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ELECTROMAGNETIC FIELD CALCULATION OF TRANSFORMER STATION 400/110 KV ERNESTINOVO USING THE CDEGS SOFTWARE

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This paper presents calculations of the electric and magnetic fields of complex busbars, transformers and transmission line structures at the transmission power station 400/110 kV Ernestinovo. By constructing and bringing the TS 400/110 kV Ernestinovo in operation, it was expected that electric and magnetic fields would arise within and outside the fence of the transformer station. The fundamental sources of low frequency electromagnetic fields in the TS Ernestinovo are the primary elements of the 400 and 110 kV open substations as well as the connected 400 kV and 110 kV overhead lines. Due to the complexity of the geometry of the substation elements, it was necessary to apply a three-dimensional approach to the calculation and analysis of the electromagnetic field. Calculations of electromagnetic fields were conducted for quasi-static states of electrical values at a power frequency of 50 Hz. The calculated electric and magnetic fields were compared with permissible levels according to Croatian regulations. The maximum permissible levels for the electric field and magnetic flux density were found to be exceeded at some locations in the station.

K e y w o r d s: electric field, magnetic field, transformer station, electromagnetic compatibility, moment method, computer program

1 INTRODUCTION

The book of regulations, which determines the permissible levels of electric and magnetic fields, has been adopted on the basis of the Law on Non-ionizing radiation protection (article 10) which is in effect in the Republic of Croatia. The Law was passed and promulgated on December 30, 2003. The regulations prescribe the obligations of utility owners to perform calculation or evaluation of the expected levels of electric and magnetic fields within and around their installations, *ie*, to provide a review on fulfilment of the requirements prescribed by Articles 7, 8, 11 and 13 of the book of regulations.

This paper presents calculations of the electromagnetic field, both in the nearby environment and within the transformer station itself and compares the results with the permissible values prescribed by the Book of Regulations.

New TS 400/110 kV Ernestinovo is in operation and it was expected that electric and magnetic fields would arise within and outside the fence of the transformer station. The fundamental sources of low frequency electromagnetic fields in the TS Ernestinovo are the primary elements of the 400 and 110 kV open substations as well as the connected 400 kV and 110 kV overhead lines. Due to the complexity of the geometry of the above mentioned elements, it is necessary to apply a three-dimensional approach to the calculation and analysis of the electromagnetic field. Calculations of electromagnetic fields were conducted for quasi-static states of electrical values at the frequency of 50 Hz due to short-term effects of transients which do not represent a risk in terms of electromagnetic influences.

The law on non-ionizing radiation protection regulates that appliances, substations and buildings which are sources of electromagnetic fields or which contain sources of electromagnetic fields shall be used and brought in operation only if they fulfil the requirements in compliance with their purpose, and when they do not expose people to electromagnetic fields above the limiting levels prescribed by the regulator. The equipment within the TS Ernestinovo generates a permanent 50 Hz electromagnetic field. Consequently, we have the following limiting levels of electric field intensity E and magnetic flux density B:

- for the field of professional exposure (8 hours per day) electric field intensity $E_{g^{8h}} = 5000$ V/m and magnetic field density $B_{g^{8h}} = 100\,\mu$T,
- for the field of enhanced sensitivity (24 hours per day) electric field intensity $E_{g^{24h}} = 2000$ V/m and magnetic field density $B_{g^{8h}} = 40\,\mu$T.

2 MATHEMATICAL MODEL

The calculations presented in this paper were carried out with the HIFREQ [6, 7] program of the CDEGS [8] software package. This program calculates the current distribution in conductor networks consisting of rectilinear segments, and uses this current distribution to com-

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pute the potential, electric field and magnetic field at selected points in space. The program can account for the presence of multiple horizontal layers of soil with different electrical characteristics. The conductors and observation points (*ie*, the points, where the potential and electromagnetic fields are computed) can be located in the air or in any of the earth layers.

