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Calculation and Measurement of Electromagnetic Fields

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1. Introduction

A man is exposed to electromagnetic fields in his environment. Electromagnetic fields always exist in nature – atmospheric static electric field, the Earth's magnetic static field, the fields of a wide range of frequencies due to the outbreaks in the atmosphere, etc. However, a man is today the most exposed to the artificial field, due to progress in technology and widespread use of electrical devices. Currents, induced by electric field of surface charges are the greatest if external electric field is parallel to the length of the body. Magnetic field induces a currents inside the body as well. Variable magnetic field acting by force on charged particles in the body and creates eddy currents according to Faraday's law. Such induced currents in the low frequency area can stimulate electrically excitable tissues, such as nerve and muscle fibers, through the mechanism of action potential triggering. The area of occupational exposure includes people who are exposed to electromagnetic fields in known circumstances during usual performing of work tasks in and around power facilities, but they are educated to take protective measures and they have all the tools and instructions provided. These people are aware of potential risks and take appropriate protective measures. The environment around the power facility falls within the area of increased sensitivity, which includes people of different ages and health conditions, including those particularly sensitive. In many cases people are not aware of exposure to electromagnetic fields and can not be expected to take protective measures to reduce exposure. Therefore, the restrictions for that area are stricter than those for area of occupational exposure. The most efficient way for reliable operation of the devices in high voltage substation is the calculation and measurement of low frequency electromagnetic fields in the substation, together with appropriate measurement procedure. Contemporary research of electromagnetic fields is based on the concept that complex theoretical research results in appropriate design solution, and developes almost exclusively as applied research. Generally, there are two directions; the first one based on calculation model development, and the second one based on models of objectivized physical measurements in hard conditions. In both cases, the goal is the same and can be summarized as follows: create the

optimal variant of the electromagnetic fields calculation, in both the existing and in new substations. Research of the way of calculation, for low frequency electromagnetic fields area (Extra Low Frequency), in stationary regimes in distribution substations in urban areas, is performing in order to obtain the level of electric and magnetic field in the areas where primary power and secondary electronic equipment is located and where the temporarily or permanently stay people within one segment of the regulations of protection against electromagnetic fields. Pragmatically, it can be concluded that power equipment causes electromagnetic effects, and electronic equipment is subject to the activity of these influences. Routes of transmission of these influences, in such complex facility, are possible through conductors, inductive and capacitive links and radiation. The specific characteristics of electromagnetic field sources in power systems are: field intensity, frequency, waveform (content of harmonics), polarization, spatial and time variation of the field. The main sources of influence for this research are induced voltages, as consequence of variable electric, magnetic and electromagnetic fields. In the low frequency area (wavelength 6000 (km) at frequency 50 (Hz)) the irradiation is happening exclusively in closer zone, in which does not worth mutual perpendicularity of electric and magnetic field in the direction of wave propagation, constant ratio of amplitudes of the electric and magnetic field and dependence of the electric and magnetic field amplitudes of the distance from the source by the law $1/r$, and power density by the law $1/r^2$. Low frequency electric and magnetic fields can be observed separately, because at these frequencies the shifted currents are negligible. Mathematical models and numerical solving, as well as the method of experimental measurements of low frequency electric and magnetic fields of power facilities are presented in this research. Calculation and measurement of low frequency electric and magnetic fields, as well as their interconnection, are the main problems in electricity transmission and distribution, in terms of standardized electromagnetic compatibility and human exposure to non-ionizing electromagnetic radiation. For solving the electromagnetic influences with complex geometry in the low frequency area, the system of Maxwell's equations that fully describe the electromagnetic field is used. Maxwell's equations can be analytically solved only for a narrow class of one-dimensional problems of static and quasistatic fields. Each two-dimensional (2D) and three-dimensional (3D) geometric arrangement requires the application of numerical methods for solving of the field by using some of the famous software packages (for example MAXWELL 3D, EFC-400, FLUX 3D, MATLAB...) and other appropriate tools necessary for successful implementation of the research, and for which is necessary to make a detailed mathematical models of transformer stations with all geometrical and electrical parameters. For 3D distribution calculation of low frequency electric field the charge simulation method is applied (CSM-Charge Simulation Method) as well as the source element method (SEM-Source Element Method) that is usually considered as a special variant of the indirect boundary element method (IBEM-Indirect Boundary Element Method). For 3D distribution calculation of low frequency magnetic field, inside and around the transformer stations, a procedure based on the application of Biot-Savart's law for magnetic flux density of straight streamline of finite length and a principle of superposition is used. Based on the analysis of theoretical calculation, a detailed operational measurement program that includes all measurements in steady state with measurement location is shown. The measurement have to be conducted in accordance with the norm HRN IEC 61786-2001 - Measurement of low frequency magnetic and electric field with regard to exposure of human beings-Spatial requirements for instruments and guidance for measurements and the instructions given in the European recommendations ENV 50166 (People exposure to the electromagnetic radiation on low frequencies). For measurement

methods under stationary conditions a modern measuring equipment (EFA-300 Field Analyzers) was used, which find application in researches and environmental studies for assessment of electric and magnetic fields in transmission and distribution power networks and facilities with belonging equipment. It is made to provide a sophisticated tool for precise researches of power low frequency influences for the engineers, experts in the field of health care, work protection and other profiles. Selection of the measurement points was made on the basis of the field intensity assessment, respectively the measurement is performed in places where the greatest intensity of electric and magnetic field was expected. The analysis of measurement results and their comparison with numerical calculations indicated the places in which the standards for people protection from electromagnetic fields are disturbed and gave suggestions for elimination of electromagnetic influences and their reduction to acceptable level. Confirmed satisfactory accuracy of the results obtained by calculations in comparison to the results of experimental measurements indicates the validity for introducing and developing a calculations for such practical problems related to design and reconstruction of substations, which is extremely important from an economic point of view, since, in this way, the demands for expensive experimental measurements and reparations are reduced. Presented mathematical models, calculation, measurement and visual 3D distribution of electric and magnetic field is a realistic assumption for research of interactions between electromagnetic fields and human bodies on the macroscopic and static level, with finding the certain optimization criteria in order to develop a new technology and process solutions and design methods. The research results are important from the scientific point of view but also they are important because of possibility for their practical application.

2. Background theory of models

Low frequency electromagnetic field around the substations is quasistatic. It has a conservative component of the electric field caused by charges and eddy component of the magnetic field caused by currents. The calculation of electric and magnetic fields at the points located far from the source (charges and currents) is obtained with thin-wired approximation and by representation of conductors with linear segments with current distribution calculation, and based on that, in the selected point of the space located in the air or in any ground layer the calculation of potentials is also obtained. The potentials and electromagnetic fields are firstly expressed in the form of components of the vector potentials, as a functions of the current in each segment of conductors network. The currents in the conductors segments are determined based on the voltage drop between a pair of network points, based on their own impedance. The ground influence on the conductor potential was taken into account by using a method of mirrors. The phasor of the electric potential at some point in the space is obtained by applying the superposition theorem, as a finite sum of potentials of elementary, time-varying charges on the surface of the conductor. The total value is represented as the integral of electrical potentials caused by charges density, which is located in the point given by a positional vector that is located on all thin-wired parts, including original conductors and their images, respecting land-air discontinuity, and given by the following integral equation:

$$\dot{\varphi} = \frac{1}{4\pi\epsilon} \int_{\Gamma'} \frac{\rho(r')dl'}{|r-r'|} + \frac{1}{4\pi\epsilon} \int_{\Gamma''} \frac{\rho(r'')dl''}{|r-r''|} \quad (1)$$

It is necessary to discretize the equation by discretizing the field of the source with unknown distribution, for example, density of line charge by using appropriate combination

of N linear, independent fundamental functions. Then, the discretization of conductor length on N segments and the discretization of observed points will be connected. We obtain the conductor division into segments of finite lengths and approximate the unknown distribution of the field with appropriate number of fundamental functions by following expression:

$$\dot{\rho} = \sum_{j=1}^N a_j' \rho_j' \text{ if it is } \dot{\rho} = \sum_{j=1}^N a_j'' \rho_j'' \quad (2)$$

where: ρ_j' is a fundamental function on segment j of the original conductor and ρ_j'' a fundamental function on segment j of the conductor in the mirror. Selected constant $a_j' = 1$ in the segment j is valid for that segment, while in other segments is 0. In that case, the potential equation can be represented as:

$$\varphi(\dot{r}) = \frac{1}{4\pi\epsilon} \sum_{j=1}^N \int_{\Delta_j'} \frac{a_j' \rho_j'(r) dl'}{|r-r'|} + \frac{1}{4\pi\epsilon} \sum_{j=1}^N \int_{\Delta_j''} \frac{a_j'' \rho_j''(r'') dl''}{|r-r''|} \quad (3)$$

In order to solve the expression, N observed points which are corresponding to energized conductors are selected in the space of known potential. It establishes a system of N equations with N unknown values, which is defined in the matrix form as:

$$[\varphi] = [M][\rho] \quad (4)$$

where the elements $M_{i,j}$ of matrix system $[M]$ represent the potential of the observed point i , located on the conductor surface with current density ρ_j . Gauss-Seidel's method is used for solving this matrix equation. When the approximation of current density on the conductors is obtained, the vector-phasor of conservative component of the electric field intensity, at the observed point with position vector r , can be determined by using the equation:

$$E(\dot{r}) = \frac{1}{4\pi\epsilon} \sum_{j=1}^N \int_{\Delta_j'} \frac{a_j' \rho_j'(r)(r-r') dl'}{|r-r'|^3} + \frac{1}{4\pi\epsilon} \sum_{j=1}^N \int_{\Delta_j''} \frac{a_j'' \rho_j''(r)(r-r'') dl''}{|r-r''|^3} \quad (5)$$

In the 3D calculation, the vector of the electric field is in each point elliptically polarized, i.e. the peak of the vector E describes an ellipse in time. Each of three components have a different size and phase shift:

$$\begin{aligned} E_x(t) &= E_{x\max} \cos(\omega t + \varphi) \\ E_y(t) &= E_{y\max} \cos(\omega t + \varphi) \\ E_z(t) &= E_{z\max} \cos(\omega t + \varphi) \end{aligned} \quad (6)$$

The vector of the electric field is elliptically polarized and rotates in time. The effective value (RMS) of the absolute value of the electric field is used for the electric field presentation according to:

$$E_{\text{ef}} = \sqrt{\frac{1}{T} \int_0^T (E_x^2(t) + E_y^2(t) + E_z^2(t)) dt} \quad (7)$$

Generally, the size of the magnetic field or magnetic flux density can be decomposed into three components that are perpendicular to each other in the space. Each of these components is time-dependent:

$$\vec{B}(t) = \vec{B}_x(t) + \vec{B}_y(t) + \vec{B}_z(t) \quad (8)$$

The largest number of magnetic fields, around power facilities, are generated by basic harmonic with dominant frequency of 50 Hz, and have a negligible contribution of higher harmonics. The components are time-dependent by sinus dependence:

$$\vec{B}(t) = \sqrt{2}B_x \sin(\omega t + \varphi_x) \vec{i} + \sqrt{2}B_y \sin(\omega t + \varphi_y) \vec{j} + \sqrt{2}B_z \sin(\omega t + \varphi_z) \vec{k} \quad (9)$$

The effective value of magnetic flux density is expressed mathematically:

$$B_{\text{ef}} = \sqrt{\frac{1}{T} \int_0^T [B(t)]^2 dt} = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (10)$$

where are:
 t - time variable
 T - period of time change
 B_x, B_y, B_z - effective values of time-variable orthogonal components B

The absolute value of magnetic field intensity is determined by the equation:

$$|\vec{H}| = \frac{I}{2\pi r} \quad (11)$$

where are:
 I - electric current intensity through conductor
 r - distance from the conductor

Three-phase AC system of 50 Hz generates elliptically polarized fields. The field vector rotates around a fixed ellipse whose radiuses of semi-axis represent the peak values. In the case of different frequencies existence, contribution to the field of individual segments are added together and integrated in time. The degree of polarization is defined by the ratio of the magnetic flux densities values between the, so-called, minor and major ellipse:

$$\frac{B_{\text{min}}}{B_{\text{max}}} \quad (12)$$

This axial ratio can take values between 0 (the magnetic field is linearly polarized) and 1 (the magnetic field is circularly polarized). For a particular value of frequency (50 Hz), the effective value of the magnetic induction can also be determined by the effective values of the magnetic flux density components along the two axis of the polarized magnetic field:

$$B_{\text{ef}} = \sqrt{B_{\text{max}}^2 + B_{\text{min}}^2} \quad (13)$$

Calculation of magnetic flux density distribution is performed based on the application of Biot-Savart's law for the induction of straight streamline of finite length and the law of superposition. Magnetic flux density at any point in the space can be calculated by superposition of contributions of each conductor in which current flows. The spatial position of conductor segments, their currents and phase angles represent the input sizes for the calculation of magnetic flux density at the desired points in the space. The direction of magnetic flux density vector is determined by the unit vector in cylindrical coordinate system related to the observed segment. As the position of segments is different in the space and so the directions of the induction vectors, it is necessary to decompose a vector of magnetic flux density to the components in the direction of each coordinate axis of the

global system that is not tied to a particular segment. The direction of magnetic flux density vector is perpendicular to the boundary plane and defined as:

$$d\vec{B}(t) = \frac{\mu_0}{4\pi} \frac{d\vec{l} \times \vec{r}}{r^3} I(t) \quad (14)$$

Sizes dB and I are generally time-dependent and are transformed into complex values for easier calculation. Suppose that the i -th segment of length l is located at the origin of the coordinate system, parallel to the x -axis, its contribution to the field at point $P(x, y, z)$ is:

$$\vec{B}_1(t) = \frac{\mu_0}{4\pi r} I_i(t) \left[\frac{L_i - x_p}{\sqrt{(L_i - x_p)^2 + r^2}} + \frac{x_p}{\sqrt{x_p^2 + r^2}} \right] \quad (15)$$

Vector components are:

$$\begin{aligned} B_{xi}(t) &= 0 \\ B_{yi}(t) &= -\frac{z_p}{\sqrt{y_p^2 + z_p^2}} |\vec{B}_1(t)| \\ B_{zi}(t) &= \frac{y_p}{\sqrt{y_p^2 + z_p^2}} |\vec{B}_1(t)| \end{aligned} \quad (16)$$

This method divides each conductor into segments whose number is determined in advance. When working with computer programs for the electric and magnetic fields calculating, the number of segments is determined by the user. If the conductors have overhangs (for example transmission lines), the programs usually simulate this situation with equivalent parable. Sufficiently high accuracy is usually achieved by selecting 10 - 20 segments. For verification, the number of segments can be increased so the accuracy of that calculation is higher than in cases with 2, 3 or 4 segments. The difference between the actual situation and model depends on the division of conductors to a finite number of segments. When calculating the field intensity, the coordinates of the considered point are transforming to the local coordinate system of a given segment. The calculation gives the contribution of a given segment to the field that is transforming back to the original coordinate system. Vector sum of field contributions gives the total amount of magnetic flux density vector, which is caused by currents of N segments and obtained by adding the contributions of all segments:

$$B(t) = \sqrt{(\sum_{i=1}^N B_{x,i}(t))^2 + (\sum_{i=1}^N B_{y,i}(t))^2 + (\sum_{i=1}^N B_{z,i}(t))^2} \quad (17)$$

where $B_{x,i}(t)$, $B_{y,i}(t)$ and $B_{z,i}(t)$ are the components of magnetic flux density of i -th segment.

