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Electric and Magnetic Fields of the High Voltage Autotransformer

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Introduction

The actuality of the problem of industrial electric and magnetic fields’ action to the workers health and to the electronic equipment arises [1, 2] in recent years.

There are European (EU) standards limiting the maximum electric and magnetic fields values, which are dangerous for the human health and can damage the electronic equipment. Recent studies show that the small electric and magnetic fields can have influence to the health of human who works at the existing powerful electrical equipment, too. By EU Directive 2004/40/EC [3] the magnetic field strength must not exceed 400 A/m and the magnetic flux density - 500 μT in the workplaces. Electric field strength should not exceed 10 kV/m. Implementation of this Directive is delayed in Lithuania. The Lithuanian main document governing the values of the electromagnetic field is the hygiene norm HN110: 2001 "The electromagnetic field of industrial frequency in the workplace." Magnetic field strength should not exceed 900 A/m, and the electrical field strength should not exceed 5 kV/m during the working day (8 hours). Now the trend is considered and discussed to reduce the maximum allowable amount of magnetic flux density value to the values equal to 0.2 or 0.3 mT. These values are equivalent to the magnetic field strength values that are proportionally reduced to 160 – 240 A/m.

High voltage transformer is one of the most powerful electrical equipment in the power system, which creates a strong electric and magnetic fields of 50 Hz frequency. Therefore, the magnetic and electric fields must be investigated in surroundings of the transformer with due attention. We investigate the 125 MVA autotransformer.

330/110/10 kV three-phase 125 MVA power step-down autotransformer

This autotransformer transmits the high voltage of 330 kV AC to 110/10 kV AC and has three windings in any of three phases: one primary and two secondary windings. They are wrapped on the magnetic core. The 330 kV wires carry 220 A nominal value AC. The secondary winding of 110 kV voltage has electrical connection to the primary winding of 330 kV voltage and is a part of the primary coils. However, only the part of electric current is transmitted by electric connection. All other current of 110 kV and 10 kV secondary windings is transformed by magnetic field.

Autotransformer magnetic core is manufactured from the electrical steel sheets. In any phase the primary and secondary windings are placed one above the other on the three cores. In order to occupy a smaller volume of the coils the cores have polygonal cross section. The cooling channels are arranged among the magnetic core plates. Magnetic core with the wrapped windings is placed in a tank with the transformer oil. The oil circulated in the tank, it refrigerates the magnetic core and windings through convection. The magnetic flux of autotransformer is closed through magnetic core, oil, metal constructions and autotransformer tank walls.

The especially strong electric field is created around the wires and around the autotransformer inlets of 330 kV voltage.

Electromagnetic field analysis by finite element method using COMSOL software package

Software package COMSOL Multiphysics can be used for modeling the main characteristics of electric and magnetic fields (magnetic flux density, magnetic field strength, coil inductors, potential difference, electric field strength, electric flux density) in and around different electric installation. This simulation package solves linear and nonlinear equations, systems in one-, two- or three-dimensional areas.

The problem solution of a given package is based on the finite element method (FEM). At first the vector or scalar electromagnetic potential is calculated. The type of potential depends on element type and two- or three-dimensional model is used.

COMSOL Multiphysics package can be used for the exploration and modeling of a time-variable electromagnetic field. Time-variables electromagnetic fields can be calculated in two ways:

1. When the process variation represents the transient process after salutatory variation of input value or electric circuit of the device. Then the computation is performed for the starting and final values of variables. This method is inappropriate when the time interval is small, and the desired modeling accuracy must be high.
2. The most accurate and convenient computation of the time-variable electromagnetic fields can be performed when the variation is sinusoidal.

Electromagnetic potential method of the package COMSOL Multiphysics can be used for the following strategies:

1. AC/DC static electric and magnetic strategy;
2. AC/DC quasi-static electric and magnetic strategy;
3. AC/DC quasi-static electromagnetic strategy.

AC/DC static electric and magnetic strategy is used for the power autotransformer investigation.

125 MVA power autotransformer magnetic fields

The magnetic flux of autotransformer is created by primary windings and inside it is directed along axes of windings. With the assumption that the field of autotransformer is plane it can be modeled in 2D area.