The methodology used in the program is described in detail in References 6 and 7. A brief summary is presented below. The potential and electromagnetic fields are first expressed in terms of the components of a vector potential, which is in turn expressed as a function of the currents flowing in each segment of the conductor network. The currents in the conductor segments are determined by the requirement that the voltage drop between pairs of points in the network be equal to the ZI drop along a path connecting the points, so that in a complex representation:

$$\int_{P_1}^{P2} \mathbf{E} \cdot \mathrm{d}\boldsymbol{l} - \int_{P_1}^{P_2} \mathbf{Z}\mathbf{I}\mathrm{d}l\,. \tag{1}$$

Here, $\mathbf{E}$ is the complex vector of electric field intensity, $\mathbf{Z}$ is the internal impedance of the conductor and $\mathbf{I}$ is the phasor of current flowing in it. Points and are normally taken as the mid-points of adjacent segments, and the integrals are carried out over the shortest path linking them.

This technique (which is a special application of the method of moments) fully accounts for mutual interactions (conductive, capacitive, and inductive) between the conductor segments, and also accounts for the potential drop along the conductors due to their self-impedance.

Application of Equation (1) yields a matrix system that can be solved for the currents in the network. Once the currents are known, they can be used to compute the potential and the electromagnetic fields.

The computation of the fields due to a conductor segment proceeds by integrating the contributions of electric dipoles distributed along the axis of the conductor segments. The contribution of an individual dipole to the electromagnetic fields is evaluated with the help of a generalized Sommerfeld integral that accounts for the presence of a multi-layered soil.

A. Calculation of the electric field

While calculating the conservative electric field, only conductors that are at known potentials are taken into consideration. Furthermore, as the charges are located at the surface of the conductors, it is necessary to distribute the charges appropriately on the conductor surface, which is later easily associated with the appropriate mathematical tool and with the field equation. The conductor surface was modelled with a thin one-dimensional wire grid. The effect of permittivity discontinuity (ε) on the ground-air interface, *ie*, the effect of ground on the electric conductor potential was taken into consideration by using the mirror technique. The phasor of the electric potential $\dot{\varphi}(\boldsymbol{r})$ located at some point in space can be obtained by applying the superposition theorem as an infinite sum of potentials caused by elementary time variable charges $\mathrm{d}\dot{q} = \dot{\lambda}(\boldsymbol{r}')\mathrm{d}l'$ on the conductor surface. The infinite sum is treated as an integral for the electric potential $\dot{\varphi}(\boldsymbol{r})$ caused by line charge density $\dot{\lambda}(\boldsymbol{r}')$, which is located at a point given by the position vector $\boldsymbol{r}'$ placed on all thin wire parts (structures), including the original conductors and their images with respect to the ground-air discontinuity, is given by the following integral equation:

$$\dot{\varphi} = \frac{1}{4\pi\varepsilon}\int_{l'} \frac{\dot{\lambda}(\boldsymbol{r}')\mathrm{d}l'}{|\boldsymbol{r}-\boldsymbol{r}'|} + \frac{1}{4\pi\varepsilon}\int_{l'} \frac{\dot{\lambda}(\boldsymbol{r}'')\mathrm{d}l''}{|\boldsymbol{r}-\boldsymbol{r}''|} \tag{2}$$

where:
$\dot{\lambda}(\boldsymbol{r}')$ – phasor of line charge density of the original conductor [A/m],
$\dot{\lambda}(\boldsymbol{r}'')$ – phasor of line charge density of the mirrored conductor [A/m],
$|\boldsymbol{r}-\boldsymbol{r}'|$ – distance between the observation point and the phasor of line charge density of the original conductor [m],
$|\boldsymbol{r}-\boldsymbol{r}''|$ – distance between the observation point and the phasor of line charge density of the mirrored conductor [m],
ε – permittivity of space in which the field is calculated, *ie* for air follows $\varepsilon = \varepsilon_0$,
l', l'' – integration on the original (mirrored) conductor.