For magnetic field presentation the effective value (RMS) of magnetic field density is used, according to:

$$B_{ef} = \sqrt{\frac{1}{T} \int_0^T (B_x^2(t) + B_y^2(t) + B_z^2(t)) dt} \quad (18)$$

3. Calculation of low frequency magnetic and electric fields of transformer station

The application of computer program EFC-400LF for calculation of the electric and magnetic fields is presented on the example of typical compact, concrete transformer station KBTS 10(20)/0.4 kV, 630 kVA. Transformer station equipment consists of:

- switchable power transformer, nominal ratio 10(20)/0.4 kV, rated power up to 630 (kVA), frequency 50 (Hz), Dyn5, shortcut voltage 4 %, voltage regulation $\pm 2 \times 2,5$ %,
- medium-voltage (MV) distribution switchgear, insulated by SF₆ gas, completely shielded and protected from dangerous contact voltage, " Ring Main Unit " (RMU) type CCF 12/24 (kV), 400 (A), " SafeRing " with 3 fields, transformer and 2 conductive fields. Conductive fields are equipped with a three pole switch disconnecter with the earthing switch, rated voltage of 24 (kV), rated current 400 (A), with auxiliary switch 2NO + 2 NC. Transformer field is equipped with a three pole switch disconnecter 24 (kV), 200 (A), 16 (kA), fuses 24 (kV), 50 (A),
- low-voltage (LV) distribution switchgear, which consists of three fields, namely: load field and two distribution fields. Rated current is 1250 (A), shortcut withstand current 25 (kA), peak withstand current 52.5 (kA), the degree of protection is IP 21. In the load field the main three-pole switch disconnecter is located, type OETL 1250, 1250 (A), 690 (V), " ABB ",
- the connecting line between the MV side of transformer and the field of MV switchgear, that is derived from three single-core cables, XLP insulated, of rated voltage 20 (kV), unit designation of the cable is 3x(XHE 49-A 1x50/16 mm²) or 3x(XHE 49-A 1x150/25 mm²), allowable current load is 210 (A). The space between clamps for fixing the cable is 600 (mm) maximum. Cables are at a distance of 1.00 (m), wrapped with plastic tapes and make a bundle,
- the connecting line between the LV side of transformer and LV distribution field that is derived from single-core cables, insulated with PVC which is resistant to temperatures up to 378.15 K/105 °C, rated voltage up to 1 (kV), unit designation of cable for phase conductors is 3x(2 x P/MT1 x 240mm² 1 kV) and for the neutral conductor 1x(P/MT1 x 240mm² 1 kV).

Since the main electrical equipment (MV and LV switchgears) is tested and certified in accordance with the applicable IEC standards (IEC439 for LV switchgears and IEC298 for MV switchgears), and considering that power transformer satisfies the requirements of standard IEC76, it can be concluded that listed technical parameters are consequently verified. Calculations of the magnetic and electric field were carried out by using a computer program EFC-400LF according to DIN VDE0848-1, which allows the simulation in 3D space. The corresponding MV 12 (kV) distribution switchgear is modeled with a maximum load current I_m of 36.4 (A) at rated voltage of transformer secondary 0.4 (kV) and the maximum load current I_m of 909 (A). The load value of 909 (A) rarely occurs, but the calculations are carried out for the worst case scenario, so on the basis of this case the other cases can be determined as cases that meet safety standards. It follows that the maximum current load of the LV side of transformer stations is evenly divided into four outputs, 227 (A) each. Significant sources of electric field in transformer station are MV and LV buses and MV outlets of power transformer, while the MV and LV circuit equipment is surrounded by grounded housings, shields or cable screens and is a negligible source of the electric field due to its complete obscurance. Calculation of the electric field was performed inside and

outside the substation, with negligence of substation housing, due to the additional increase in safety with regard to the protection rules for electromagnetic fields. 2D and 3D views of the substation disposition in EFC-400LF are shown in Fig. 1, where the difference between reality and model depends of redistribution of conductors to a finite number of segments. Redistribution of substation conductors was performed on 635 segments, on resolution size $dx = dy = dz = 0.10$ (m). EFC-400LF program is able to solve a set of differential equations for the matrix with 16000×16000 elements (Methods: LU-decomposition or conjugate gradient). For given example calculation was done with a 261×261 matrix elements, which gives the values of electric and magnetic fields in the 68.121 points of the observed plane, surface 169 (m^2), with the resolution size $dx = dy = dz = 0.05$ (m) and matrix of 261×101 elements, which gives values of electric and magnetic fields in the 26.361 points of the observed plane, surface 65 (m^2), the resolution size $dx = dy = dz = 0.05$ (m). Visual view of the obtained results of magnetic flux density and electric field intensity was made in the computer program "Matlab", using "Runal.B" and "Runal.E" while subroutines "Crtajgraf.B" and "Crtajgraf.E" serve to open, load and display the results of calculations of magnetic flux density and electric field intensity.

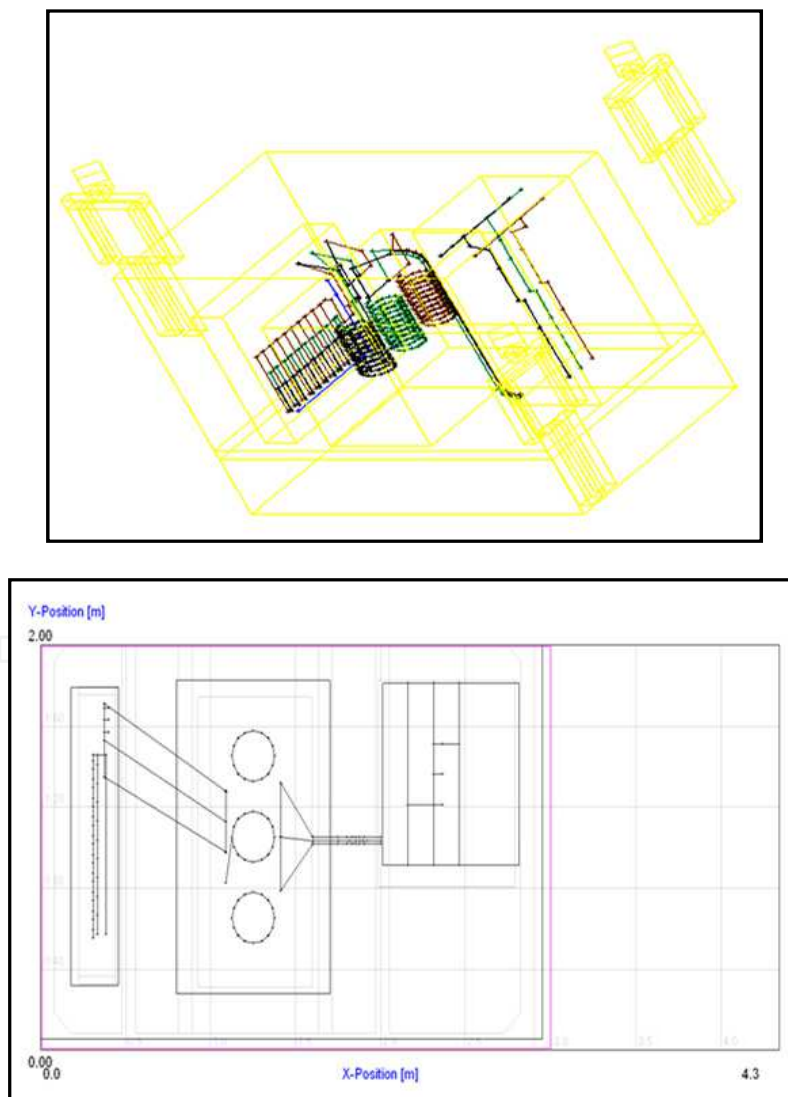


Fig. 1. 2D and 3D view of substation disposition in EFC-400.

The calculation of the electric and magnetic field was made:

- i. In XY plane of transformer station at $-5 \text{ (m)} \leq x \leq 8 \text{ (m)}$ and $-5 \text{ (m)} \leq y \leq 8 \text{ (m)}$
 - at a height $z = 1.75 \text{ (m)}$ from the ground. It is a plane with greatest values of electric and magnetic field outside the substation, in which a human head can be found,
- ii. In XZ plane of transformer station at $-5 \text{ (m)} \leq x \leq 8 \text{ (m)}$ and $0 \leq z \leq 5 \text{ (m)}$
 - for $y = -0.20 \text{ (m)}$, accordingly 0.20 (m) of the longitudinal south side of substation,
 - for $y = 2.10 \text{ (m)}$, accordingly 0.20 (m) of the longitudinal north side of substation,
- iii. In YZ plane of transformer station at $-5 \text{ (m)} \leq y \leq 8 \text{ (m)}$ and $0 \leq z \leq 5 \text{ (m)}$
 - for $x = -0.20 \text{ (m)}$, accordingly 0.20 (m) of the eastern side of substation,
 - for $x = 3.10 \text{ (m)}$, accordingly 0.20 (m) of the western side of substation.

3.1 Distribution calculation of electric and magnetic field in xy plane for $z = 1.75 \text{ (m)}$ ($-5 \text{ (m)} \leq x \leq 8 \text{ (m)}$, $-5 \text{ (m)} \leq y \leq 8 \text{ (m)}$)

The values of magnetic flux density and electric field intensity are observed in the areas I, II, III and IV of XY plane, at distances 0.20 (m) , 1.00 (m) , 1.50 (m) and 2.00 (m) from the walls of the substation, at height $z = 1.75 \text{ (m)}$ from the ground level, and shown in Fig. 2 and 4.

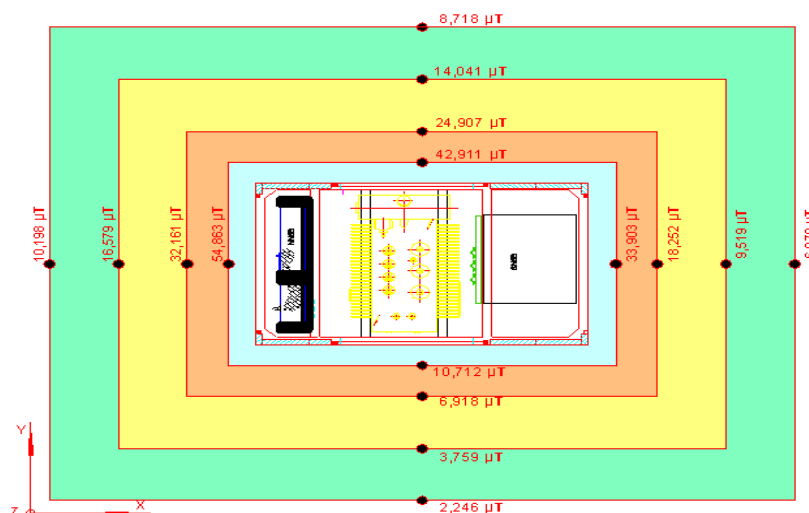


Fig. 2. The maximum magnetic flux density values calculated for areas I, II, III and IV at XY plane of observation ($z = 1.75 \text{ m}$)

The maximum values of magnetic flux density in area I are in the range from $10.712 \text{ (}\mu\text{T)}$ to $54.863 \text{ (}\mu\text{T)}$, in area II from $6.918 \text{ (}\mu\text{T)}$ to $32.161 \text{ (}\mu\text{T)}$, in area III from $3.759 \text{ (}\mu\text{T)}$ to $16.579 \text{ (}\mu\text{T)}$, and in area IV from $2.246 \text{ (}\mu\text{T)}$ to $10.198 \text{ (}\mu\text{T)}$. Densities of magnetic flows inside the substation reach their maximum values at the intersection of XY plane with the primary transformer outlets, achieved by cable connections to buses of MV and LV switchgears, which, because of substation construction, can not be avoided, and are in the range from 0.05 (mT) to 6.40 (mT) , while outside the housing they decrease to the values from $100 \text{ (}\mu\text{T)}$ to $50 \text{ (}\mu\text{T)}$. Calculation results show that the value of magnetic flux density outside the substations do not exceed $54.863 \text{ (}\mu\text{T)}$, in certain points of the area I, at a distance 0.20 (m) from the western cross side of the substation, at the level of transformer box. But, already at a distance from 0.50 (m) to 1.50 (m) from the substation the values decrease to level from

32.161 (μT) to 2.246 (μT). Respecting the fact that magnetic flux density is proportional to the load force, and taking into account the usual loads of transformer station in normal operation of approximately 50 % of rated power, the maximum amount of magnetic flux density will not exceed the prescribed limit for the area of increased sensitivity. 2D and 3D distribution of magnetic flux density in the continuous distribution is given in Fig. 3 by using isolines. The maximum values of the electric field in area I are in the range from 0.052 (kV/m) to 0.352 (kV/m), in area II from 0.060 (kV/m) to 0.177 (kV/m), in area III from 0.023 (kV/m) to 0.081 (kV/m), and in area IV from 0.019 (kV/m) to 0.061 (kV/m). The maximum values of the electric field inside the substation are visible at the intersection of XY plane with a MV transformer outlets and cable connections of MV switchgear with the primary side of power transformer, and are in the range from 415.302 (kV/m) to 452.363 (kV/m), and with transformer box in the range from 2.194 (kV/m) to 16.912 (kV/m), while outside the housing they falling to the values between 1.00 (kV/m) and 0.50 (kV/m). 2D and 3D view of electric field distribution in the continuous distribution is shown in Fig. 5.

