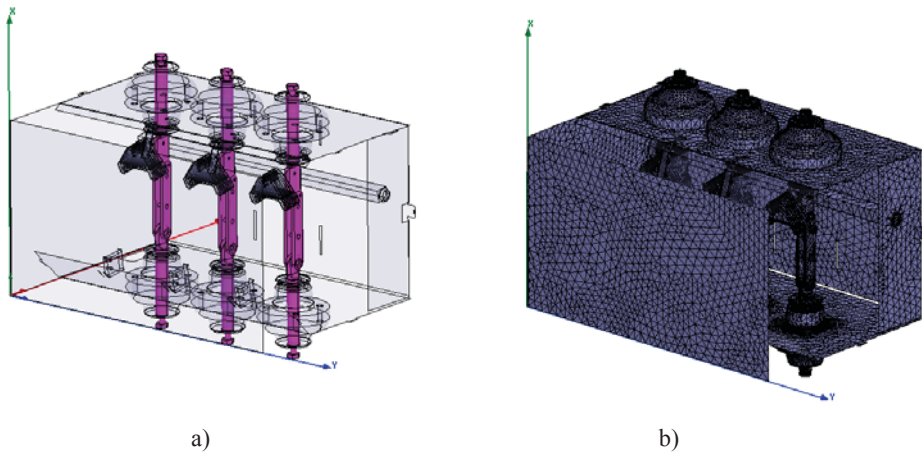


Fig. 3. Load switch with closed contacts; general view (a) and its approximation with finite elements (b); colour denotes the energized elements

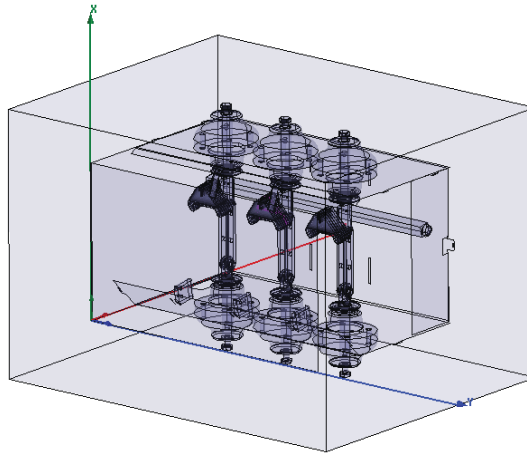


Fig. 4. Load-switch compartment surrounded by domain with homogeneous Dirichlet's boundary condition at its external boundary

The object approximation with the finite elements is exhibited in Figure 3b. Some inessential non-conducting elements have been omitted in the applied numerical model. As it is shown in Figures 2 and 3, the switch casing is partially opened. Therefore, it has to be surrounded by an external domain with homogeneous Dirichlet's boundary condition on its outer boundary. This external domain is exhibited in Figure 4.

6. NUMERICAL RESULTS

Numerical results of the electric field strength inside of the considered GIS compartment are presented in this section. The overall dimensions of this compartment are: in x direction 280 mm, in y direction 500 mm and in z direction 368 mm.

The electric field distributions on several horizontal plane surfaces have been estimated. Computational results are presented in Figures 5 – 8.

The electric field distributions on the horizontal parts of the bottom and top surfaces of the steel compartment enclosure are presented in Figures 5a and 5b, respectively. The field distribution around the bushings is especially interesting from the practical point of view. A distance between the bushings and earthed metal enclosure is of minimum value at the above surfaces. Therefore, the electric field strength reaches its maximum value on these surfaces. It can be observed, in Figure 5, that the electric field distributions around the bottom and top bushings are very similar. It results from the fact that the top and bottom bushings are of the identical shape and dimensions; however, the top and bottom casing surfaces are of the different geometry. The electric field strength slightly exceeds 50 kV/cm in this region. The computed values are much smaller than the withstand electric field strength of the insulator material (epoxy resin).

In Figures 6a and 6b, the field distributions at the levels of 40 mm and 240 mm, (that refer to the caps of the bottom and top insulators) are presented, respectively. The electric field strength attains on these surfaces about 13 kV/cm. This value is much smaller than the reference value of 75 kV/cm.

Consecutive results concern the electric field distribution in the surroundings of the bare energized elements (load-switch contacts). These results are very important from the technical point of view because the above elements represent the weakest points of the considered insulation system. The breakdown of the gaseous insulation (sparkover) is most frequently initialised at the surfaces of such bare live elements. In Figures 7 and 8, the electric field distributions around the bare energized conductors (at the levels of: 80, 120, 160 and 200 mm) are presented. It is evident from these figures that the maximum value of the electric field strength reaches only 25 kV/cm around the load-switch contacts. This value is three times smaller than the reference value of 75 kV/cm.