Since the line charge density appearing under the integral sign is an unknown function, expression (1) has to be solved using a numerical method due to the lack of a more appropriate analytical expression. In this paper, the moment method (MOM), which has proven to be effective when solving electromagnetic tasks in unlimited space, was used for solving Equation (1). In order to use the moment method for solving Equation (1), it is necessary to perform a discretization of this equation. This is performed through the discretization of an unknown distribution of field source, *ie*, line charge density $\dot{\lambda}(\boldsymbol{r}')$ by using a combination of appropriate number of N linearly independent fundamental functions. Thereupon, the discretization of conductor length on N segments and the discretization of observation points will be conducted. First, it is necessary to divide the conductors into segments of finite lengths Δl ($j = 1,\ N$), which can be a line or ring depending on the desired accuracy. Then it is necessary to approximate the unknown distribution of field source with the appropriate number of fundamental functions λ_j in the form of the following expression:

$$\dot{\lambda} = \sum_{j=1}^{N} a_j'\lambda_j' \text{ that is } \dot{\lambda} = \sum_{j=1}^{N} a_j''\lambda_j'' \tag{3}$$

where:
λ_j' – fundamental function on segment j of the original conductor,

λ''_j – fundamental function on segment j of the mirrored conductor.

A constant on the segment was chosen, and $a'_j = 1$ is on the observed segment, whereas it is zero on other segments. The same goes for a''_j. Taking into consideration that the constant on the segment has been chosen as the fundamental function and that great accuracy is required, the number of segments per conductor has been increased so that the longest segment length does not exceed the length of 1 m. Based on the above discussion, expression (1) can be written as:

$$\dot{\varphi}(\boldsymbol{r}) = \frac{1}{4\pi\varepsilon}\sum_{j=1}^{N}\int_{\Delta l'_j}\frac{a'_j\lambda'_j(\boldsymbol{r}')\mathrm{d}l'}{|\boldsymbol{r}-\boldsymbol{r}'|} + \frac{1}{4\pi\varepsilon}\sum_{j=1}^{N}\int_{\Delta l''_j}\frac{a''_j\lambda''_j(\boldsymbol{r}'')\mathrm{d}l''}{|\boldsymbol{r}-\boldsymbol{r}''|}. \quad (4)$$

Since $\lambda' = -\lambda''$, it is obvious that the expression (4) has N unknowns on the right side. In order to solve the expression, N observation points in space where the potential is known, and which corresponds to the conductors under voltage, have to be chosen. Thus the system of N equations with N unknowns is obtained, which is determined in matrix form as

$$[\varphi] = [p][\lambda] \quad (5)$$

where the elements $p_{i,j}$ of the matrix system $[p]$ represent the potential at observation point "i" placed on the conductor surface of line current density λ_j.

The Gauss-Seidel iterative method was used for solving the matrix equation. In this process, the iteration was considered successful the moment a relative accuracy of 10^{-7} was reached. Once equation (5) has been solved, *ie*, an approximation of the line current density on the conductors has been obtained, the vector-phasor of the conservative component of electric field intensity on the observation point with a position vector $\boldsymbol{r}$ can be determined by using the following equation (6).

$$\dot{\mathbf{E}}(\boldsymbol{r}) = \frac{1}{4\pi\varepsilon}\sum_{j=1}^{N}\int_{\Delta l'_j}\frac{a'_j\lambda'_j(\boldsymbol{r})(\boldsymbol{r}-\boldsymbol{r}')\mathrm{d}l'}{|\boldsymbol{r}-\boldsymbol{r}'|^3} + \frac{1}{4\pi\varepsilon}\sum_{j=1}^{N}\int_{\Delta l''_j}\frac{a''_j\lambda''_j(\boldsymbol{r})(\boldsymbol{r}-\boldsymbol{r}'')\mathrm{d}l''}{|\boldsymbol{r}-\boldsymbol{r}''|^3}. \quad (6)$$

Considering that a three-dimensional calculation of the electric field intensity vector, which is caused by the line charge density of a three-phase system that are mutually phase shifted by 120° and at the same time spatially displaced (space between phases), is required, it should be taken into account that electric field intensity is elliptically polarized at every point in space.