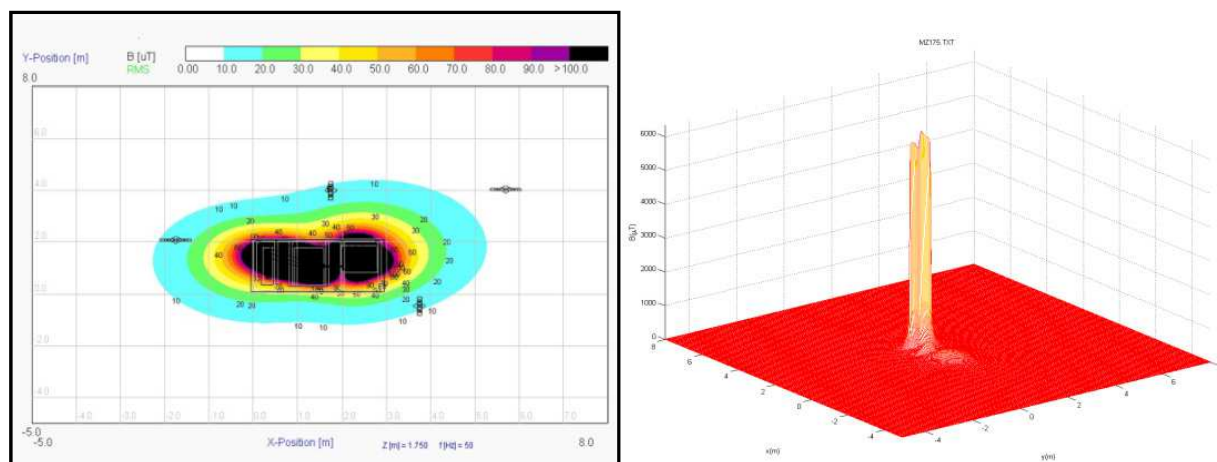


Fig. 3. Continuous distribution of magnetic flux density at XY plane ($z = 1.75 \text{ m}$)

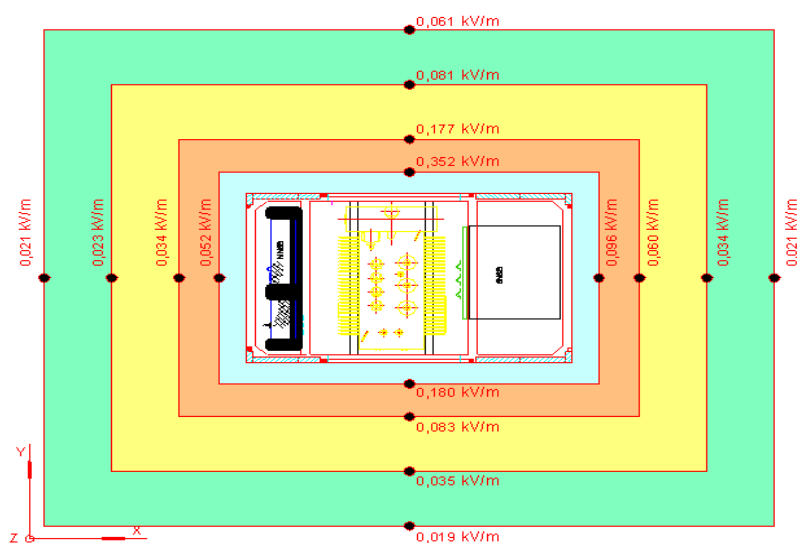


Fig. 4. The maximum electric field values calculated for areas I, II, III and IV at XY plane of observation ($z = 1.75 \text{ m}$)

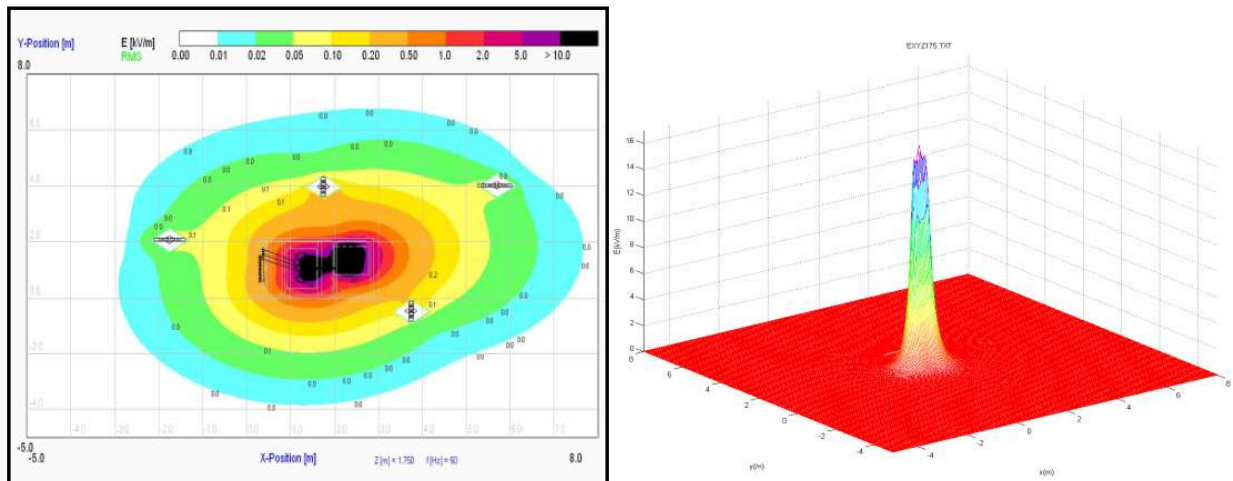


Fig. 5. Continuous distribution of electric field at XY plane (z = 1.75 m)

3.2 Distribution calculation of electric and magnetic field in xz plane for y = - 0.20 (m) (-5 (m) ≤ x ≤ 8 (m), 0 ≤ z ≤ 5 (m))

At a distance 0.20 (m) from the longitudinal south side of the substation (y = - 0.20 m), for observed XZ plane (-5 (m) ≤ x ≤ 8 (m), 0 ≤ z ≤ 5 (m)), the value of the magnetic flux density at z = 0.50 ÷ 1.75 (m) across the LV switchgear, is in the range from 14.051 (μT) to 10.686 (μT), while across the MV distribution switchgear the value is 8.111 (μT). The values of magnetic flux density across the power transformer are from 10.095 (μT) to 12.539 (μT) at z = 1.00 ÷ 1.50 (m). The highest values of the electric field are from 0.180 (kV/m) to 0.186 (kV/m) across the power transformer at z = 1.50 ÷ 1.75 (m). 2D and 3D view of magnetic flux density and electric field distribution in the continuous distribution is shown in Fig. 6 and 7.

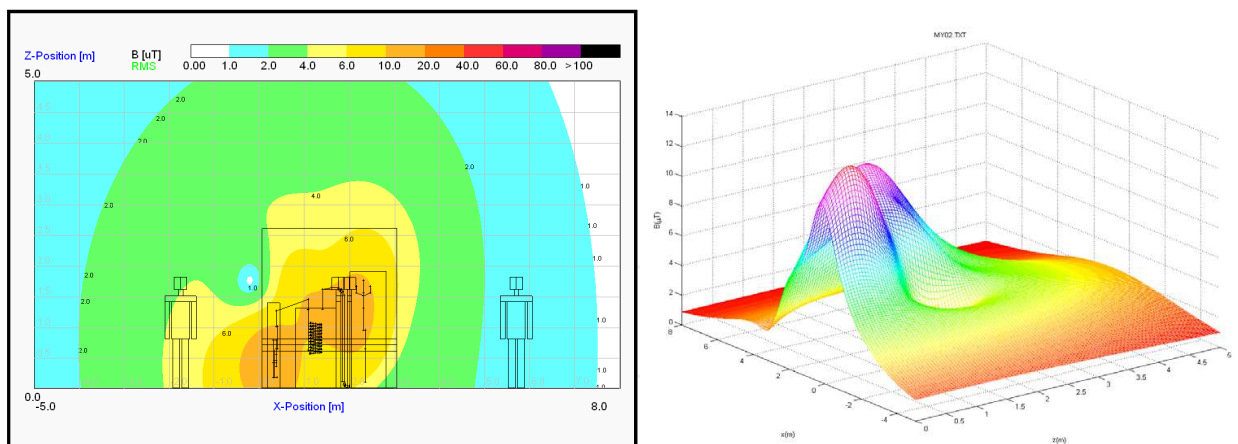


Fig. 6. Continuous distribution of magnetic flux density at XZ plane (y = - 0.20 m)

3.3 Distribution calculation of electric and magnetic field in xz plane for y = 2.10 (m) (-5 (m) ≤ x ≤ 8 (m), 0 ≤ z ≤ 5 (m))

At a distance 0.20 (m) from the longitudinal north side of the substation (y = 2.10 m), for observed XZ plane (-5 (m) ≤ x ≤ 8 (m), 0 ≤ z ≤ 5 (m)), the value of magnetic flux density is in the range from 101.102 (μT) to 145.202 (μT) at z = 1.00 (m) across the LV distribution switchgear, from 51.521 (μT) to 80.082 (μT) at z = 1.00 ÷ 1.75 (m) across the MV distribution

switchgear, respectively from 35.197 (μT) to 74.145 (μT) across the power transformer. The highest values of the electric field are in the range from 0.500 (kV/m) to 0.795 (kV/m) at $z = 1.00 \div 1.75$ (m) across the power transformer and implemented MV and LV cable connections. 2D and 3D view of magnetic flux density and electric field distribution in the continuous distribution is shown in Fig. 8 and 9.

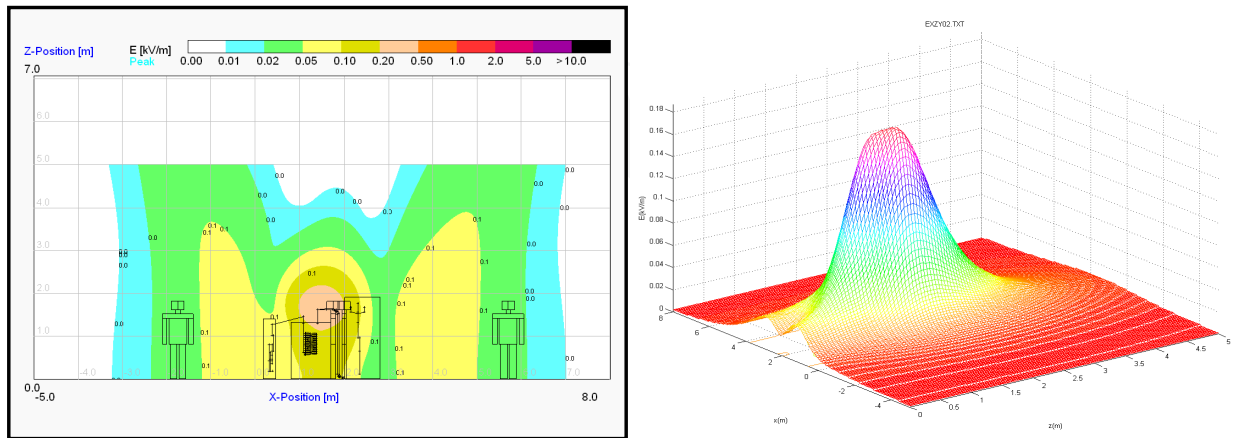


Fig. 7. Continuous distribution of electric field at XZ plane ($y = -0.20$ m)

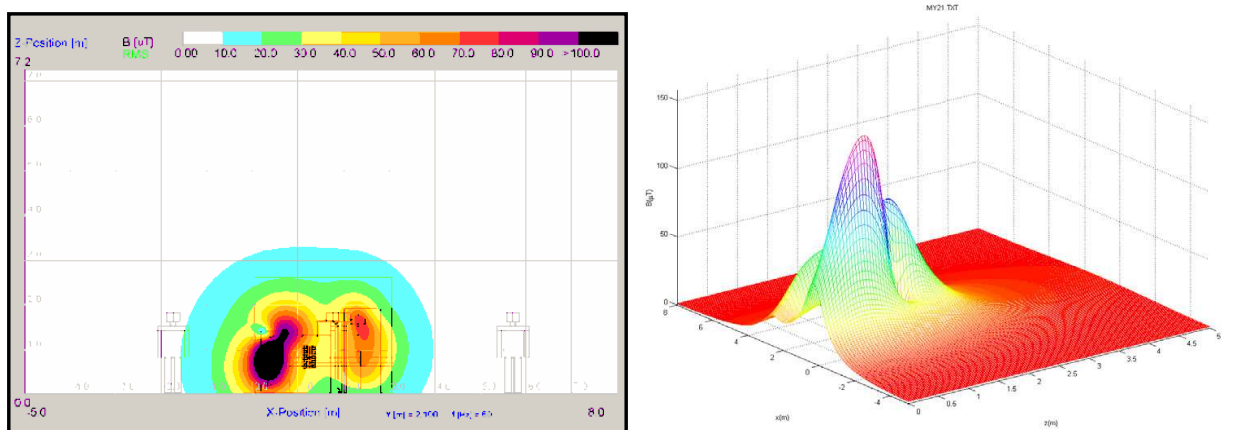


Fig. 8. Continuous distribution of magnetic flux density at XZ plane ($y = 2.10$ m)

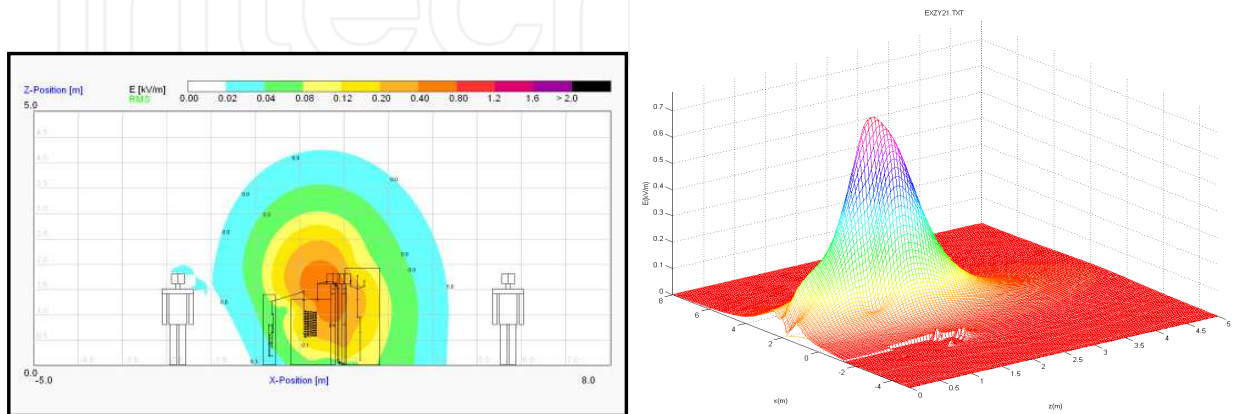


Fig. 9. Continuous distribution of electric field at XZ plane ($y = 2.10$ m)

3.4 Distribution calculation of electric and magnetic field in yz plane for $x = -0.20$ (m) (-5 (m) $\leq y \leq 8$ (m), $0 \leq z \leq 5$ (m))

At a distance 0.20 (m) of the western side of substation ($x = -0.20$ m), for observed YZ plane (-5 (m) $\leq y \leq 8$ (m), $0 \leq z \leq 5$ (m)), the value of magnetic flux density is in the range from 96.238 (μ T) to 131.326 (μ T), at $z = 0.20 \div 0.50$ (m) across the LV distribution switchgear, while at $z = 1.00 \div 1.75$ (m) the value decreases to 54.843 (μ T). The highest values of the electric field are in the range from 0.049 (kV/m) to 0.050 (kV/m) at $z = 1.75$ (m) across the LV distribution switchgear, and implemented cable connections with LV power transformer outlets. 2D and 3D view of magnetic flux density and electric field distribution in the continuous distribution is shown in Fig. 10 and 11.