The above presented numerical analysis indicates that the apparatus compartment under consideration is oversized and its dimensions can be significantly reduced. The similar computations have been done for other switchgear compartments and the identical conclusion can be formulated for these switchgear regions.

The presented computational results have been obtained using a PC equipped with processor Intel Core i7-2600K 3,4 GHz and RAM of 8 GB. The total solution time (including the mesh generation, calculation of algebraic equation coefficients and solution of the algebraic equation system) is about 2.5 h.

7. CONCLUSIONS

The detailed numerical analysis of the electric field distribution in the load-switch compartment of the compact GIS of 24 kV has been presented.

The obtained results have enabled to determine points of the maximum electric field strength in the considered GIS domain.

The reported attempt clearly indicates that the apparatus compartment under consideration is oversized and its overall dimensions can be reduced. Similar results have been obtained for the remaining switchgear compartments.

The above conclusion has been corroborated experimentally during laboratory tests. Namely, the appropriate rated frequency and lightning impulse withstand voltages have been applied to the switchgear in question. In the tested device, the SF₆ insulation has been replaced by the dry air insulation. The electric withstand of the dry air is three times smaller than withstand of SF₆. The positive results of these laboratory tests indicate that the switchgear with the SF₆ insulation is oversized.

The electric field computations will be repeated after changes and modifications of the switchgear geometry that will be accomplished by the factory R&D section.

After the successful numerical evaluation of the redesigned appliance, the indispensable laboratory tests [19, 20] (for the rated frequency and lightning impulse withstand voltages) of the new prototype of the redesigned device will be done. The effects of these new investigations will be reported in the consecutive article.

As it is shown in the paper, the proposed computational approach can be a promising way for the improvement and amelioration of the designing and redesigning processes of the gaseous switchgears and other electric power appliances.