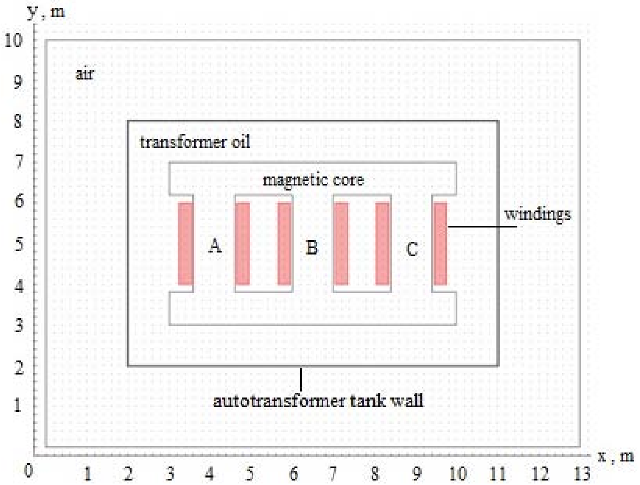

Fig. 1. Longitudinal of autotransformer

There is presented (Fig. 1) the longitudinal which passes via the autotransformer windings axes. For the electromagnetic problem solution Ampere's equation can be used

$$\nabla\cdot\mathbf{H}=\mathbf{J}+\frac{\partial\mathbf{D}}{\partial t}=\sigma\mathbf{E}+\mathbf{J}+\frac{\partial\mathbf{D}}{\partial t}, \qquad (1)$$

where ∇ is the nabla operator; ***H*** is the magnetic field strength vector; ***J*** is the current density vector; ***D*** represents the electric flux density vector; ***E*** represents the electric field density vector: σ is the electrical conductivity.

The standard way of equation (1) solution is expression of magnetic and electric characteristics by magnetic ***A*** and electric *V* potentials and calculation of these potentials [4–6]. The strength and flux density of magnetic and electric fields can be expressed as:

$$\boldsymbol{B}=\nabla\times\boldsymbol{A}\,,\ \boldsymbol{E}=-\nabla V-\partial\boldsymbol{A}/\partial t\,,\ \boldsymbol{B}=\mu_r\mu_0\boldsymbol{H}\,,\ \boldsymbol{D}=\varepsilon_r\varepsilon_0\boldsymbol{E}\,, \qquad (2)$$

where ***B*** is the magnetic flux density vector; ***A*** is the vector magnetic potential; ∇V is scalar electric potential difference; μ_r is relative permeability; $\mu_0=4\pi\cdot10^{-7}$ H/m is magnetic constant; ε_r is relative permittivity; $\varepsilon_0=8{,}85\cdot10^{-12}$ F/m is electric constant.

Evaluating these expressions and sinusoidal variation of potentials we obtain of (1)

$$(\mathrm{j}\omega\sigma-\omega^2\varepsilon_0\varepsilon_r)\mathbf{A}+\nabla\cdot(\mu_0^{-1}\mu_r^{-1}\nabla\cdot\mathbf{A})=\frac{\sigma\nabla V}{d}+\mathbf{J}\,, \qquad (3)$$

where *d* is the mean diameter of winding; $\omega=2\pi f$ is angular frequency.

For area in which the magnetic field is actual for us we can suppose that $\sigma=0$. For the frequency $f=50$ Hz the inequality $\omega^2\varepsilon_0\varepsilon_r<<1$ is right. From equation (2) we obtain

$$\mu_0{}^{-1}\mu_r{}^{-1}\nabla^2\boldsymbol{A}=\boldsymbol{J}\,. \qquad (4)$$

We relate with plane of Fig. 1 the axes *x* and *y*. In this plane the current density of windings is directed perpendicular to plane, therefore, the current density is directed along *z* axis: $\boldsymbol{J}=\boldsymbol{e}_z J_z$. The vector ***A*** is parallel to ***J*** and it has only component A_z, too. The (4) equation in the rectangular coordinate system can be written as follows

$$\frac{1}{\mu_r}\left(\frac{\partial^2 A_z}{\partial x^2}+\frac{\partial^2 A_z}{\partial y^2}\right)=-\mu_0 J_z\,. \qquad (5)$$

Current density J_z can be expressed in this way

$$J_z=\frac{N\cdot I}{S}\,, \qquad (6)$$

where *N* is the phase number turns of primary winding; *I* is the phase current; *S* is the phase windings area.

The solution of (5) equation is based on the finite element smoothing technique. Finite element mesh is created using the COMSOL Multiphysics package. Autotransformer tank walls are made of electrical steel with a thickness of 18 mm and the steel magnetic permeability μ_r is chosen according to the electrical steel magnetization curve of catalogue. The magnetic permeability of the transformer oil is the same as the air – $\mu_r=1$.

Finite element mesh selected automatically, so all elements of the modeled shape adapt to and shape bending. Number of cells in finite element model is obtained $n_{\text{f.e.}}=31320$, while the number of grid nodes is obtained $n_\text{n}=87070$. Finite element mesh model is shown in Fig. 2.

The maximum magnetic field strength value was obtained equal to 1617 A/m. It is located inside the autotransformer magnetic core vertical branches on which the A, B, C phase windings are mounted.