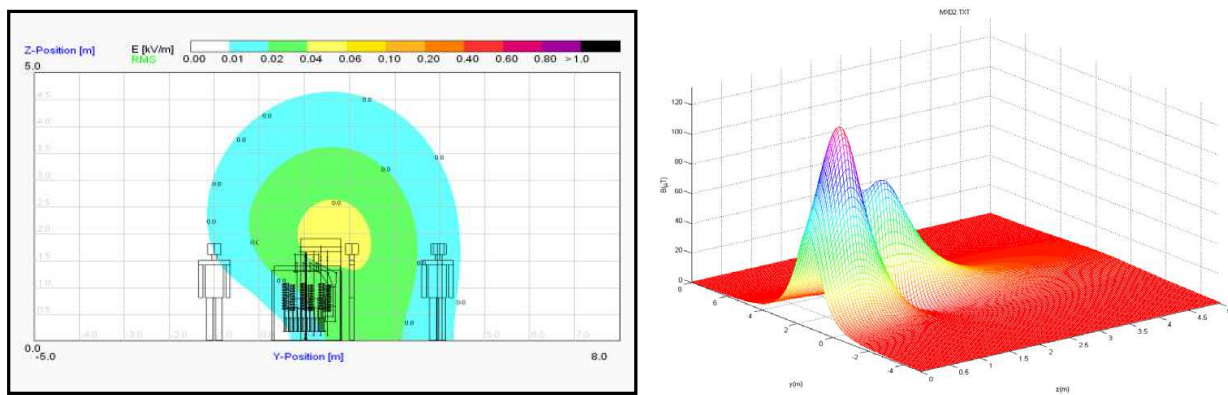


Fig. 10. Continuous distribution of magnetic flux density at YZ plane ($x = -0.20$ m)

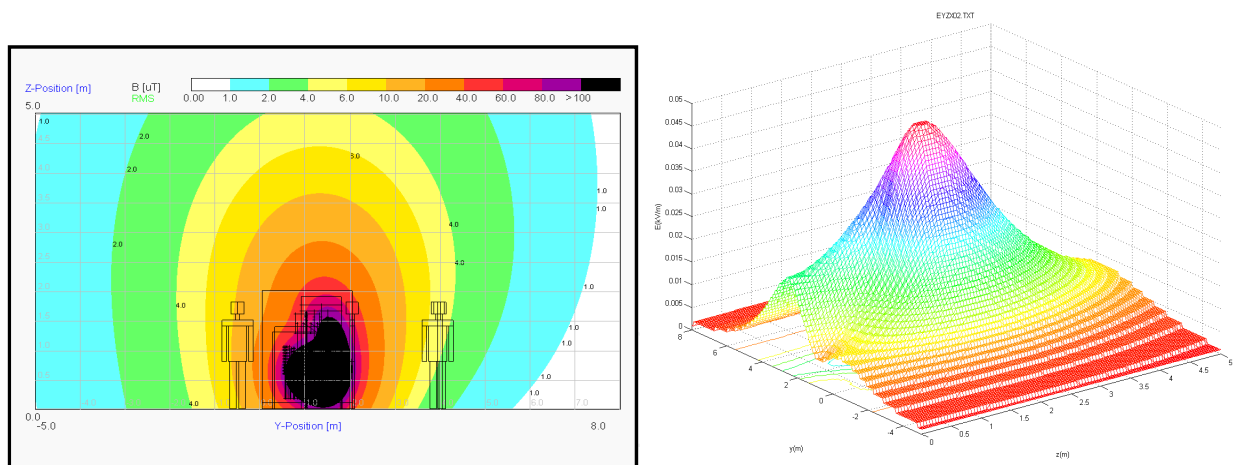


Fig. 11. Continuous distribution of electric field at YZ plane ($x = -0.20$ m)

3.5 Distribution calculation of electric and magnetic field in yz plane for $x = 3.10$ (m) (-5 (m) $\leq y \leq 8$ (m), $0 \leq z \leq 5$ (m))

At a distance 0.20 (m) from the western side of substation ($x = 3.10$ m), for observed YZ plane (-5 (m) $\leq y \leq 8$ (m), $0 \leq z \leq 5$ (m)), the value of magnetic flux density is in the range from 40.194 (μ T) to 68.846 (μ T), at $z = 0.20 \div 1.00$ (m) across the MV distribution switchgear and connecting MV network cables, while at $z = 1.00 \div 2.00$ (m) toward the buses it falls to 27.954 (μ T). The highest values of the electric field are in the range from 0.083 (kV/m) to

0.097(kV/m), at $z = 1.00 \div 1.55$ (m) across the MV switchgear and implemented cable connections with MV power transformer outlets. 2D and 3D view of magnetic flux density and electric field distribution in the continuous distribution is shown in Fig. 12 and 13.

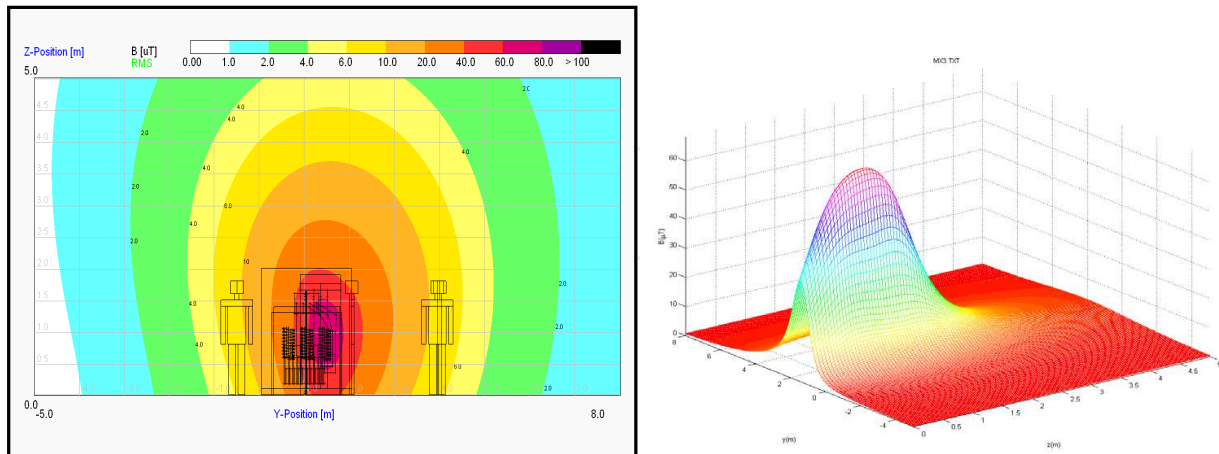


Fig. 12. Continuous distribution of magnetic flux density at YZ plane ($x = 3.10$ m)

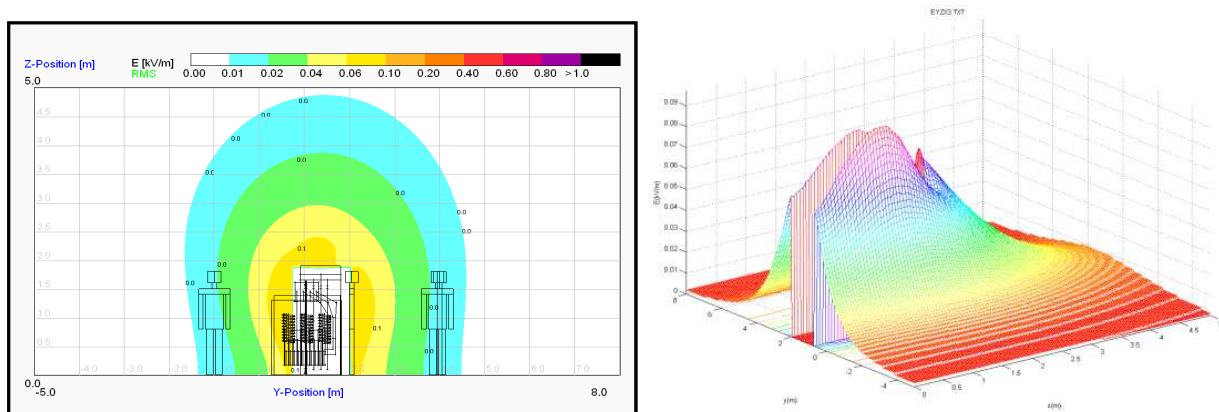


Fig. 13. Continuous distribution of electric field at YZ plane ($x = 3.10$ m)

In XY plane for $z = 1.75$ (m) and XZ plane for $y = -0.20$ (m) calculated values of magnetic flux density satisfy limited values for area of occupational exposure ($B_{\max} = 500$ (μT), $E_{\max} = 10$ (kV/m)) and area of increased sensitivity ($B_{\max} = 100$ (μT), $E_{\max} = 5$ (kV/m)) in accordance with ICNIRP (1998) International commission on non-ionizing radiation protection.

In XZ plane for $y = 2.10$ (m) and YZ plane for $x = -0.20$ (m) calculated values of magnetic flux density do not satisfy limited values according to ICNIRP. Based on the above, the conclusion can be, that for reduction of magnetic field, it is necessary implementing of high-permeability protection in the form of shielding of LV switchgear with metal plates of steel and aluminum, thickness from 1 (mm) to 5 (mm). The values of the electric field are less than the maximum allowed according to ICNIRP.

In YZ plane for $x = 3.10$ (m) calculated values of magnetic flux density satisfy limited values for area of occupational exposure, and for most part of the observed area at a height $z = 0.80 \div 1.00$ (m) do not satisfy limited values for area of increased sensitivity, but it is also very

unlikely that people will stay longer in this area. The values of the electric field are less than the maximum allowed according to ICNIRP.

4. Measurements of low frequency magnetic and electric fields of transformer station

Calculations of the values of low frequency electric and magnetic fields in electric power networks and facilities are usually limited by configurations, for which a fields sources can be quite simplified. Generally, when calculating, observing of all relevant emissions of individual supplements is carried out to be able to estimate their contribution to the resulting field. To calculate the electric field of electric power networks the voltage must be known, while magnetic fields are defined by currents. The phase voltage is generally constant, but the phase currents can vary within a wide area, depending of the load. Modern computer programs can calculate the distribution of the field of very complex power systems, and there is a need for confirmation of the results by measurements. When measuring the magnetic and electric fields it is necessary that the source of electromagnetic radiation and its environment in which measurements take place be precisely defined. The source of the field is each conductor flowed by current. Extremely dangerous are the sources which have winding conductors flowed by current (inductors, transformers). Shielding of such devices in ferromagnetic materials significantly reduces the field in their vicinity. The magnetic field can easily penetrate into buildings from external sources and therefore is considered as more dangerous than the electric field, which is usually attenuated by the first physical obstacle. Selection of points where the measurement will take place should be made based on assessment of the field intensity, or in the way that measuring have to be done in places where the largest values of electric and magnetic fields are expected. Measurement is necessary to be done in accordance with the regulations of the HRN IEC 61786-2001 - Measurement of low-frequency magnetic and electric field with regard to exposure of human beings - Spacial requirements for instrumants and guidance for measurements and the instructions given in ENV 50166 European recommendations (People exposure to electromagnetic radiation on the low frequencies). For measuring the magnetic and electric fields intensity a digital measuring instrument EFA-300 is used, which finds application in researches and environmental studies for assessment of the electric and magnetic fields of electric power transmission and distribution networks and facilities with appropriate equipment and devices. It is designed to provide a sophisticated tool for precise studies of low-frequency energy impacts for engineers, experts in the field of health, safety and other profiles. The best choice to measure the fields that have one frequency component is the broadband mode. Broadband measurement in the range from 5 (Hz) to 32 (kHz) is performing by using the built-in isotropic probes. In the broadband mode, large display allows simultaneous viewing of measurement results and frequencies. There is a possibility of adding option, so-called "plug-in" which will extend the measurements possibilities. Smaller, "sniffer" probe, has a radius of 3 (cm) while a larger, more sensitive probe, has a surface of 100 (cm²). The user selects between the measurement of the effective or peak value in dynamic range from 1 (nT) to 31.6 (mT) for magnetic fields and from 1 (V/m) to 100 (kV/m) for electric fields.

The construction of the instrument can cause the error in measuring in a number of ways:

- measuring probe and a source of electromagnetic field can be capacitively coupled, which causes the increased values of the field on the instrument up to 100 times higher than the actual values. Such phenomenon can be caused by the parasitic capacitance between the mass of the instrument and the Earth,
- problem of instrument frequency band. It happens that instrument is sensitive outside of the nominal frequency area or even has a higher sensitivity. Then the signal, which is not expected, because it is outside the measurement range, creates the appearance of large values of the measuring field,
- dispersion phenomena that occurs on the surface of the irradiated object. Due to the reflection of the secondary radiation caused by the induced currents, on the uneven surfaces of the irradiated object field is deformed. The problem is particularly expressed in the electric field due to perturbations in the vicinity of any conductive object, including humans. Be sure to measure the electric field using dielectric tripods and probes holders. During measuring of the magnetic field the problem is less expressed, because the field perturbation occurs only in the vicinity of ferromagnetic materials, and the presence of people in the measuring field (metrologist) has no effect on his perturbation.

Uncertainty in measuring of the electric and magnetic field intensity with these instruments is complex measuring. Uncertainty consists of two components:

- uncertainty of calibration of the instrument (u_{cal}) - establishing a relationship between the values of parameters shown by the instrument and the corresponding values realized by standards. It is expressed by calibration certificate (certificate of calibration),
- uncertainty of instrument digital indicator resolution (u_{rez}) - caused by the resolution (the largest number of decimal places) of image of the instrument digital pointer.