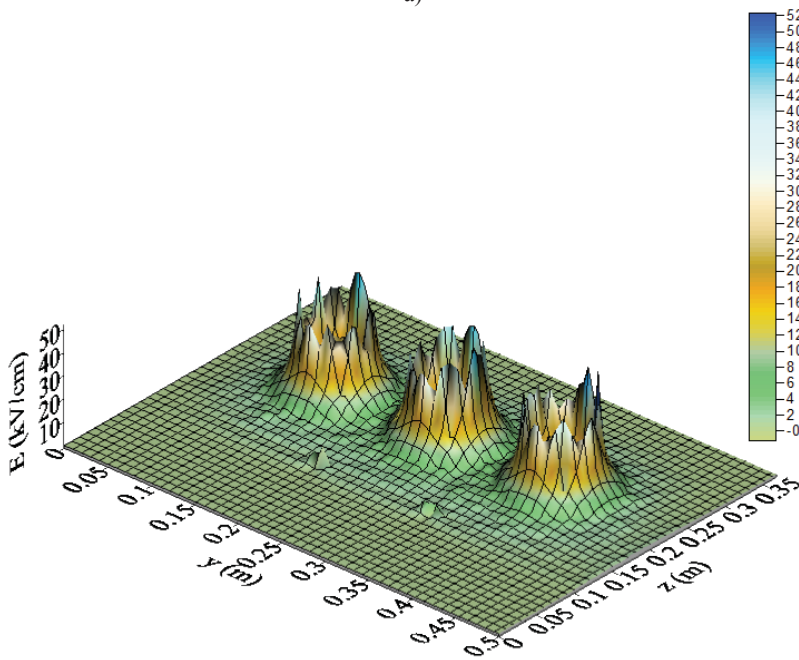
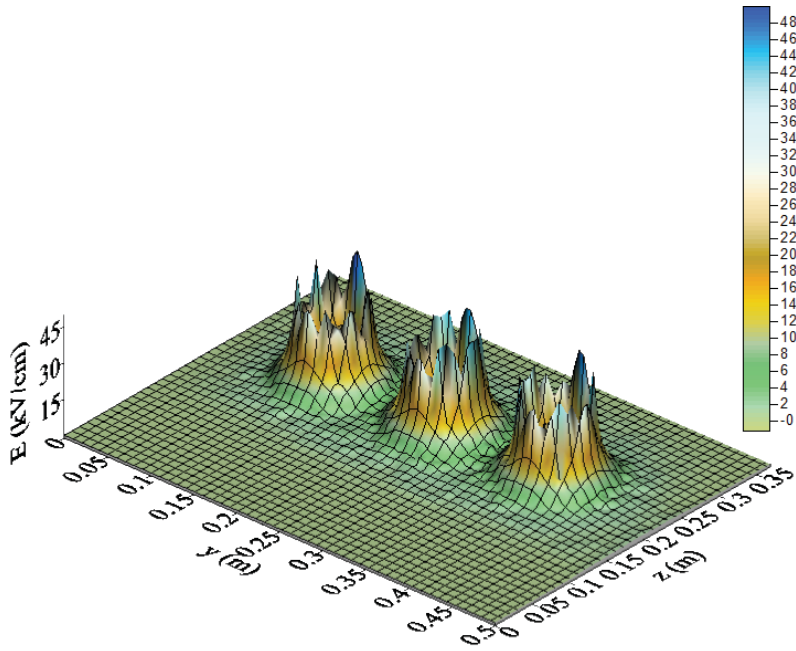
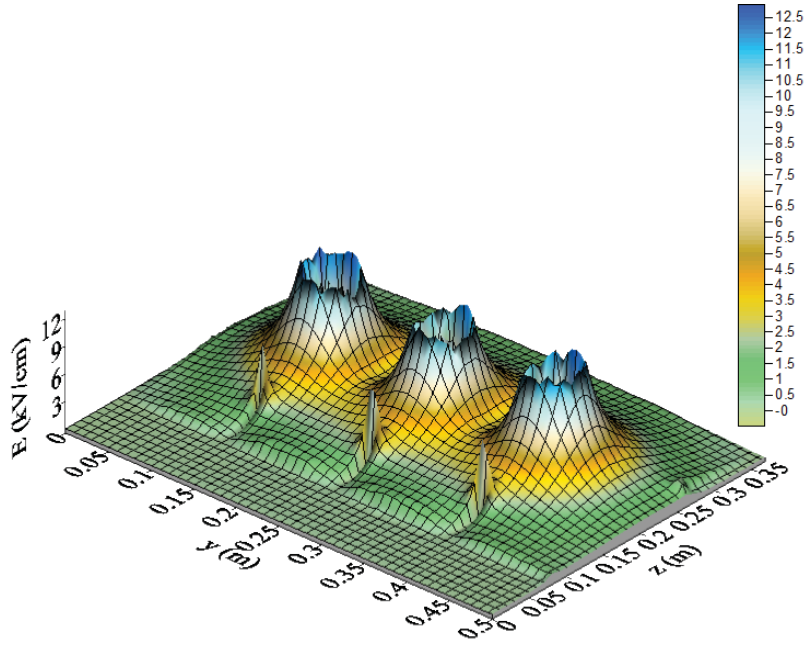
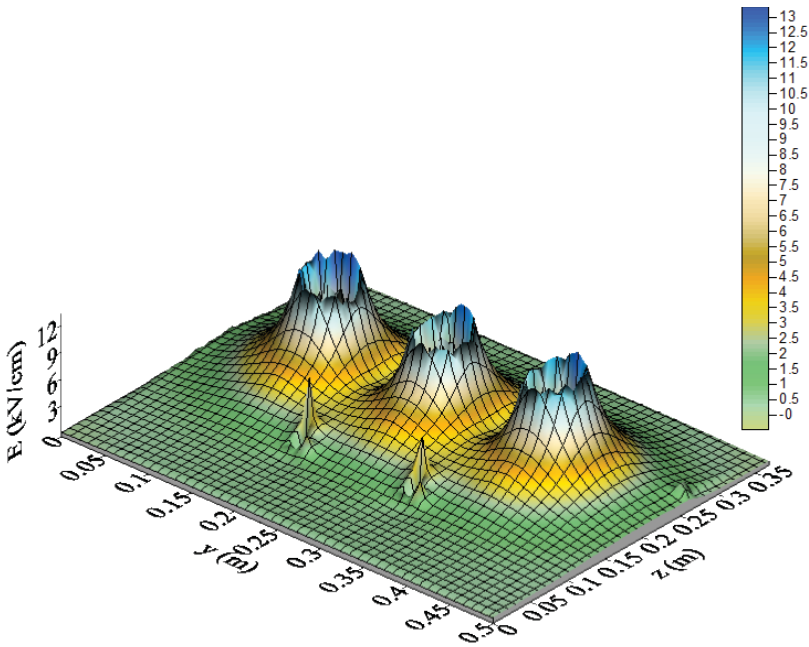


