Simulation of high-voltage equipment electromagnetic radiation

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Abstract. The article is devoted to problems of simulation an electromagnetic field distribution near high-voltage power equipment. A radiating model of the power autotransformer 500 kV is presented. This model includes sizes and relative positioning of the autotransformer’s case and radiating elements, different constructions and earth existence, materials properties. The elements and constructions, located near the high-voltage equipment, such as cooling radiators, wireline passes, additions to lead-in wires, auxiliary columns, support for bus wire fastening, fire extinguisher system, concrete partitions are considered. Models of an electrical power object which contains above-mentioned elements and constructions are developed. The models are used for calculation electromagnetic field distribution on the electrical power object. Pictures of electromagnetic field distribution on a real electrical power object are calculated and presented in the form of direction patterns. Influence of the separate elements and constructions on the form of the directional pattern of the electrical power object model is estimated both in a form and in absolute values of electric-field strength of vertical polarization. The results achieved might be used at diagnostics of the high-voltage power equipment by electromagnetic control method.

1. Introduction

Operation of a high-voltage electrotechnical equipment (HVPE) is characterized by increased responsibility of the functions which are carried out and has the high price of failure. It demands to pay special attention to ensuring its trouble-free operation. Currently, there are various ways to assess the technical state of HVPE on the main and secondary indicators of its work. The priority is given to indicators which can be traced without intervention to technological process. One of such indicators are characteristics of electromagnetic radiation which carry a wide range of information for HVPE technical condition assessment [1].

Experts consider electromagnetic radiation primarily as a source of information about partial discharges (PD) in HVPE isolation [2, 3]. In this case, the electromagnetic method of PD detecting has its advantages [4], therefore work is underway on its development. Sensors with different characteristics for PD registration, such as patch antenna [5], Hilbert antenna [6], peano fractal antenna [7] and others, are developed. Technologies are improved for UHF detection and PD localization in HVPE [8], including in factory tests [9]. Special attention is paid to recognition and noise reduction of the received signals [10-13].

Antennas and UHF sensors usage demands a detailed research of features of electromagnetic waves distribution [14] for the purpose of their optimum placement [15]. Models of electrical power objects
are developed for this purpose. The correct development of such models allows to determine the diagnostic electromagnetic environment and to choose the optimal place for measuring equipment accommodation with a sufficient degree of accuracy. Creation of such model is a complex task that requires taking into account influence of the earth, shields, various conductive and dielectric structures [16, 17].

There is a HVPE radiating model [18] which include the minimum quantity of construction elements, such as a main tank, an oil conservator, lead-in wires of high and low voltage. This model was developed for the purposes of HVPE technical state electromagnetic control [19], as a result it was used to represent electromagnetic field distribution in the form of direction pattern.

HVPE on stations and substations is usually surrounded by constructions with various sizes, shapes and materials. These constructions can have a significant impact to the propagation of electromagnetic waves. In view of this, it is reasonable to pursue research of influence on electromagnetic field distribution as it is possible bigger number of elements and constructions which are parts of an electrical power object. The purpose of this article is to simulate electromagnetic field distribution on an electrical power object using a model that takes into account the influence of presented elements and constructions.

2. Electrical power object modeling method

As part of this study, models of an electric power object were developed. These models include a 167 MVA power autotransformer with 500, 220 and 10 kV nominal voltages, as well as combinations of the following elements and constructions: cooling radiators at the autotransformer model, wireline passes and additions to lead-in wires, auxiliary columns, a support for 220 kV bus wire fastening, a fire extinguisher system located around the autotransformer, concrete partitions located at the left, on the right or on both sides from the autotransformer.

Dimensions, position, material and approximate shape of the above elements and constructions are taken into account at the presented models of the electric power object. The case of the autotransformer is presented by the hollow steel rectangular parallelepiped (the main tank) connected by steel wires to a hollow cylinder (the oil conservator). Lead-in wires of the autotransformer were presented by copper wires having voltage sources at flanges. Each of these elements has finite dimensions and thickness.

The case of the autotransformer in several presented models also has the cooling radiators presented by the hollow rectangular parallelepipeds integrated with the main tank and having the same material and thickness. The wireline passes and additions to lead-in wires are presented by aluminum wires of the same diameter, as the autotransformer lead-in wires.