When assessing the overall uncertainty, some partial uncertainties are taken for the range at which the measurement was made, and the total measurement uncertainty is expressed by the equation:

$$U = \sqrt{u_{cal}^2 + u_{rez}^2}$$

4.1 Measuring results of magnetic and electric field (KBTS 10(20)/0.4 kV, 630 kVA)

During the measurement preparations, based on project documentation according to which the subject substation is constructed (KBTS 10(20)/0.4 kV, 630 kVA), a total number of 36 measuring points was selected, outside the substation, where the maximum level of electric and magnetic field was expected, as well as 7 measurement points inside the substation. At distances 0.50 (m), 1.00 (m) and 1.50 (m), outside the walls of substation, and heights 1.75 (m), 1.50 (m) and 1.00 (m) above the ground level, corresponding to the head, chest and lower human extremities, a 108 measurement points were located. Inside the substation, a measurement points were chosen in the vicinity of MV and LV switchgears, transformer and transformer outlets, as well as in the vicinity of the implemented cable connections to the MV and LV buses (Fig. 14).

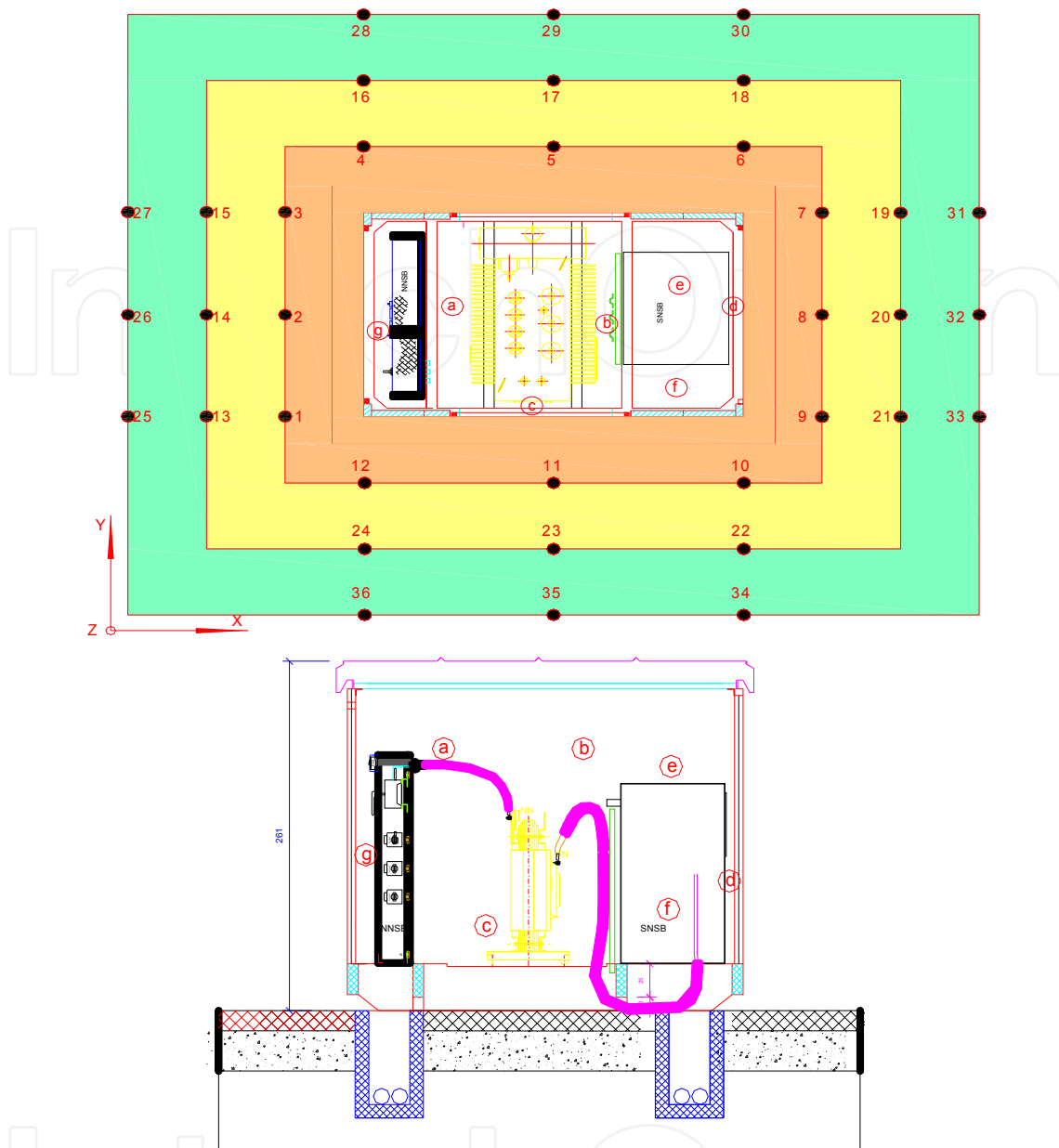


Fig. 14. Measurement points of electric and magnetic field outside and inside the substation

Measurement area was related to occupational exposure area and an area of increased sensitivity. The measurement was performed from 14:05 AM to 16:25 PM, at a temperature 20.9°C and relative humidity 28.4 % in the substation, and air temperature 22°C and relative humidity 27 % outside the building, with constant substation load. After locating the measurement points, measuring instrument EFA-300 Field Analyzers has been checked, climatic conditions were collected, and measurements and analysis of the magnetic and electric fields were performed in the substation that is connected to 50/60 Hz power transmission system and distribution network with devices that use such an energy (Fig. 15). The results of the measured values of magnetic flux density and electric field intensity at measurement points are related to the currently load of substation of 40 % of rated power, with measured current at LV side of 375 (A) and MV side load current of 15 (A). The highest values of magnetic flux density outside the substation at a heights 1.75 (m), 1.50 (m), and

1.00 (m) above ground level (Table 1) were measured at the lateral of the LV side of transformer station, at a distance of 0.50 (m), and were in the range from 57.699 (μT) to 24.892 (μT), while by increasing the distance from the substation to 1.00 (m) that values were falling to the range from 27.750 (μT) to 16.937 (μT), and at a distance of 1.50 (m) they dropped to 8.378 (μT). Magnetic flux density measured inside the substation reaches its maximum values at LV and MV transformer outlets, implemented cable connections with MV and LV switchgears, in the point "a" 172.150 (μT) and in the point "b" 195.100 (μT), while in the LV switchgear, at a height 1.00 (m) above the ground level, the maximum value of magnetic flux density at point "g" is 119.185 (μT). Measurement results prove the statement obtained by numerical calculations of substation magnetic flux density, under maximum load, that the value of magnetic flux density outside the lateral of LV side of substation exceed the value of 57.699 (μT), but even at a distance of 1.50 (m) from the substation they are falling to the value of 2.897 (μT). The measured values of magnetic flux density outside the substations satisfy the limited values for area of occupational exposure according to ICNIRP. The measurement results of the electric field intensity outside the substation walls, at distances from 0.50 (m) to 2.00 (m) do not exceed the value of 0.176 (kV/m), and are far less than the maximum allowed values for the area of increased sensitivity and the area of occupational exposure according to ICNIRP. The measured values of electric field inside the substation are at point "a" 8.120 (kV/m), point "b" 10.155 (kV/m), and point "c" 6.550 (kV/m) but outside the equipment housing they are falling to the values from 0.583 (kV/m) to 0.087 (kV/m), and thus satisfy limited values for the area of professional exposure.

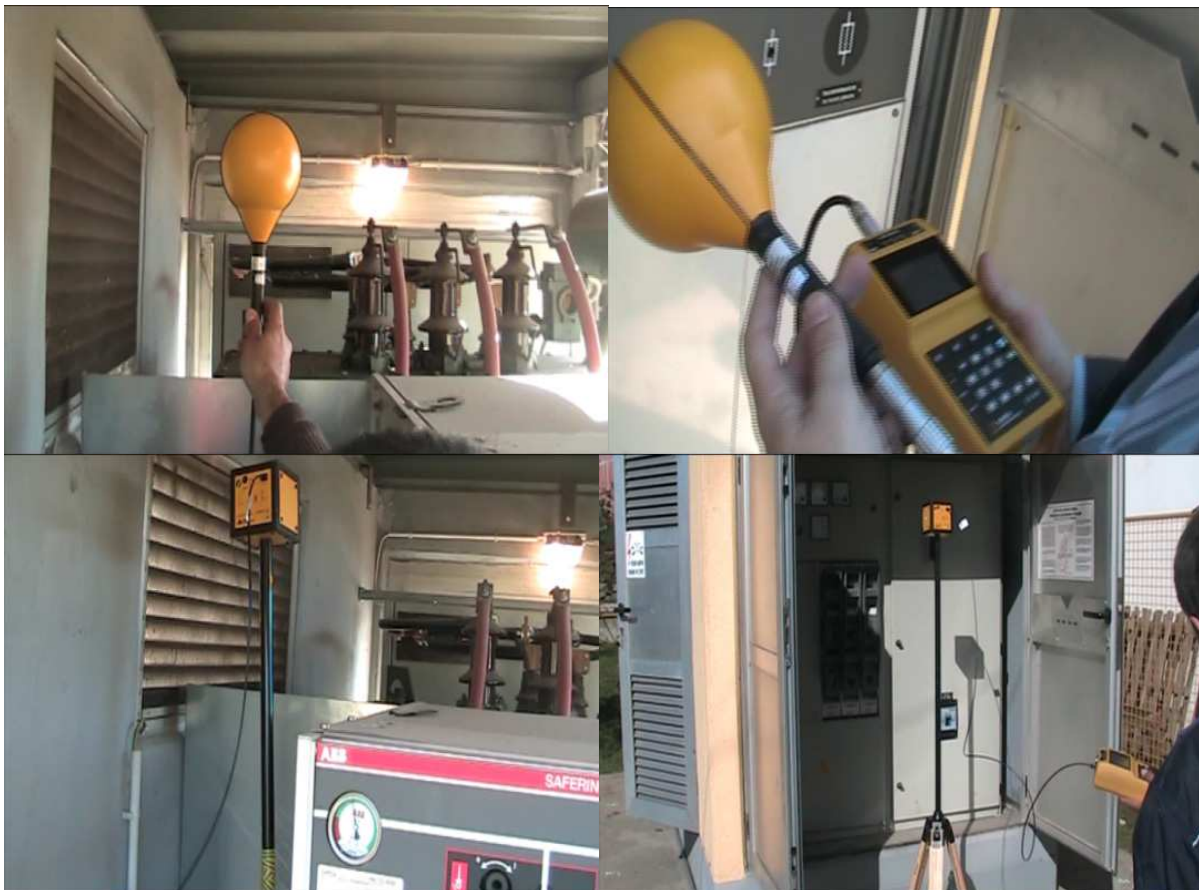


Fig. 15. The measurement of magnetic and electric fields in KBTS 10(20)/0.4 kV

4.2 Calculation results of magnetic and electric fields (KBTS 10(20)/0.4 kV, 630 kVA)

For a given substation loaded with 40 % of rated power, with measured current at LV side of 375 (A) and on the MV side of 15 (A), the numerical calculation of the magnetic field distribution was performed in the XY plane of the substation and at a heights 1.75 (m), 1.50 (m) and 1.00 (m) from the ground level. Calculation of the electric field distribution in the XY plane of the substation, at $-5 \text{ (m)} \leq x \leq 8 \text{ (m)}$ and $-5 \text{ (m)} \leq y \leq 8 \text{ (m)}$, at a height $z = 1.75 \text{ (m)}$ from the ground level is identical to the calculation of the electric field outside the walls and inside the substation at full load, because the electric field depends on the voltage which does not change its value at any substation load. Calculated values of magnetic flux density satisfy limited values for area of occupational exposure ($B_{\max} = 500 \text{ (}\mu\text{T)}$, $E_{\max} = 10 \text{ (kV/m)}$) and area of increased sensitivity ($B_{\max} = 100 \text{ (}\mu\text{T)}$, $E_{\max} = 5 \text{ (kV/m)}$) in accordance with ICNIRP (1998) International commission on non-ionizing radiation protection. The obtained calculation results are presented in different variants of graphical formats that describe 2D and 3D continuous distribution of magnetic flux density (Fig. 16 to 18).

4.2.1 Calculation results of magnetic field distribution in xy plane for $z = 1.75 \text{ (m)}$ ($-5 \text{ (m)} \leq x \leq 8 \text{ (m)}$ and $-5 \text{ (m)} \leq y \leq 8 \text{ (m)}$)

The values of magnetic flux density for $z = 1.75 \text{ (m)}$, at a distance of 0.50 (m) from the substation sites are in the range from 4.932 (μT) to 18.240 (μT), at a distance of 1.00 (m) are in the range from 3.125 (μT) to 14.355 (μT), and at a distance of 1.50 (m) are in the range from 3.041 (μT) to 10.634 (μT). Magnetic flux density inside the substation reaches its maximum values at the intersection of XY plane with the primary transformer outlets, implemented cable connections to MV and LV switchgears and is in the range from 0.150 (mT) to 0.366 (mT). Calculation results show that the values of magnetic flux density outside the substation do not exceed 22.433 (μT) in certain points at a distance of 0.20 (m) from the northern transversal side of the substation, in the level of transformer box. Already, at a distance from 0.50 (m) to 2.00 (m) from the substation they are decreasing to the value from 18.240 (μT) to 7.810 (μT).