Fig. 5. Electric field distribution at the top (a) and bottom (b) surfaces of the steel load-switch casing

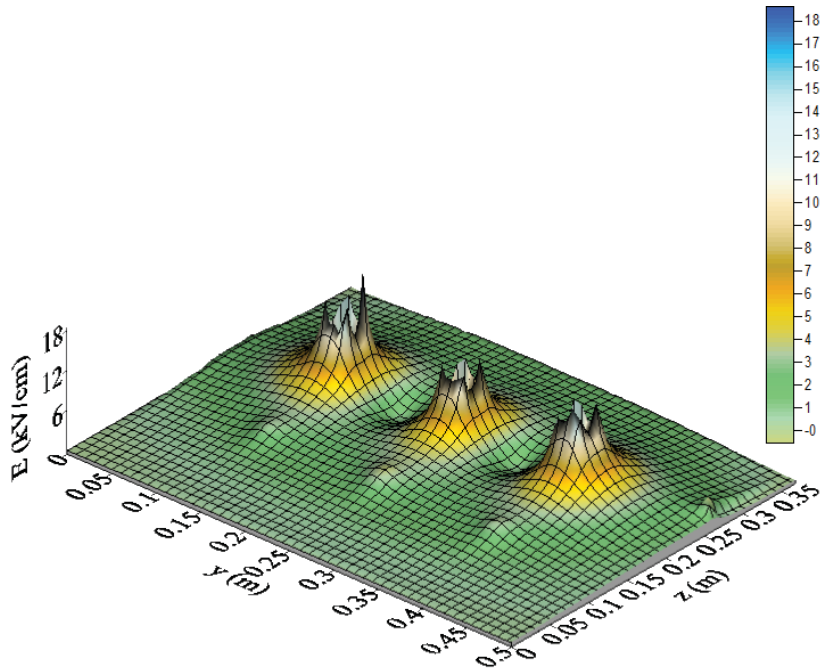


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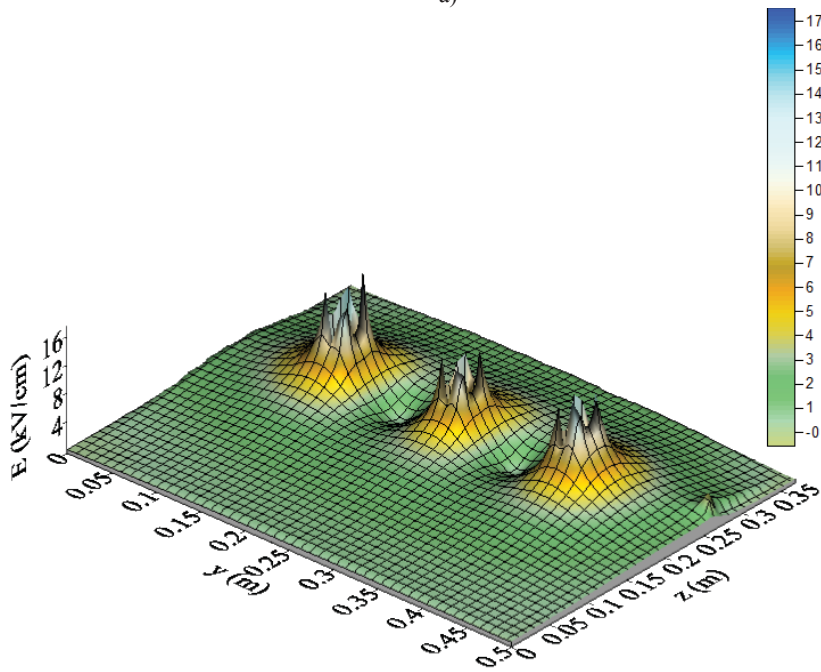


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Fig. 6. Electric field distribution at the level of 40 mm (a) and 240 mm (b)