The maximal magnetic field strength values that are penetrated through the autotransformer tank walls are equal to 625 A/m on the model surface. They are obtained near to an external autotransformer tank walls. Moving away from the autotransformer magnetic field value decreases exponentially depending on the distance and moving away from the autotransformer in 2.5 m the magnetic field is still as low as 375 A/m. The dependence of magnetic field strength distribution on distance is presented in Fig. 3.

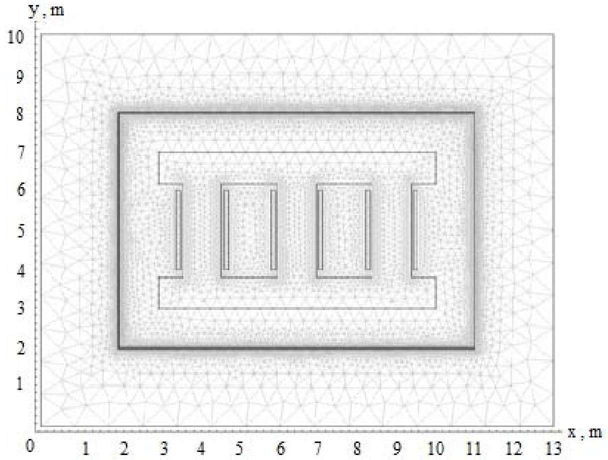

Fig. 2. Finite element mesh model of magnetic core

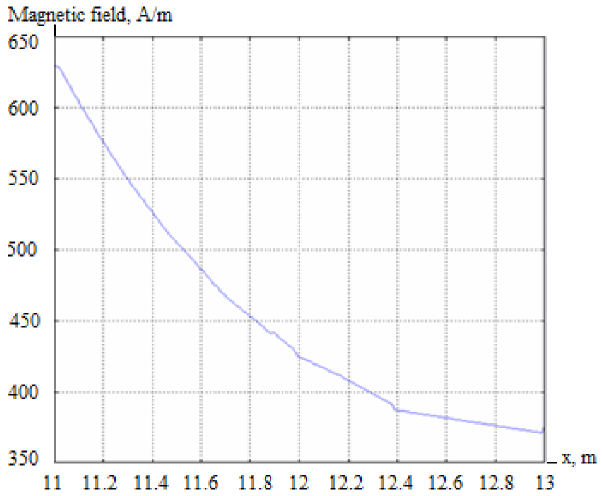

Fig. 3. Magnetic field distribution outside the transformer

125 MVA autotransformer electric field

We suppose that in the area around the transformer there are not the zones with volume charge. Therefore the Laplace equation is right for electric potential

$$\nabla^2 V = 0 . \qquad (7)$$

The electric field around the 10 kV network is not strong. Therefore Multiphysics the finite element mesh of autotransformer with 330 and 110 kV lines and surroundings is performed using COMSOL (Fig. 4).

The 2D model is used for the preliminary investigation of the places with the strongest field.

Autotransformer is surrounded by air with relative permittivity ε_r=1. For the land, all equipment on the land, and the autotransformer frame the potential V=0 was set.

Finite element mesh is performed automatically, so all elements of the modeled shape adapt to the shape and bending of modeled object.

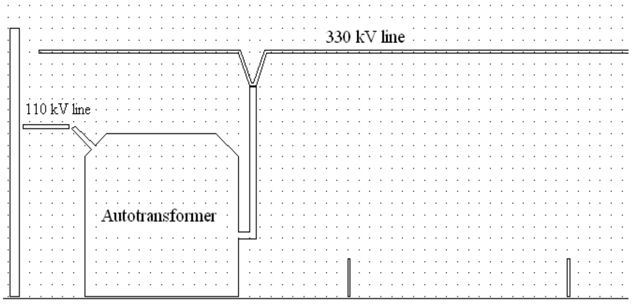

Fig. 4. Autotransformer and a high voltage lines

The number of finite elements of model is obtained $n_{f.e.}$=17428, and the number of nodes is obtained n_n=48450. Finite element mesh model shown in Fig. 5.

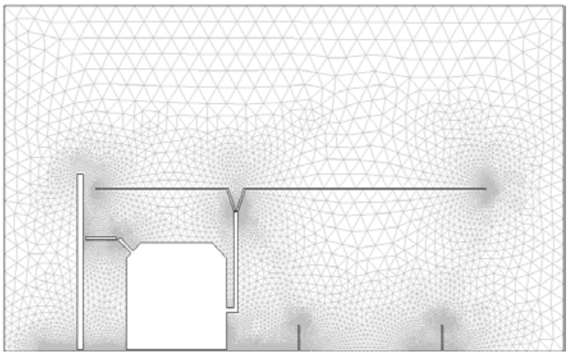

Fig. 5. Finite element mesh of autotransformer

The electric field strength distribution in the environment around the autotransformer is shown in Fig. 6.