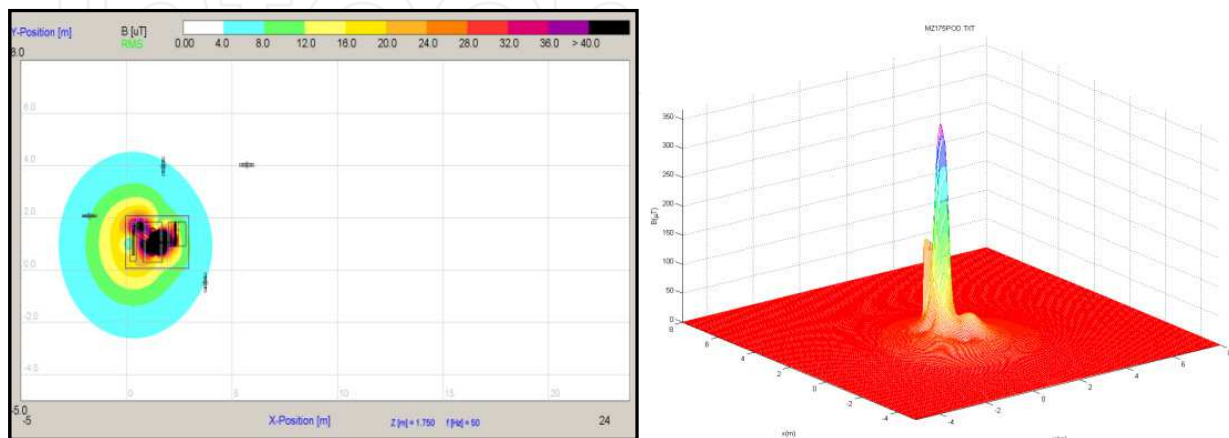


Fig. 16. Continuous distribution of magnetic flux density at XY plane ($z = 1.75 \text{ m}$)

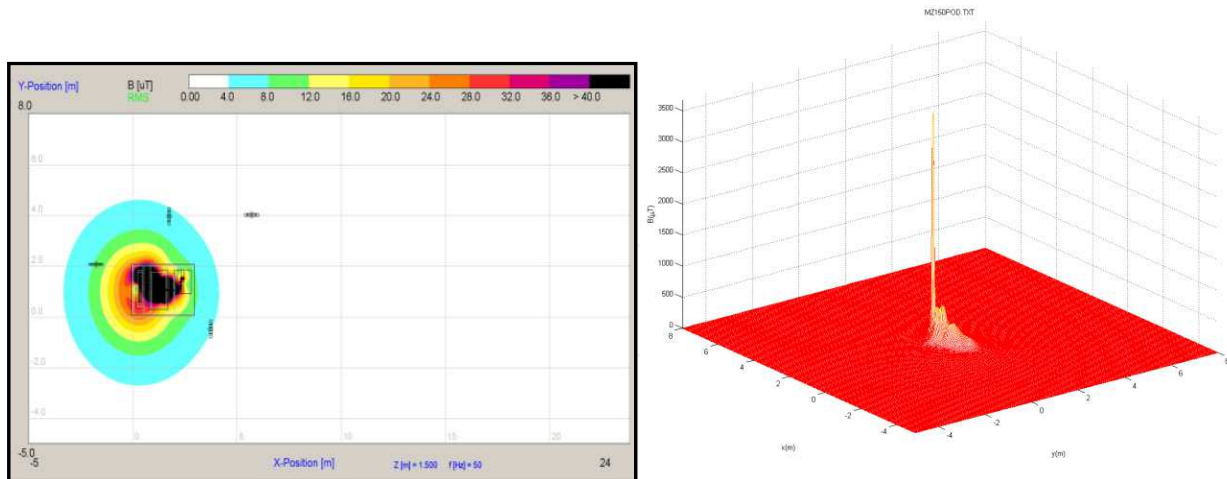


Fig. 17. Continuous distribution of magnetic flux density at XY plane ($z = 1.50$ m)

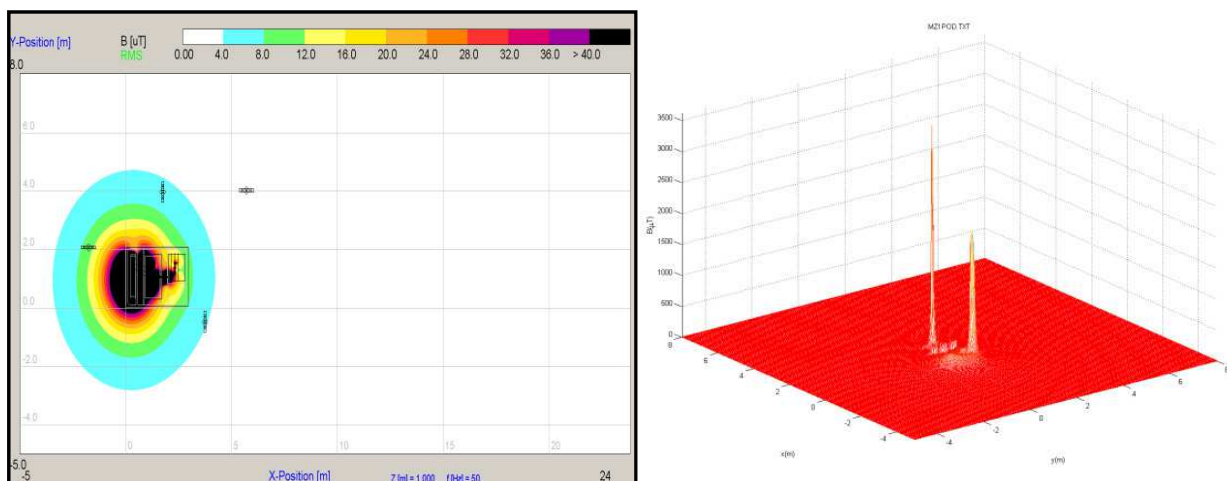


Fig. 18. Continuous distribution of magnetic flux density at XY plane ($z = 1.00$ m)

4.2.2 Calculation results of magnetic field distribution in xy plane for $z = 1.50$ (m) (-5 (m) $\leq x \leq 8$ (m) and -5 (m) $\leq y \leq 8$ (m))

The values of magnetic flux density for $z = 1.50$ (m), at a distance of 0.50 (m) from the substation sites, are in the range from 5.299 (μT) to 26.518 (μT), at a distance of 1.00 (m) are in the range from 4.032 (μT) to 18.876 (μT) and at a distance of 1.50 (m) are in the range from 3.169 (μT) to 12.672 (μT). Magnetic flux density inside the substation reaches its maximum value at the intersection of XY plane with the primary transformer outlets, implemented cable connections with MV switchgear and the block of MV buses, and is in the range from 1.067 (mT) to 3.671 (mT). Calculation results show that the value of magnetic flux density outside the substation does not exceed 33.461 (μT) in certain areas points, at a distance of 0.20 (m) from the western lateral side of the substation, in the level of LV switchgear. Already, at a distance from 0.50 (m) to 2.00 (m) from the substation it falls to the value from 26.518 (μT) to 8.706 (μT).

4.2.3 Calculation results of magnetic field distribution in xy plane for z = 1.00 (m) (-5 (m) ≤ x ≤ 8 (m) and -5 (m) ≤ y ≤ 8 (m))

The values of magnetic flux density for z = 1.00 (m), at a distance of 0.50 (m) from the substation sites are in the range from 5.742 (μT) to 60.964 (μT), at a distance of 1.00 (m) are in the range from 4.293 (μT) to 29.109 (μT) and at a distance of 1.50 (m) are in the range from 3.333 (μT) to 16.367 (μT). Magnetic flux density inside the substation reaches its maximum value at the intersection of XY plane with the primary transformer outlets, implemented cable connections with MV switchgear, where is in the range from 1.184 (mT) to 3.610 (mT), and at the LV cable outlets and LV busbar connections, where is in the range from 1.048 (mT) to 2.015 (mT), while outside of the equipment housing decreases to the value from 100 (μT) to 50 (μT).

4.3 Comparison of calculation results and measurements of low frequency magnetic and electric fields (KBTS 10 (20)/0.4 kV, 630 kVA)

If we want to make a comparison of calculation results and measurements we will note certain differences. By calculation a distribution of magnetic and electric fields is obtained in the XY, XZ, YZ planes of the substation, while measuring only give distribution of magnetic and electric fields in XY plane at a height 1.75 (m), 1.50 (m) and 1.00 (m) from the ground level. From above, follows the importance of calculation for determining the levels of emitted magnetic and electric fields, caused by the substation. It is also important to notice the importance of projection of diagram parts that connects the points at which the magnetic flux density or electric field intensity are approximated. In this way, this ensures that in any case, human bodies will not lead to a situation that they are exposed to the values of magnetic and electric fields that exceed the limits prescribed by the Regulations on Non-Ionising Radiation. In addition, it is interesting to observe where can be terminate the consideration of substation as a significant source of magnetic and electric fields, because this releases substation from the prescribed periodic measurements. From a comparison the problem that appears in the measurement of magnetic and electric fields of the substation can be noted. By measuring, the value of magnetic and electric field can be obtained only at a certain height. But, for a precise view, the field should be measured at a different heights, and only then a data that would be relevant to determine the nature and level of magnetic and electric fields will be obtained. In addition, there is a problem with number of suitable places at which measuring can be done. Number of places is limited because sometimes the field conditions greatly complicate the implementation of measurement. Beside, the measurement of magnetic field is performed under certain substations load, which changes according to the daily and annual load diagram, so that comes into play only measuring of the electric field that is mostly constant. In Tables 1 to 4, the measured and calculated values of electric and magnetic fields are shown, as well as the percentage measurement error in relation to the calculation.

Diagrams on Fig. 19 to 22 present calculated and measured values of magnetic flux density inside and outside the substation, as well as the errors of measured relative to the calculated values.

Mark of measurement place outside transformer station			Calculated B above ground of TS			Measured B above ground of TS			Error		
			z=1.75 m	z=1.50 m	z=1.00 m	z=1.75 m	z=1.50 m	z=1.00 m			
(m)			B (μT)			B (μT)			(%)		
1	x = 0.50	y = 0.00	15.183	33.291	20.395	14.304	31.450	19.280	5.79	5.53	5.47
2	x = 0.50	y = 1.05	16.853	60.772	26.486	15.720	57.699	25.176	6.72	5.06	4.95
3	x = 0.50	y = 2.10	15.533	26.433	19.131	14.570	24.892	18.186	6.20	5.83	4.94
4	x = 0.00	y = 2.60	13.219	17.187	14.952	12.376	15.996	13.950	6.38	6.93	6.70
5	x = 1.45	y = 2.60	9.989	14.108	11.822	9.263	13.139	11.050	7.27	6.87	6.53
6	x = 2.90	y = 2.60	5.236	6.392	5.731	4.897	6.056	5.436	6.47	5.26	5.15
7	x = 3.40	y = 2.10	4.932	5.742	5.299	4.613	5.391	4.990	6.47	6.11	5.83
8	x = 3.40	y = 1.05	6.001	6.720	6.370	5.607	6.305	5.980	6.57	6.18	6.12
9	x = 3.40	y = 0.00	5.275	5.747	5.513	4.954	5.386	5.168	6.09	6.28	6.26
10	x = 2.90	y = -0.50	5.845	6.437	6.122	5.492	6.120	5.824	6.04	4.92	4.87
11	x = 1.45	y = -0.50	10.297	14.981	12.287	9.644	14.174	11.555	6.34	5.39	5.96
12	x = 0.00	y = -0.50	13.700	25.061	17.217	12.801	23.758	16.356	6.56	5.20	5.00
13	x = 1.00	y = 0.00	12.073	20.467	14.891	11.464	19.247	14.128	5.04	5.96	5.12
14	x = 1.00	y = 1.05	14.355	29.025	18.863	13.644	27.750	18.052	4.95	4.39	4.30
15	x = 1.00	y = 2.10	11.755	17.939	13.932	11.246	16.935	13.248	4.33	5.60	4.91
16	x = 0.00	y = 3.10	9.067	11.102	9.971	8.514	10.490	9.365	6.10	5.51	6.08
17	x = 1.45	y = 3.10	7.494	9.525	8.379	6.942	8.804	7.790	7.37	7.57	7.03
18	x = 2.90	y = 3.10	4.361	5.171	4.517	4.087	4.865	4.242	6.28	5.92	6.09
19	x = 3.90	y = 2.10	3.825	4.293	4.032	3.565	4.029	3.775	6.80	6.15	6.37
20	x = 3.90	y = 1.05	4.373	4.903	4.581	4.147	4.615	4.315	5.17	5.87	5.81
21	x = 3.90	y = 0.00	4.031	4.355	4.181	3.822	4.085	3.951	5.18	6.20	5.50
22	x = 2.90	y = -1.00	4.867	5.316	5.073	4.516	4.922	4.705	7.21	7.41	7.25
23	x = 1.45	y = -1.00	8.347	10.481	9.328	7.886	9.828	8.827	5.52	6.23	5.37
24	x = 0.00	y = -1.00	9.985	14.406	11.568	9.296	13.655	10.920	6.90	5.21	5.60
25	x = 1.50	y = 0.00	9.186	13.155	10.645	8.731	12.381	10.185	4.95	5.88	4.32
26	x = 1.50	y = 1.05	10.630	16.328	12.661	9.980	15.350	11.910	6.11	5.99	5.93
27	x = 1.50	y = 2.10	8.863	11.974	10.059	8.378	11.274	9.460	5.47	5.85	5.95
28	x = 0.00	y = 3.60	6.540	7.642	7.036	6.125	7.143	6.628	6.35	6.53	5.80
29	x = 1.45	y = 3.60	5.690	6.781	6.169	5.277	6.286	5.725	7.26	7.30	7.20
30	x = 2.90	y = 3.60	3.667	4.221	3.899	3.426	3.942	3.650	6.57	6.61	6.39
31	x = 4.40	y = 2.10	3.041	3.333	3.169	2.895	3.148	3.011	4.80	5.55	4.99
32	x = 4.40	y = 1.05	3.352	3.625	3.480	3.158	3.397	3.276	5.79	6.29	5.86
33	x = 4.40	y = 0.00	3.170	3.373	3.268	3.028	3.189	3.095	4.48	5.46	5.29
34	x = 2.90	y = -1.50	4.690	4.396	4.220	4.386	4.090	4.005	6.48	6.96	5.09
35	x = 1.45	y = -1.50	6.372	7.517	6.838	6.013	7.072	6.493	5.63	5.92	5.05
36	x = 0.00	y = -1.50	7.305	9.278	8.070	6.802	8.652	7.515	6.89	6.75	6.88

Table 1. Comparison of measured and calculated values of magnetic flux density outside TS

Mark of measurement place inside transformer station				Measured value	Calculated value	Error
(m)				B (μT)		(%)
A	x = 1.30	y = 1.10	z = 1.75	172.150	183.498	6.18
B	x = 1.70	y = 1.10	z = 1.75	195.100	211.018	7.54
C	x = 1.45	y = 1.80	z = 0.30	5.876	6.385	7.97
D	x = 2.80	y = 1.00	z = 1.00	17.152	18.401	6.79
E	x = 2.50	y = 1.05	z = 2.15	5.858	6.355	7.82
F	x = 2.50	y = 1.00	z = 1.50	16.155	17.304	6.64
G	x = 0.15	y = 1.05	z = 1.00	119.185	129.367	7.87

Table 2. Comparison of measured and calculated values of magnetic flux density inside TS