Auxiliary columns are presented by hollow steel tubes of finite thickness, which have at the top steel platforms of certain thickness. The auxiliary columns also have steel platforms of finite thickness on the top. The support for bus wire fastening is presented by a relatively difficult metal construction executed by the crossed steel wires of finite thickness.

The fire extinguishing system located around the autotransformer is presented by construction that consists of the hollow steel tubes having different diameter and uniform thickness. Concrete partitions are presented by rectangular parallelepipeds of the final dimensions filled with concrete. The earth is presented in the form of the homogeneous infinite surface having parameters of soil of a power substation which has the autotransformer.

The constructed electrical power object models were designed to simulate the distribution of the electromagnetic field in the far-field region. This distribution is taken into account on the basis of the calculated direction patterns of the electric field of vertical polarization. The calculation was executed using the program complex for numerical electromagnetic modeling Altair FEKO. The method of moments was used during the direction patterns calculation. The program complex partitions wires into segments, surfaces into triangles, and volumes into tetrahedrons so length of each segment or edge should be much lower than the set wavelength. The photo of the power autotransformer is shown
in Figure 1a. The radiating model, including the autotransformer and all the above elements and constructions, is presented in Figure 1b.

The calculation of electromagnetic field distribution is carried out for frequencies corresponding to resonance frequencies of the considered autotransformer radiating elements [20]. Within this article results for the frequency 17.69 MHz are presented. The frequency corresponds to a resonance of lead-in wire 500 kV. The electromagnetic field distribution is represented in the form of direction patterns for electric field strength of vertical polarization. Direction patterns are presented in polar coordinates at value of a corner θ = 86 degrees (4 degrees over ground level) because measuring equipment is usually located at such height. Direction zero degrees of a corner φ corresponds to a front side of the autotransformer according to Figure 1.

![Figure 1](image1.jpg)

Figure 1. Photo of the electrical power object (a) and its model (b).

3. Results of direction patterns calculation

The first results of direction patterns calculation are presented in Figure 2a. These results were obtained using models for three types of electrical power objects. The first model takes into account the presence of the autotransformer only. The second model takes into account the presence of the autotransformer and the cooling radiators. The third model takes into account the presence of the autotransformer and the auxiliary columns. It follows from the figure that the presence of the radiators reduces the radiation intensity by 25% at angle φ from 180 to 340 degrees. The presence of the auxiliary columns reduces the radiation intensity by 50% at angle φ from 90 to 140 degrees and increases it by 42% at angle φ from 280 to 80 degrees.
Figure 2. Direction patterns calculated using radiating autotransformer models, which take into account: 1) nothing else; 2) the cooling radiators; 3) the auxiliary columns; 4) the support for bus wire fastening 220 kV; 5) the fire extinguishing system.

The second results of direction patterns calculation are presented in Figure 2b. These results were obtained using models for three types of electrical power objects, which take into account the presence of the autotransformer, the support for bus wire fastening, the fire extinguisher system. Each of the above constructions contributes to shape distortion of the direction pattern. Existence of the support for bus wire fastening narrows and extends the direction pattern, changing its direction approximately by 45 degrees clockwise. The presence of the fire extinguisher system reduces the radiation intensity by 20-46% at angle φ from 0 to 280 degrees and increases it by 33% at angle φ from 300 to 350 degrees.

The third results of direction patterns calculation are presented in Figure 3a. These results were obtained using models for four types of electrical power objects, which take into account the presence of the autotransformer and concrete partitions located on the right, at the left or on both sides from it. As follows from the figure, concrete partitions do not have a significant effect on directional patterns. It allows not to take concrete partitions influence into account during electric power object modeling.
Figure 3. Direction patterns calculated using radiating autotransformer models, which take into account: 1) nothing else; 2) a concrete partition on the left; 3) a concrete partition on the right; 4) concrete partitions on both sides; 5) the wireline passes and additions to lead-in wires; 6) the auxiliary columns, the support for bus wire fastening, the fire extinguisher system; 7) the radiators and all listed above elements and structures.

The fourth results of direction patterns calculation are presented in Figure 3b. These results were obtained using models for four types of electrical power objects. The first model takes into account the presence of the autotransformer only. The second model takes into account the presence of the autotransformer and the wireline passes and additions to lead-in wires. The third model takes into account the presence of the autotransformer, the auxiliary columns, the support for bus wire fastening and the fire extinguisher system. The fourth model takes into account the presence of a set of all elements and constructions listed in this article, including the autotransformer. As follows from the figure, the greatest contribution to the electromagnetic field distribution is made by the wireline passes and additions to lead-in wires of the autotransformer, which increase up to 2-2.5 times the radiation intensity at angle $\phi$ from 270 to 90 degrees.