Since each of the three components of the electric field have a different sum and phase shift, the following can be applied:

$$\begin{aligned} E_x(t) &= E_{x,\max}\sin(\omega t + \varphi_x) \\ E_y(t) &= E_{y,\max}\sin(\omega t + \varphi_y) \\ E_z(t) &= E_{z,\max}\sin(\omega t + \varphi_z)\,. \end{aligned} \quad (7)$$

where $\omega = 2\pi f$ and in our case $f = 50$ Hz. The absolute value of the electric field intensity vector is defined by the following expression

$$E(t) = \sqrt{E_x^2(t) + E_y^2(t) + E_z^2(t)} \quad (8)$$

whereas the RMS value of the absolute value of electric field intensity is defined by the following expression:

$$E = \frac{1}{\sqrt{2}}\sqrt{E_{x,\max}^2 + E_{y,\max}^2 + E_{z,\max}^2}\,. \quad (9)$$

B. Calculation of the magnetic field

Space (air), where the rotational component of the EMF was calculated, has been modelled as a linear isotropic half-space having the same properties as a vacuum, *ie*, $\varepsilon = \varepsilon_0$, $\mu = \mu_0$, $\kappa = 0$. Discontinuity of these properties arises on the plane separating ground and air, which is defined by the coordinate $z = 0$. The electric properties of the half-space below the limiting ground-air plane are defined by the soil characteristics $\varepsilon_r \approx 80$, $\mu = \mu_0$ and $\kappa = 0.01$ S/m. The coordinate system has been chosen so that unit vector $\boldsymbol{a}_z$ is perpendicular to the limiting plane.

The magnetic field in the observed part of the half-space is defined as:

$$\mathbf{B} = \frac{\mu_0}{4\pi}\int_{l_j}\frac{\dot{I}\mathrm{d}\boldsymbol{l}\times(\boldsymbol{r}-\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|}, \quad (10)$$

where the electric field is defined by expression (6). Both expressions (6) and (10) are discretized, *ie*, the integral is calculated as the sum of effects of all conductor segments at the observation point.