Mark of measurement place outside transformer station			Calculated value	Measured value	Error
(m)			z=1.75m		(%)
			E (kV/m)		
1	x = 0.50	y = 0.00	0.015	0.014	6.67
2	x = 0.50	y = 1.05	0.028	0.030	-7.14
3	x = 0.50	y = 2.10	0.033	0.035	-6.06
4	x = 0.00	y = 2.60	0.046	0.043	6.52
5	x = 1.45	y = 2.60	0.176	0.164	6.82
6	x = 2.90	y = 2.60	0.057	0.055	3.51
7	x = 3.40	y = 2.10	0.046	0.043	6.52
8	x = 3.40	y = 1.05	0.057	0.060	-5.26
9	x = 3.40	y = 0.00	0.039	0.040	-2.56
10	x = 2.90	y = -0.50	0.037	0.035	5.41
11	x = 1.45	y = -0.50	0.083	0.085	-2.41
12	x = 0.00	y = -0.50	0.020	0.019	5.00
13	x = 1.00	y = 0.00	0.010	0.010	0.00
14	x = 1.00	y = 1.05	0.017	0.016	5.88
15	x = 1.00	y = 2.10	0.022	0.020	9.09
16	x = 0.00	y = 3.10	0.031	0.028	9.68
17	x = 1.45	y = 3.10	0.079	0.080	-1.27
18	x = 2.90	y = 3.10	0.038	0.035	7.89
19	x = 3.90	y = 2.10	0.030	0.028	6.67
20	x = 3.90	y = 1.05	0.033	0.030	9.09
21	x = 3.90	y = 0.00	0.025	0.025	0.00
22	x = 2.90	y = -1.00	0.022	0.020	9.09
23	x = 1.45	y = -1.00	0.033	0.030	9.09
24	x = 0.00	y = -1.00	0.011	0.010	9.09
25	x = 1.50	y = 0.00	0.010	0.011	-10.00
26	x = 1.50	y = 1.05	0.011	0.010	9.09
27	x = 1.50	y = 2.10	0.001	0.001	0.00
28	x = 0.00	y = 3.60	0.021	0.020	4.76
29	x = 1.45	y = 3.60	0.050	0.047	6.00

30	x = 2.90	y = 3.60	0.024	0.025	-4.17
31	x = 4.40	y = 2.10	0.020	0.020	0.00
32	x = 4.40	y = 1.05	0.021	0.020	4.76
33	x = 4.40	y = 0.00	0.015	0.014	6.67
34	x = 2.90	y = -1.50	0.014	0.015	-7.14
35	x = 1.45	y = -1.50	0.018	0.020	-11.11
36	x = 0.00	y = -1.50	0.009	0.010	-11.11
37	x = 1.45	y = -2.00	0.011	0.010	9.09
38	x = 2.00	y = 1.05	0.008	0.008	0.00
39	x = 1.45	y = 4.10	0.023	0.021	8.70
40	x = 4.90	y = 1.05	0.014	0.015	-7.14

Table 3. Comparison of measured and calculated values of electric field intensity outside TS

Mark of measurement place inside transformer station				Measured value	Calculated value	Error
(m)				E (kV/m)		(%)
A	x = 1.30	y = 1.10	z = 1.75	8.120	8.757	7.27
B	x = 1.70	y = 1.10	z = 1.75	10.155	10.957	7.32
C	x = 1.45	y = 1.80	z = 0.30	6.550	7.105	7.81
D	x = 2.80	y = 1.00	z = 1.00	0.001	0.001	0.00
E	x = 2.50	y = 1.05	z = 2.15	0.001	0.001	0.00
F	x = 2.50	y = 1.00	z = 1.50	0.001	0.001	0.00
G	x = 0.15	y = 1.05	z = 1.00	0.085	0.090	5.56

Table 4. Comparison of measured and calculated values of electric field intensity inside TS

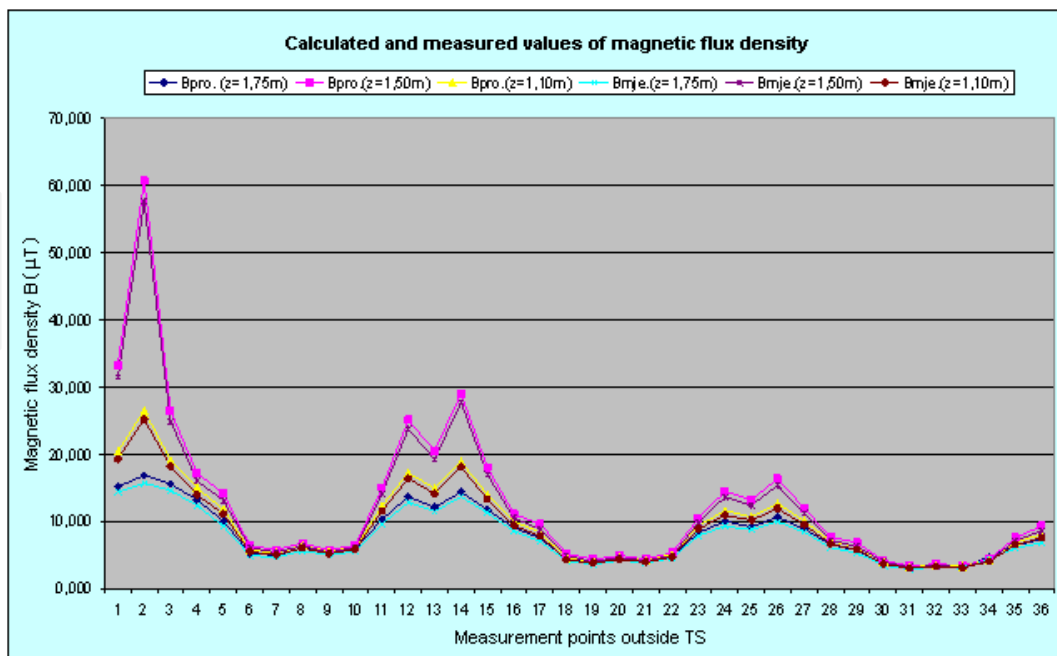


Fig. 19. Diagram of calculated and measured values of magnetic flux density outside the substation

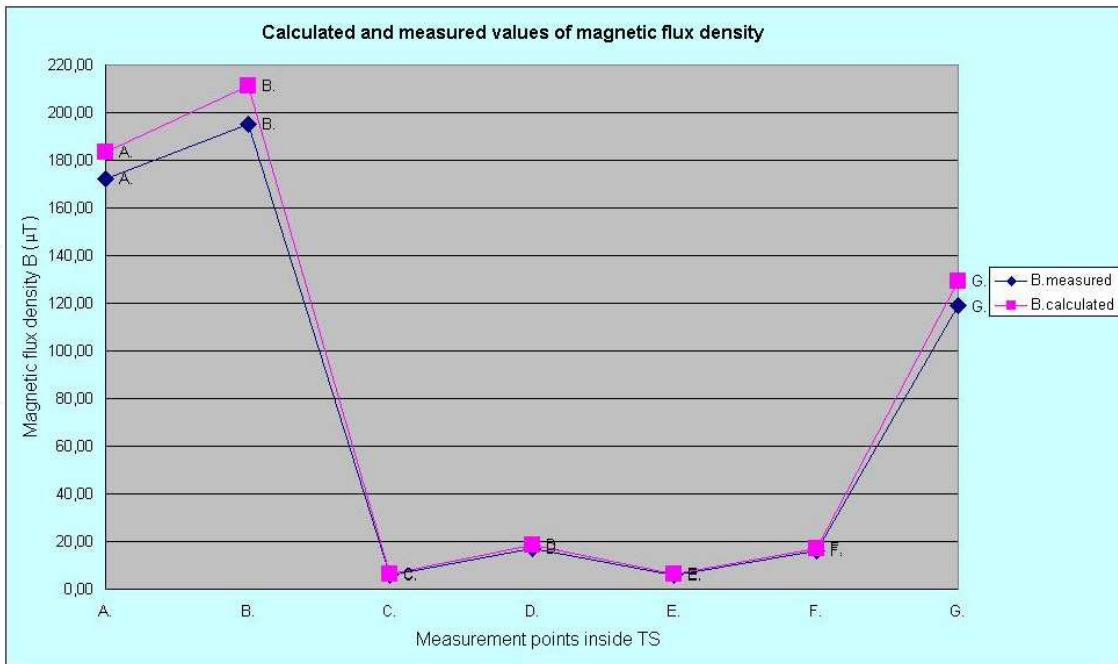


Fig. 20. Diagram of calculated and measured values of magnetic flux density inside the substation

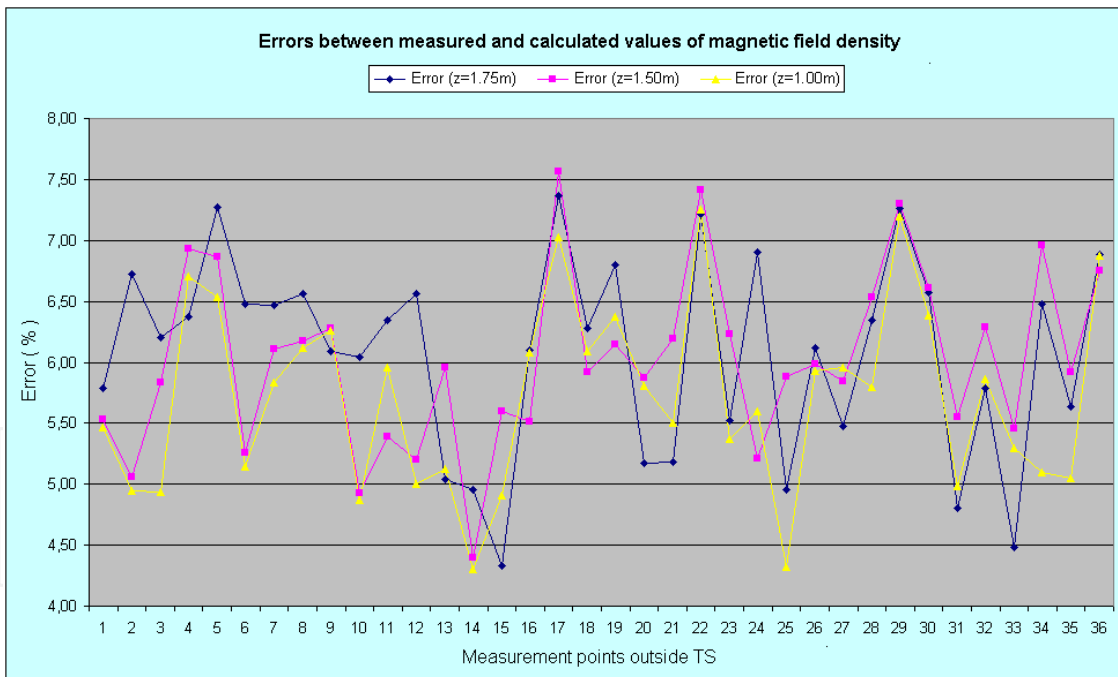


Fig. 21. Errors between measured and calculated values of magnetic flux density outside the substation

From the diagrams it is evident that the values of magnetic flux density obtained by calculation appropriately follow changes in the measured values. The presented calculation gives the percentage error between measured and calculated values for some measuring points, and which ranges from 4.32 % to 7.25 % outside, or from 6.18 % to 7.97 % inside the substation.

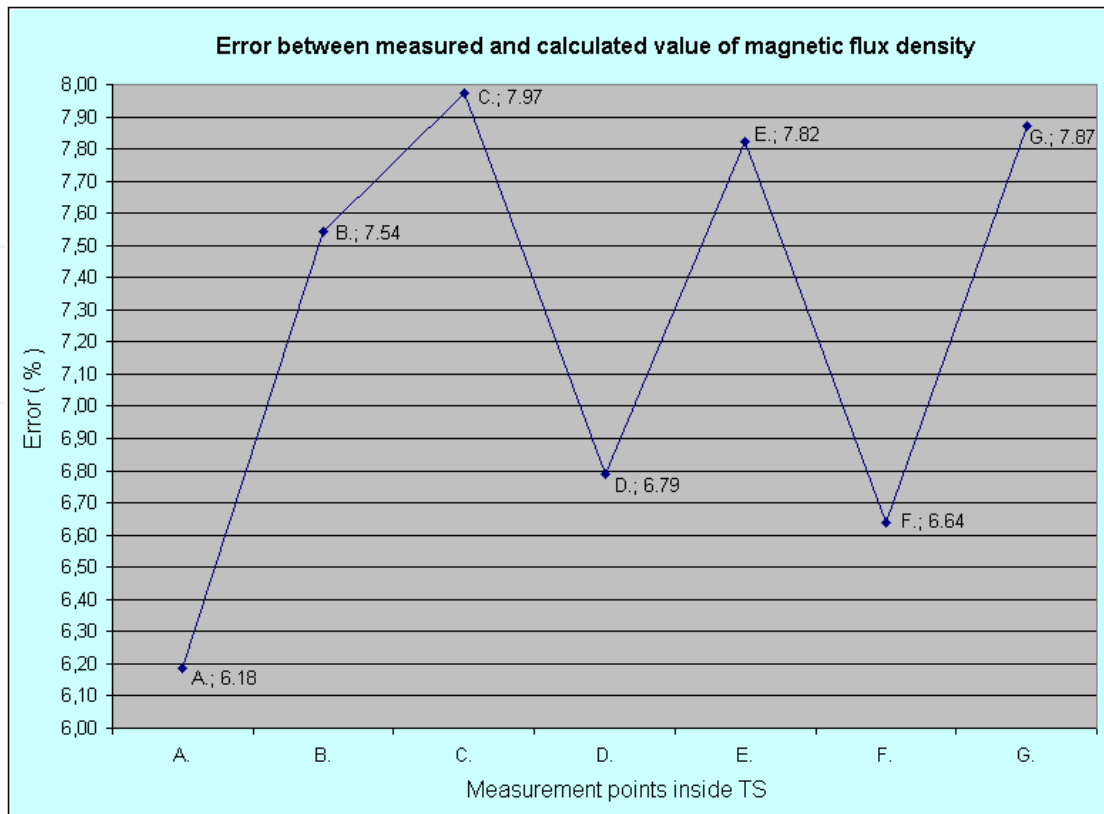


Fig. 22. Errors between measured and calculated values of magnetic flux density inside the substation

Calculated and measured values of electric field intensity inside and outside the substation are presented at a diagrams on Fig. 23 to 26, as well as the errors of measured in relation to the calculated values. From a diagrams it is evident that the value of electric field intensity obtained by calculation appropriately follow changes in the measured values. The presented calculation gives the percentage error between measured and calculated values for some measuring points outside the substation, which ranges from -11.11 % to 9.68 % and 7.81 % inside the substation.