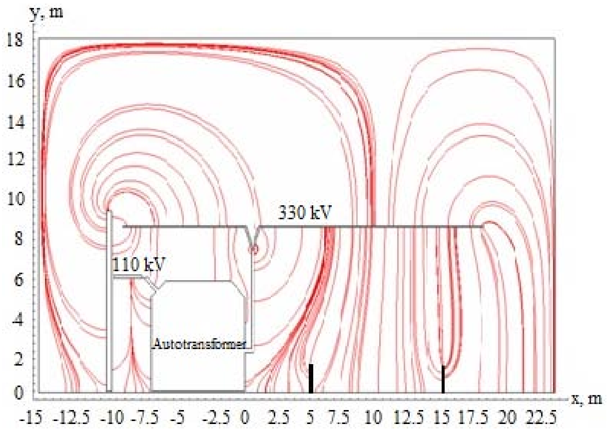

Fig. 6. Electric field strength distribution near the autotransformer

The modeling results show that the minimum electric field strength is at 110 kV autotransformer terminal (left side of model), but it arises with moving further away from the autotransformer. In this side of the autotransformer the maximum electric field strength value is equal to 1.75 kV/m. The maximum value is obtained by moving away from the autotransformer to 9 m and 1.5 m above the ground.

The other results are obtained at 330 kV autotransformer inlets side (right side). The electric field strength value is equal to the 3 kV/m in the 1.5 m height near the autotransformer under 330 kV inlets. Moving away from the autotransformer inlets along the line of 330 kV the electric field strength value significantly increases. The two metal fences, which height are equal to 1.6 m, have the important influence to the electric field rising. They are under the 330 kV air line. The electric field strength values along the distance from autotransformer at 1.5 m height are presented in Table.

Numerical electric field strength values are fixed moving further away in every 2 meters. The maximum value which is equal to 57 kV/m was obtained in distance at autotransformer equal to 14 m.

Table 1. Electric field strength dependence on the distance of 330 kV air line

l, m	0	2	4	5	8	10	12	15	16	18	20
E, kV/m	3	4	5	35	8	9	10	57	13	10	10

In the distance at 5 to 20 meters the electric field strength is above 25 kV/m (the hygiene norm HN 110: 2001). The values of the electric field strength in the height 2 m above the ground are greater than in the height of 1.5 m.

Conclusions

1. The modeling results shows that the magnetic field penetrates the autotransformer tank walls. The magnetic field strength near the wall is higher than European norms but does not exceed the values set in the Lithuanian Hygiene Norm (HN 110 2001). Magnetic field strength in the environment decreases very rapidly and in distance at 2,5m is not exceeded the European norms, too.

2. There are some areas near the autotransformer at the side of the 330 kV overhead line in which the electric field strength can exceed the Lithuanian and European norms. The electric field strength in these areas must be reduced and screened.

3. Using the finite element automatic mesh electromagnetic field strength calculation the modeling of particular objects of irregular geometry becomes simpler and more accurate.

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High voltage power autotransformer is one of the strongest sources of the electric and magnetic fields in the electrical power systems. The autotransformer with surroundings was modelled using finite element method for evaluate magnetic and electric fields distribution around it. The modelling results show that magnetic field near autotransformer is not dangerous for human practically. But there are zones near autotransformer and connected to it 330 kV network, where the electric field strength can exceed the maximal admissible values. Therefore the measures must be used for the electric field damping in these zones. Ill. 6, bibl. 6, tabl. 1 (in English; abstracts in English and Lithuanian).

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Elektros energetikos sistemoje aukštosios įtampos galios autotransformatorius yra vienas iš galingiausių elektrinio ir magnetinio laukų kūrimo šaltinių. Autotransformatorius ir jį supanti aplinka aprašyti baigtinių elementų metodu. Magnetinio ir elektrinio lauko skaičiavimais nustatyta, kad magnetinio lauko stiprio vertės arti autotransformatoriaus neviršija leistinųjų verčių. Skirtingai nei magnetinio, elektrinio lauko stiprio vertės ties autotransformatoriumi ir oro linija viršija didžiausias leistinąsias vertes. Į bendrą 50 Hz dažnio 330 kV elektros energetikos sistemą įjungtas autotransformatorius kuria intensyvius elektrinį ir magnetinį laukus. Didžiausioms elektrinio ir magnetinio laukų stiprių vertėms slopinti siūloma ekranuoti įtampos galios autotransformatorius. Il. 6, bibl. 6, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).