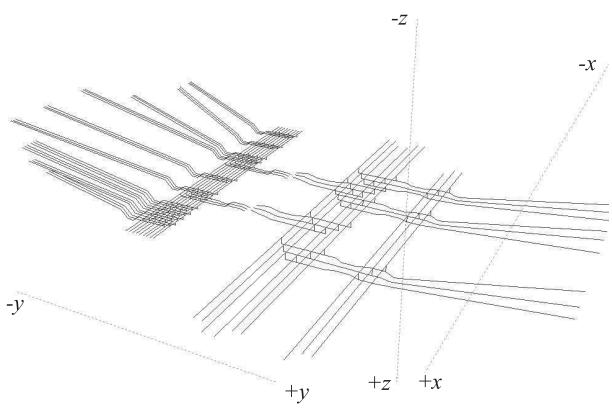

Fig. 1. Model of TS Ernestinovo used in calculations

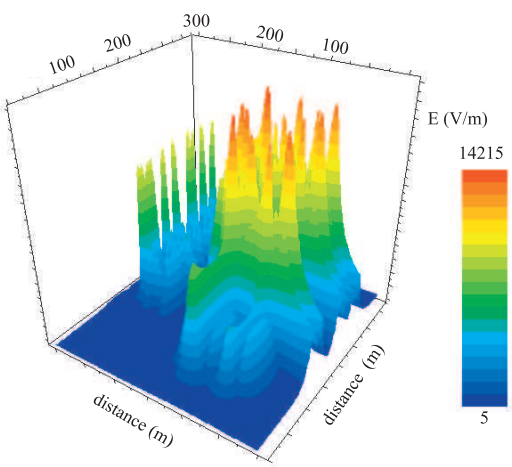

Fig. 2. Spatial distribution of electric field intensity inside TS Ernestinovo

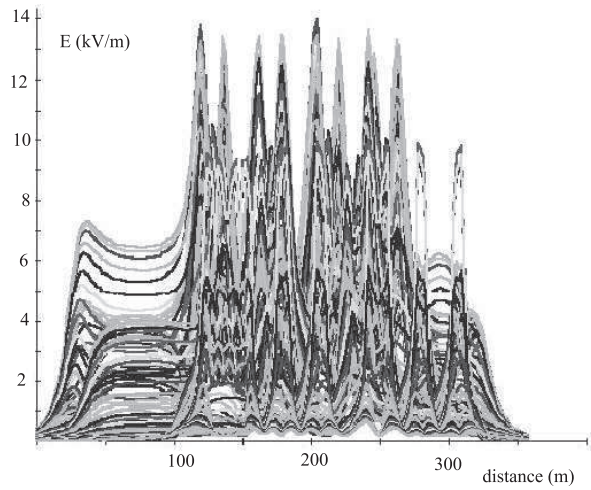

Fig. 3. Profile presentation of electric field

The electromagnetic field is determined at points located at the nodes of a rectangular grid with equal mesh size at a height of 2 m above the ground, which lies in the x-y plane, *ie*, parallel to the plane separating ground from air. The space between two consecutive observation points in the x and y directions is 2 m for observation points that are in areas where the RMS value of the electromagnetic field is low and 1 m in areas where the RMS value is high.

3 CALCULATION OF THE ELECTRIC FIELD IN TRANSFORMER STATION 400/110 KV

A graphical model of TS Ernestinovo used for the calculation of electric field is shown in Fig. 1, as modelled in the HIFREQ module of the CDEGS software [9]. While calculating the conservative electric field, the phase voltages of a three-phase balanced system was imposed on the conductors.

The 760 elements were entered into the computer model for the substation, along with each busbar, connection of voltage and current transformers, re-closers, connectors with surge arresters, power transformers and transmission lines.

The phase voltages of the conductors in the part of the substation operated at 400 kV are:

$$\varphi_A = 231214\, e^{j0}\,\mathrm{V};\ \ \varphi_B = 231214\, e^{j240}\,\mathrm{V};$$
$$\varphi_C = 231214 e^{j120}\ \ \mathrm{V}.$$

The phase voltages of the conductors in the part of the substation operated at 110 kV are:

$$\varphi_A = 63584\, e^{j0}\,\mathrm{V};\ \ \varphi_B = 63584\, e^{j240}\,\mathrm{V};$$
$$\varphi_C = 63584 e^{j120}\ \ \mathrm{V}.$$

The subject of this analysis is a long-term (eight-hour or twenty four-hour) exposure of people to the electric field. Consequently, the field of the balanced voltage system has been calculated since the unbalanced states (failures, switching operation, ...) are of short-term duration so that permanent system unbalance at these voltage levels can be disregarded.

C. Electric field intensity inside TS 400/110 kV Ernestinovo

The spatial distribution of the electric field inside TS Ernestinovo is presented in Fig. 2 and Fig. 3. All calculations have been conducted for the surface located 2 m above the ground, since this is the highest field where people could stay.

The computed electric field much exceeds the permissible limit inside the transformer station. The white line in Fig. 1 shows the maximum allowed field intensity of 5000 (V/m).

The greatest values occur under the 400 kV busbars (14000 V/m), the connection conductors between 400 kV busbars and power transformers and on the 110 kV side of the substation under the 110 kV breakers and re-closers.

The calculated electric field for an eight-hour exposure time for working personnel is colour coded and incorporated into the drawing of the transformer station shown in Fig. 4 and Fig. 5.