The calculation results give a satisfactory coincidence with the results of experimental measurements, indicating the validity of implementing and developing such a calculations for practical purposes related to the design and reconstruction of existing substations. From the economic point of view, it is possible to achieve significant savings because an expensive experimental measurements and repairs can be reduced. For evaluation the field distribution both procedures are necessary, as they supplemented each other and thus allow a safe assessment of fields sizes. Interestingly, the maximum value of magnetic flux density is calculated and measured at a height $z = 1.00$ (m), the area of human hips, so this height is imposed as a referece regarding the allowable sizes of exposure to the non-ionizing radiation of electromagnetic fields. When measuring the values of the magnetic field density around the substation, some differences in values measured at different transformer station walls were detected. The reason for this is the way of placement of the main sources of magnetic field inside the substation which are the MV and LV transformer outlets and LV distribution outlets.

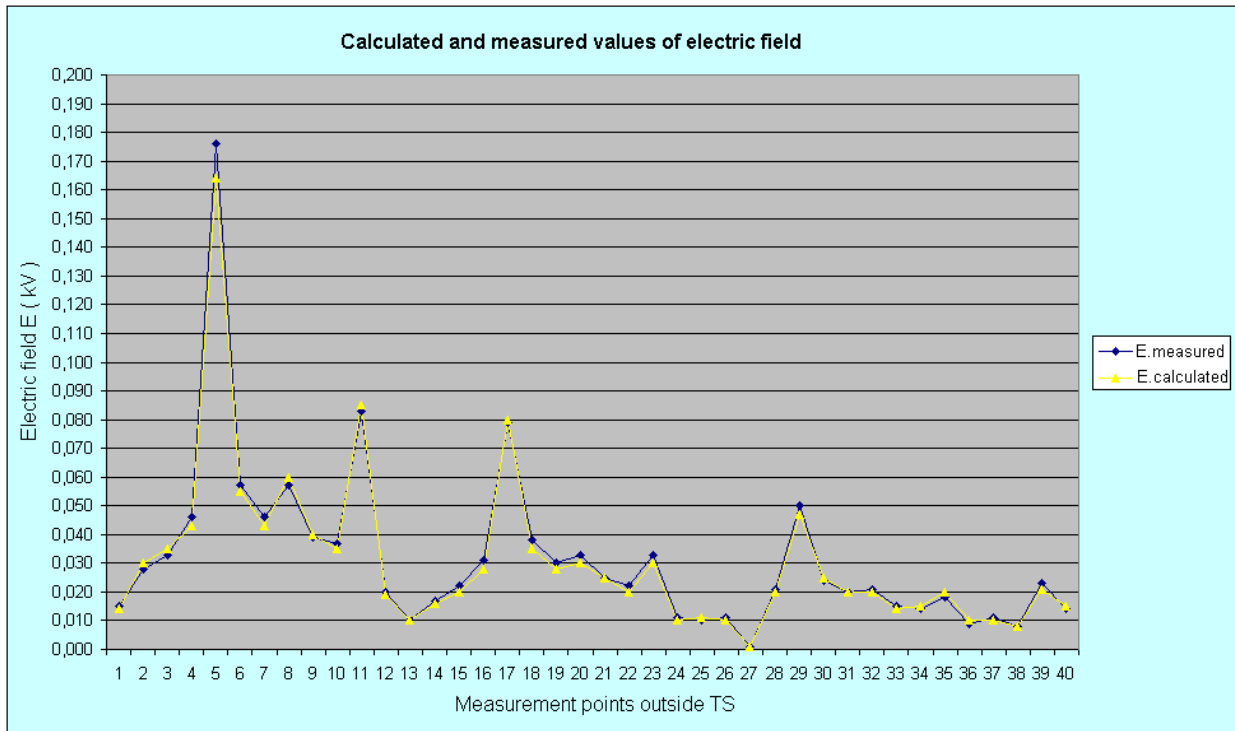


Fig. 23. Diagram of calculated and measured values of electric field intensity outside the substation

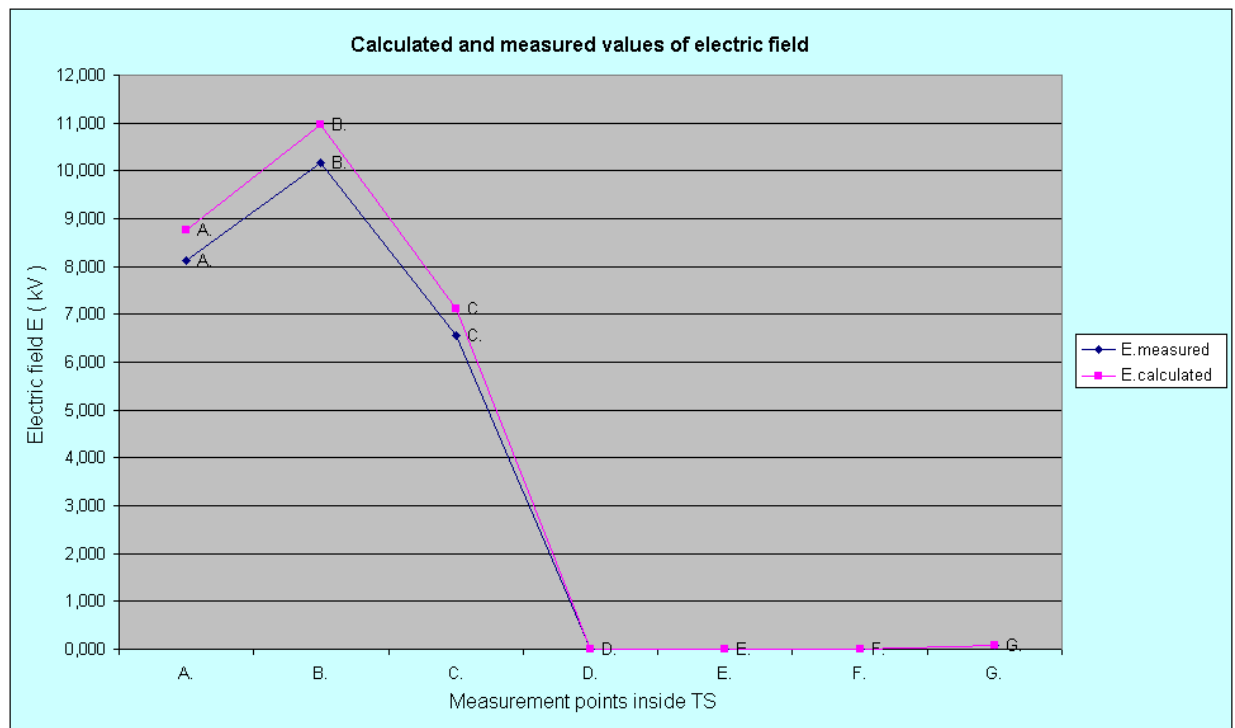


Fig. 24. Diagram of calculated and measured values of electric field intensity inside the substation

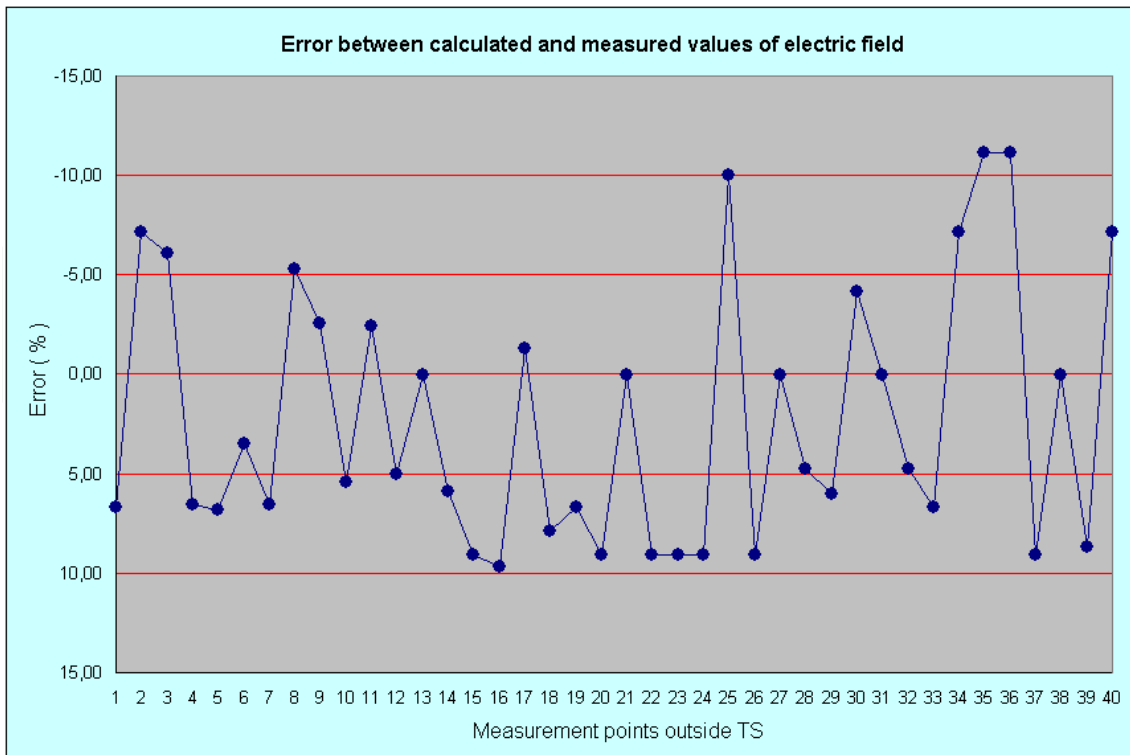


Fig. 25. Errors between measured and calculated value of electric field intensity outside the substation

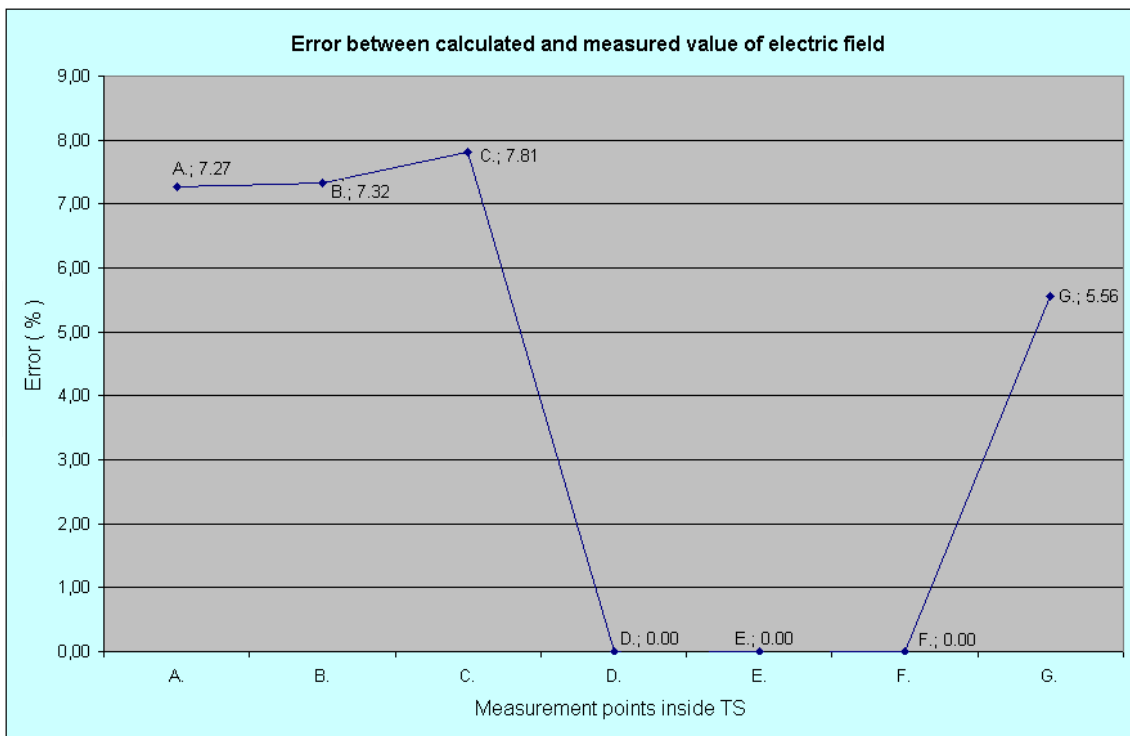


Fig. 26. Errors between measured and calculated value of electric field intensity outside and inside transformer station

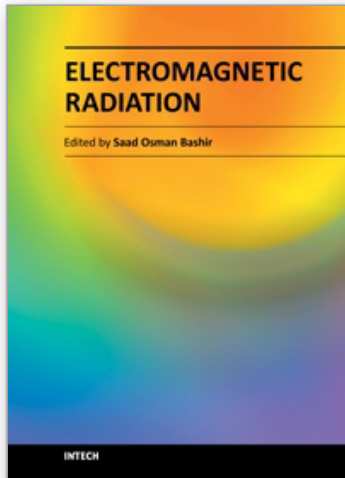
5. Conclusion

Calculation and measurement of LV electric and magnetic fields and their interconnectivity are the main problems in transmission and distribution of power energy in terms of standardized electromagnetic compatibility and human exposure to non-ionizing electromagnetic radiation. Solving of these problems is reduced to solving nonlinear differential equations by modeling and application of numerical methods and experimental measurements of low-frequency electric and magnetic fields. The research presents the application of mathematical models and charge simulation method (CSM) for calculating of low-frequency electric field distribution, while the calculation of magnetic flux density distribution inside and around the substation, which indicates the level of low-frequency magnetic field, is performed by the procedure based on the application of Biot-Savart's law for the induction of straight stream line of finite length. The original scientific contribution of this research is determining the 3D distribution of low-frequency electric and magnetic fields, their interaction under conditions of complex geometry and standardized substation electromagnetic compatibility (EMC) in the area of biological effects of electromagnetic fields. Obtained 3D models represent very complex functional dependence of electric and magnetic fields distribution, as the basis for the objectified physical measurements to develop an optimal variants for solving electromagnetic compatibility (EMC) in existing and new power facilities. Satisfactory accuracy of the results obtained by calculations with the results of experimental measurements of EFA-300 Field Analyzers instrument is confirmed, which indicate validity of implementation and development of such calculations for the executable solutions of transformer stations. From an economic point of view this method of calculation could reduce the need for expensive experimental measurements and repairs of power plants, providing confirmation that complicated theoretical researches resulting in appropriate executable solutions. Presented mathematical models, calculation, measurement and visual 3D distribution of electric and magnetic fields represent a realistic assumption for the study of interactions between electromagnetic fields and human bodies at the macroscopic and static level, with finding of certain optimization criterias, in order to create a new technological, process solutions and design methods. The research results are important both from the scientific point of view and from the standpoint of possibilities for practical applications.

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