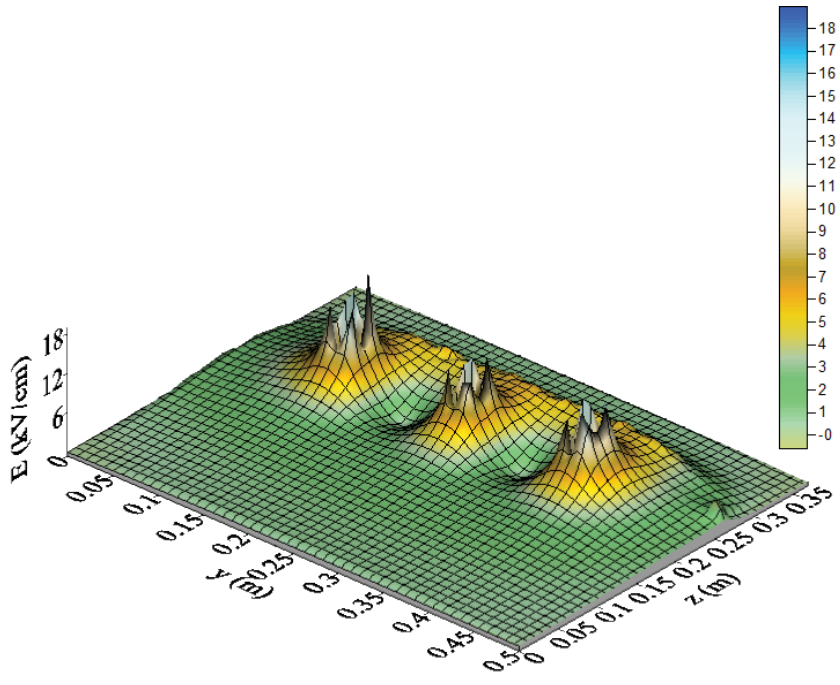


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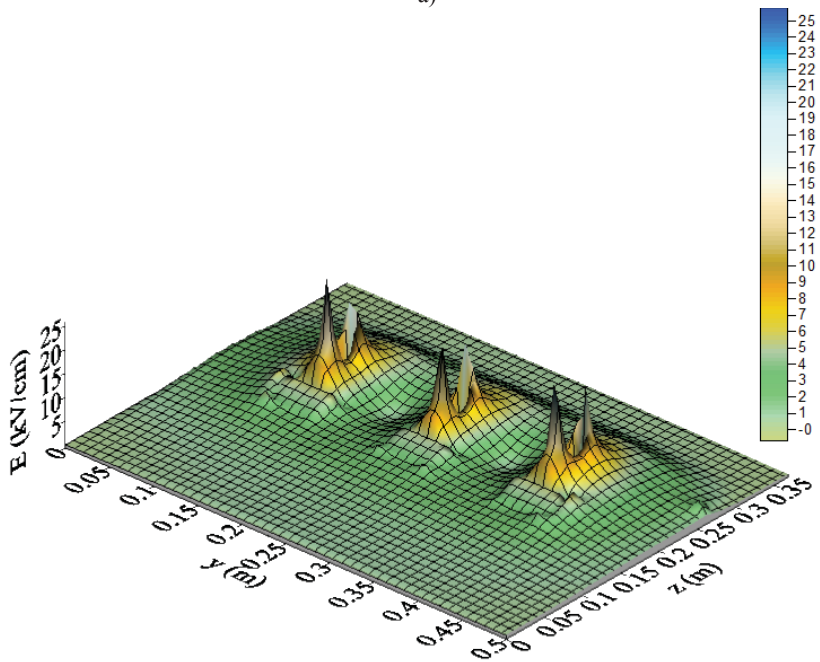


b)

Fig. 7. Electric field distributions near the load switch contacts at the levels of 80 mm (a) and 120 mm (b)



a)



b)

Fig. 8. Electric field distributions near the load-switch contacts at the levels of 160 mm (a) and 200 mm