The calculated electric field around the fence of the transformer station is separated into four areas. In area I, the field is less than 2000 (V/m), areas III and IV have less than 1000 (V/m). The maximum is in the area II under the 400 kV transmission lines (2000- 4000 V/m), which is greater than the limit (2000 V/m for 24-hours exposure time for humans).

4 CALCULATION OF THE MAGNETIC FIELD IN TRANSFORMER STATION 400/110 KV

Calculation of the magnetic field can not be accurately specified because of the impossibility to predict the currents flowing through the conductors at a given moment.

Namely, loads are random incidents and unbalance are unpredictable. Only severe seasonal and daily load variations can be predicted. Unbalance occurring at the 400 and 110 kV level can be disregarded so that the transmission lines, power transformers and other parts of the substation are considered to be loaded by a balanced system of phase currents.

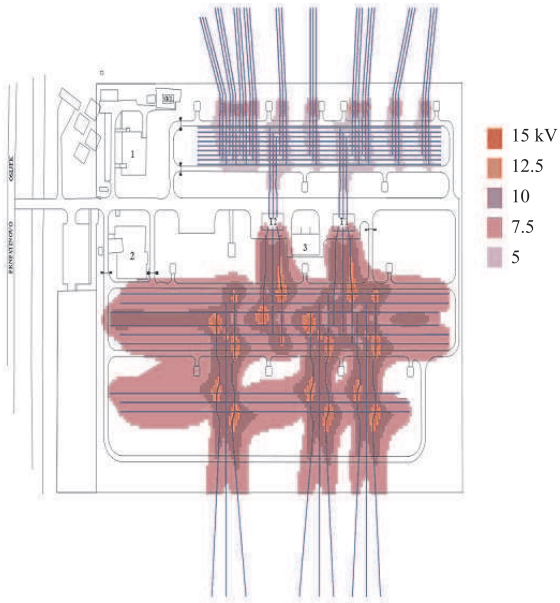

Fig. 4. Areas where an eight-hour stay is not allowed shaded

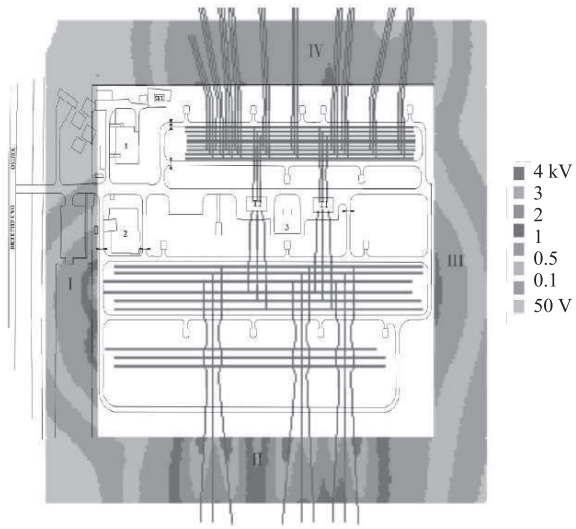

Fig. 5. Areas where an 24-hour stay is not allowed, shaded

TS Ernestinovo has been connected to the transmission network, which includes 13 transmission lines, 3 of which are connected to the 400 kV network and 10 to the 110 kV network. Two 400/110 kV power transformers, both having a capacity of 300 MVA, have been installed in TS Ernestinovo. Estimation of loading current should be based on an actual switching state and particular substation elements. In the main project of TS Ernestinovo (L2, L3), loading currents that represent the maximums occurring during exploitation and that were used for substation dimensioning, are specified. The probability of such load occurrences is very low (and their duration is very short) since they represent emergency states that are not our primary concern. We are primarily interested in stationary states. The loading currents should be based both on the expected values of transmission line and power transformer current ratings and power flow calculation. Basic technical data for the transmission lines and power transformers are selected for a temperature of 20 °C:

Loads for 110 kV transmission lines, in all cases Al/Fe 240/40 mm^2 and $I_{term} = 735$ A, according to the data from schematic R. Končar plan E02–400:

TL Ernest-Dakovo(1) ,	TL Ernest-Dakovo(2)
TL Ernest-Našice ,	TL Ernest-Osijek 1/1
TL Ernest-Osijek 1/2 ,	TL Ernest-Osijek 4
TL Ernest-Osijek 2/1 ,	TL Ernest-Osijek 2/2
TL Ernest-Vukovar ,	TL Ernest-Vinkovci

and loads for 400 kV transmission lines, in all cases Al/Fe2x490/65 mm^2 and $I_{term} = 1920$ A:

TL Ernes -Žerjavin,	TL Ernest -Mladost
TL Ernest-Ugljevik	

For the power transformers:
TR 400/110 kV, 300 MVA, primary current $I_{pr} = 433$ A, secondary current $I_{sek} = 1506$ A

For the purpose of estimating the load of the 400 kV TL Ernestinovo-Žerjavinec, we can only use the data on maximum loading from the year 1989 when this line was connecting TS Ernestinovo and TS Tumbri with a value over 1000 MVA, *ie*, 1445 A. Besides, the UCTE recommends that the interconnection lines should not be loaded more than 50 % of thermal line current, which in our case is 960 A. A current of 1000 A/1000 A current will be used for calculations of the magnetic field in the transformer station.

Considering the above discussion, for the maximum load, the following current values were used:

1. For 110 kV TL 70% of thermal line current,
2. For 400 kV TL 50% of thermal line current,
3. For transformers maximum primary/secondary currents.

The most unfavourable possibility of bus loading is to connect all lines and transformers to one bus system. Considering all loading possibilities, a distribution of loading currents through the 400/110 kV substation Ernestinovo is shown in Fig. 6.

Furthermore, it should be mentioned that such a high loading condition is not expected to occur inside a real substation but is used only as a worst case to calculate the magnetic fields.

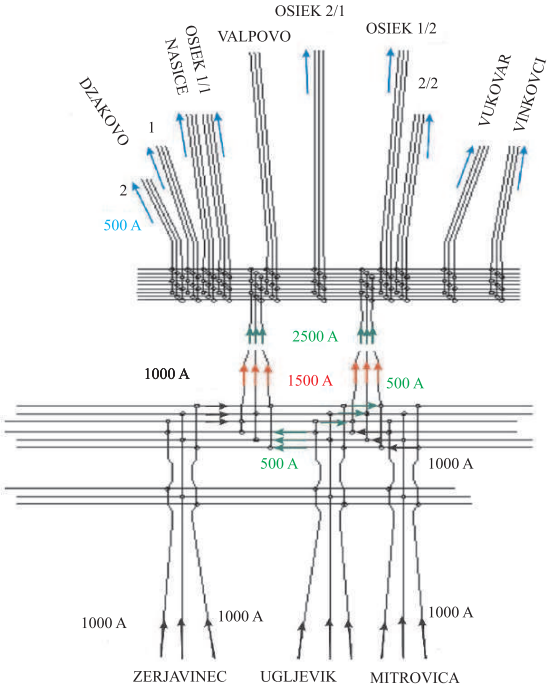

Fig. 6. Model of loading currents

D. Magnetic flux density inside TS Ernestinovo

Magnetic field computation was also performed using the HIFREQ module of the CDEGS software. The spatial distribution of the magnetic field inside TS Ernestinovo is shown in Fig. 7. All calculations have been conducted for an observation surface 2 m above the ground.