The influence of the listed above elements and constructions on the directional pattern was evaluated. The evaluation was carried out by calculating the deviation of the electric field strength absolute values $\Delta E_{i,\%}$ and by deviations in the shape of the directional pattern $\Delta E_{\text{max},\%}$ for each value of angle $\phi$, using the following equations:

$$\Delta E_{i,\%} = \left| \frac{E_i - E_0}{E_0} \right| \cdot 100\%,$$

$$\Delta E_{\text{max},\%} = \left| \frac{E_i}{E_{\text{max}}} - \frac{E_0}{E_{0\text{max}}} \right| \cdot 100\%,$$

where $E_i$ – value of electric field strength from model with number “i” for the set angle $\phi$; $E_0$ – value of electric field strength from the radiating autotransformer model for the set angle $\phi$; $E_{\text{max}}$ – the maximal value of electric field strength from the radiating autotransformer model.

Arithmetic averages $\Delta E_{i,\%}$ and geometric averages $\Delta E_{\text{max},\%}$ of deviation values are calculated and presented individually for each model in Table 1.
Table 1. Calculation results of separate elements and constructions influence on the direction patterns.

| №  | The elements and constructions added to autotransformer model | $\Delta E_i$ | $\Delta E_{\text{max}}$ |
|----|---------------------------------------------------------------|--------------|-------------------------|
|    |                                                               | arithmetic average | geometric average | arithmetic average | geometric average |
| 1  | the cooling radiators                                         | 17,0%         | 12,3%                   | 14,3%               | 11,3%               |
| 2  | the auxiliary columns                                         | 14,6%         | 11,6%                   | 10,2%               | 4,9%                |
| 3  | the support for bus wire fastening                            | 30,5%         | 25,4%                   | 22,0%               | 17,6%               |
| 4  | the fire extinguisher system                                  | 26,4%         | 22,7%                   | 18,4%               | 14,8%               |
| 5  | a concrete partition on the left                              | 1,5%          | 1,2%                    | 1,1%                | 0,7%                |
| 6  | a concrete partition on the right                             | 1,1%          | 0,7%                    | 1,0%                | 0,7%                |
| 7  | concrete partitions on both sides                             | 1,9%          | 1,2%                    | 1,2%                | 0,8%                |
| 8  | the wireline passes and additions to lead-in wires            | 70,8%         | 50,1%                   | 24,5%               | 17,3%               |
|    | lines 2-4                                                    | 37,8%         | 26,6%                   | 30,0%               | 22,3%               |
| 9  | lines 1-8                                                    | 70,3%         | 45,6%                   | 28,7%               | 16,6%               |

As appears from the Table 1, existence of the wireline passes and additions to lead-in wires has the greatest impact on the electrical power object directional pattern simulation. This effect is twice the impact of the cumulative accounting of auxiliary columns, support for bus wire fastening and fire extinguisher system for the deviation of the electric field strength absolute values $\Delta E_i$. The analysis shows that the form of the directional pattern is most dependent on accounting for the wireline passes and additions to lead-in wires (up to 25%), the support for bus wire fastening (up to 22%), the fire extinguishing system (up to 18.5%). To a lesser extent the form of the directional pattern depends on accounting of the cooling radiators (up to 14.5%) and auxiliary columns (up to 10.5%). Influence of concrete partitions is in limit of 2% therefore they might be neglected on the electrical power object model.

The results of electrical power object direction patterns correspond to the frequency 17.69 MHz, which is a resonance frequency of the autotransformer lead-in wire 500 kV. Direction patterns have an even sharper appearance at higher frequencies (27.57, 170.45, 127.12 MHz) corresponding to resonances of other autotransformer lead-in wires. The features revealed above appear more clearly at these frequencies.

4. Conclusions

The analysis of the achieved results showed that it is necessary to consider wireline passes, additions to lead-in wires, support for bus wire fastening, fire extinguisher system, cooling radiators, auxiliary columns during modeling electrical power object. Existence of these elements and constructions significantly influences to electromagnetic field distribution. It is important for correct arrangement of measuring equipment near HVPE. The created direction patterns might be used during preparation and carrying out HVPE technical condition electromagnetic control.

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