LITERATURE

1. Messerer F., Boeck W., Steinbigler H. and Chakravorti S.: "Enhanced Field Calculation for HVDC GIS", *Gaseous Dielectrics IX*, Edited by Christophorou and Olthoff, Kluwer Academic/Plenum Publishers, New York, 2001
2. Krajewski W.: "Numerical modelling of the electric field in HV substations", *IEE Proc. Sci. Meas. Technol.*, Vol. 151, No. 4, 2004, pp. 267-272
3. Trkulja B., Štih Ž.: "Computation of electric fields inside large substations," *IEEE Trans. on Power Delivery*, Vol. 24, No. 4, 2009, pp. 1898-1902
4. Ranković A., Savić M.S.: "Generalized charge simulation method for the calculation of the electric field in high voltage substations", *Electrical Engineering*, Vol. 92, No. 2, July 2010, pp. 69-77
5. Metwally I.A.: "Reduction of electric-field intensification inside GIS by controlling spacer material and design", *Journal of Electrostatics*, Vol. 70, 2012, pp. 217-224
6. Shaalan E.M., Ghania S.M., Ward S.A.: "Analysis and measurement of electric field exposure inside 500/220 kV air insulated substation", *Journal of Electrical Engineering*, Vol. 12, Issue 2, 2012, pp. 77-84
7. Zhang Z., Xie X., Li L., Xiao D., He W.: "Super-fast multipole method for power frequency electric field in substations", *COMPEL*, Vol. 33, No. 1-2, 2014, pp. 594-610
8. Krajewski W., Sibilski H., Wojciechowski R.: "Electric field analysis in a switchgear of medium voltage", *Prace Instytutu Elektrotechniki (Proceedings of Electrotechnical Institute)*, No. 263, 2013, pp. 33-49 (in Polish)
9. Krajewski W., Sibilski H., Wojciechowski R.: "Numerical modeling of the electric field in a 24 kV switchgear", *4th International Conference on High Voltage Engineering and Applications*, Poznań, 2014
10. <http://zpue.pl/en/mv-switchgear/tpm/information.html>
11. "Kyoto Protocol to the United Nations Framework Convention on Climate Change", *United Nations*, 1998
12. "Switchgear and SF₆ gas", *European Low Voltage Switchgear and Controlgear Association, CAPIEL HV-ESDD1-R1-1.02*, 31 January, 2002
13. Kuffel E., Kuffel J., Zaengl W.S.: "High Voltage Engineering Fundamentals", Newnes, 2000
14. Fotyma M., Życzyńska B.: "Withstand of sulfur hexafluoride in different electrode configurations", *Prace Instytutu Elektrotechniki (Proceedings of Electrotechnical Institute)*, No. 49, 1966, pp. 91-109 (in Polish)
15. Peak W.F.: "Dielectric Phenomena in High Voltage Engineering", McGraw-Hill, 1929
16. Zienkiewicz O.C.: "The Finite Element in Engineering Science", McGraw-Hill, New York, 1971
17. Brebbia C.A., Telles J.C.F, Wrobel L.C.: "Boundary Element Techniques", Springer, Berlin Heidelberg New York, 1984
18. Krajewski W.: "Boundary and line elements in the analysis of selected EMC problems of low frequency", *Prace Instytutu Elektrotechniki (Proceedings of Electrotechnical Institute)*, No. 224, 2005, (Monograph in Polish)

19. PN-EN 60694: "Common specifications for high-voltage switchgear and controlgear standards", PKN (Polish Normalization Committee), 6th September, 2004
20. PN-EN 62271-200: 2012 "High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV", PKN (Polish Normalization Committee)

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NUMERYCZNE WYZNACZANIE POLA ELEKTRYCZNEGO W KOMPAKTOWEJ ROZDZIELNICY ŚREDNIEGO NAPIĘCIA

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STRESZCZENIE *Numeryczne wyznaczanie rozkładów pola elektrycznego, zarówno w otoczeniu, jak i wewnątrz urządzeń elektroenergetycznych, może w istotny sposób usprawnić proces ich projektowanie bądź przekonstruowania. W artykule przedstawiono zastosowanie tego rodzaju obliczeń w odniesieniu do kompaktowej rozdzielnicy średniego napięcia z izolacją gazową SF₆, w kontekście możliwości poddania jej procesowi miniaturyzacji. Zastosowano profesjonalne oprogramowanie Maxwell firmy Ansoft bazujące na metodzie elementów skończonych. W wyniku obliczeń wyznaczono obszary o największych wartościach natężenia pola elektrycznego w przedziale rozłącznika rozważanej rozdzielnicy. Stwierdzono, że aparat jest przewymiarowane i może być poddany procesowi miniaturyzacji.*

Słowa kluczowe: *rozdzielnica kompaktowa, izolacja gazowa, metoda elementów skończonych, pole elektryczne, rozłącznik*



Assoc. Professor Wojciech KRAJEWSKI received the M.Sc. and Ph.D. degrees in electrical engineering from the Warsaw University of Technology in 1977 and 1984, respectively. He received the D.Sc. degree (habilitation) from the Electrotechnical Institute, Warsaw, Poland, in 2007, in technical science. He is with the above Institute since 1981 up to now. He works on numerical modelling of electromagnetic fields in electrical machines and devices as well as in the human environment and human organism. He is an author and co-author of computer software packages based on the boundary element method and over fifty scientific papers published in domestic and international journals. Assoc. Professor Wojciech Krajewski is a member of the Association of Polish Electricians (SEP) and the Institution of Engineering and Technology (IET).