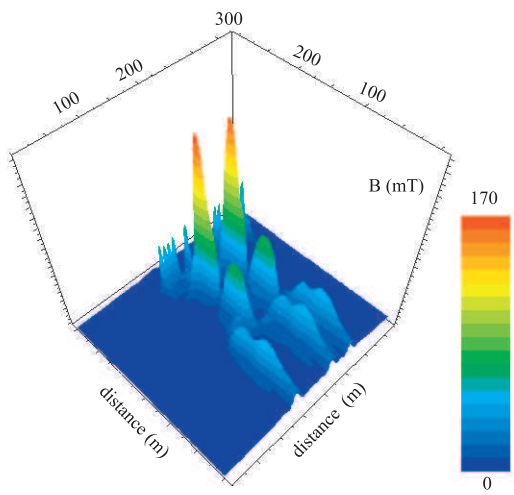

Fig. 7. Spatial distribution of the magnetic field intensity inside TS Ernestinovo

Figure 8 presents profiles of magnetic filed density in μT. There were 140 profiles used for calculation of magnetic field density on every 1 m of distance.

The permissible level for the magnetic field intensity (B) in the transformer station is 100 μT for working personnel for an 8-hour exposure time. This value is exceeded only in two places under the conductors between the power transformers and the 400 kV and 110 kV busbars.

The situation with the magnetic field density is much better since only a small region exhibits values greater than 100 μT as shown in Fig. 9.

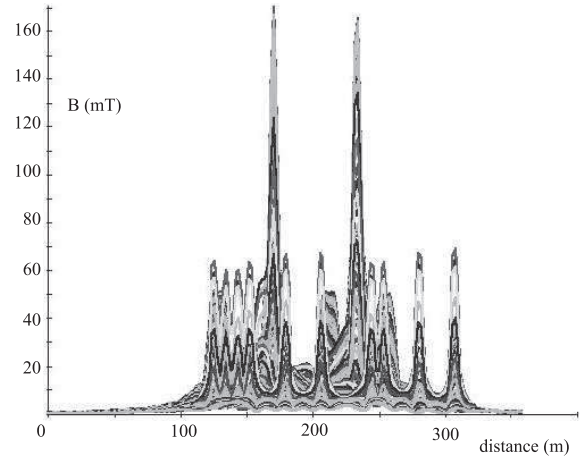

Fig. 8. Profile presentation of magnetic field density inside TS Ernestinovo

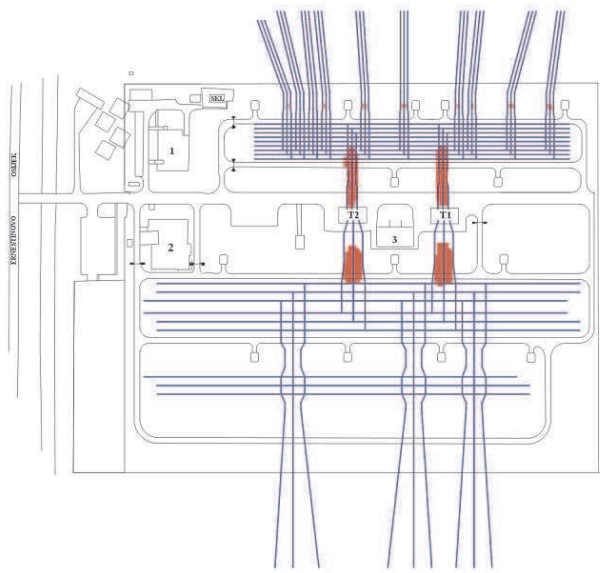

Fig. 9. Area where the magnetic flux density exceeds the permissible level of 100 μT

5 CONCLUSION

High values of electromagnetic field can cause deleterious effects on humans exposed to them, so there is a need and obligation according to Croatian law to calculate and measure these fields. This paper presents a mathematical model and calculations of electric field intensity (E) and

magnetic field density (B) in a high voltage power transformer station TS 400/110 kV Ernestinovo. Simulations were performed using CDEGS software for an observation plane at 2 m above the ground. The results are presented in 3D and 2D plots for the spatial distribution of electric field (E) and magnetic flux density (B) in the station.

Several areas in the substation were over the permissible values for the electric field intensity, especially under the 400 kV lines, busbars and around the power transformers. For the magnetic field density, the situation is not as bad, since only a small region under the 400 and 110 kV busbars that connect power transformers exceed the maximum allowed levels.

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