Numerical Solving and Experimental Measuring of Low-frequency Electromagnetic Fields in Aspect of Exposure to Non-ionizing Electromagnetic Radiation

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Abstract-Mathematical models and numerical solving of low-frequency electric and magnetic fields in transformer stations in conditions of standardized electromagnetic compatibility are represented in this work, as well as methods of experimental measuring of low-frequency electric and magnetic fields. Calculation and measuring of low-frequency electric and magnetic fields, as well as their correlation, are the basic problems in transmission and distribution of electric power in conditions of standardized electromagnetic compatibility and exposure of humans to no-ionizing electromagnetic radiation.

Keywords: Numerical solving, Experimental measuring, Low-frequency electromagnetic fields, Exposure to non-ionizing electromagnetic radiation

1. INTRODUCTION

Research of calculation modality for electromagnetic fields in low-frequency band (Extra Low Frequency) in stationary regimes for transformer stations in urban areas is conducted for purposes of gaining acceptable levels of electric and magnetic fields in areas where the electrical equipment is being installed and where the humans are stationed temporarily or permanently, as one segment of electromagnetic compatibility. In low-frequency band (wave length 6000km and 50Hz frequency) radiation occurs exclusively in near zone, where mutual perpendicular of electric field, magnetic field and direction of wave propagation, constant ratio of magnetic and electric field amplitudes and dependence of electric and magnetic field amplitude from source distance by law 1/r, apropos strength density by $1/r^2$, do not apply. Therefore it is necessary to separately observe electric and magnetic field. For solving complex geometry electromagnetic fields in low-frequency band a system of Maxwell equations which are fully describing electromagnetic field, are used. Maxwell equations can be analytically solved only for narrow class of one-dimensional problems of static and quasi-static fields. Every two-dimensional and three-dimensional geometrical spacing requires implementation of numerical methods for solving field problems by usage of known software packages (e.g. MAXWELL 3D, EFC-400, FLUX 3D, MATLAB) as well as other appropriate tools necessary for successful realization of research, for which it is needed to construct detailed mathematical models of transformer facility with all geometrical and electrical parameters. According to standards for protection from electromagnetic field in domain of occupational exposure and domain of increased sensitivity, limitation values of electromagnetic fields have to be carefully observed in area 5,0m from the source for transformer station and in area 1,0m from the source for cables. Since the distribution transformer stations are closed electrical facilities and therefore the space accessible to humans is limited by walls, metal fences and screens, the strength of electric field strives to zero and therefore the aim is on maintaining the limitation value of magnetic flux density. While researching a ways of optimization of magnetic field the aim is to preserve limit value of 100μT on distance of 20cm from the tactile surface of one power device, at one definite emission point.

2. CALCULATION OF LOW-FREQUENCY MAGNETIC AND ELECTRIC FIELD OF A TRANSFORMER STATION

a) For a calculation of 3D distribution of low-frequncy electric field CSM-Charge Simulation Method and SEM-Source Element Method, that is usually considered as a special version of IBEM-Indirect Boundary Element Method, is used.

b) For a calculation of 3D distribution of low-frequency magnetic field, for calculation of magnetic flux density distribution inside and outside a transformer station, a procedure based on implementation of Bio-Savart law for flux density of flat finite length streamline and a law of superposition is used.

On frequencies of 50Hz, electromagnetic field surrounding transformer station is quasi-static, it possesses conservative component of the electric field caused by charges and vortical component of the electromagnetic field caused by currents. Complex geometry of transformer station elements requires three-dimensional calculation. Calculation of electric and magnetic fields in points far from sources (charge or current) is performed by thin-wire approximation and by representing the wires with one-dimensional lines with neglecting the insulators, cause their influence on the electric field is of local character. While calculating the conservative electric field, wires on known potentials are used. In calculation earth is considered as wire on zero potential, and its influence is modeled by mirroring technique. Also, in calculation, vortical components of electromagnetic field are modeled as linear isotropic half-space in free space with knowledge of currents in wires. Calculations of magnetic field are performed by software package EFC-400, according DIN-VDE0848-1 standard, which allows simulation in three-dimensional space. Two-dimensional and three-dimensional display of facility disposition by EFC 400 software is given on Figure 1., having in mind that a difference between a model and a reality depends on a subdivision of conductors on finite number of segments. Analyses were performed with subdivision of conductors on 635 segments of a resolution dx=dy=dz=0,05m. For calculation of field strength coordinates of the observed point are transformed in a local coordinate system of the corresponding segment. This is performed by rotation and translation operations. Calculation gives a contribution of each segment to a total field vector that has to be transferred back to earth coordinate system. Vector additioning of each contribution gives total field vector. In case there is a mix of different frequencies contributions to a field from each segment are temporarily extended, superimposed and integraled in time domain. EFC-400 calculates absolute value, each component and peak value. Interpolation mode is also available, which speeds up a calculation over large areas. In this mode predefined number of points within one calculation interval is estimated by third order polynomial. EFC-400 is capable of solving a set of differential equations for matrix with 16000x16000 elements (Method: LU-decomposition or conjunction gradient). Predefined geometry of conductor can be approximated with 16000 segments. For our example a matrix with 261x261 elements is used, which gives a values of electric and magnetic field in 68121 points of observed plain with total calculation surface of 169m^2. Software package EFC-400LF, allows representation of medium-voltage and low-voltage blocks as well as power transformers, by boxes connected with wires which form constructive unit of transformer station. For a given load of transformer station of 40% of nominal power, with measured current on low voltage side of 375A and current load on medium voltage side of 15A, a numerical calculation of magnetic field density and electric field is performed on XY plain of transformer station with $-5m \le x \le 8m$ and $-5m \le y \le 8m$, on height z=1,75m above ground level. The values of magnetic flux density and electric field are observed in areas of XY plain, on height of 1,75m from the ground, on distances of 0,5m, 1,0m and 1,5m from the walls of the transformer station, where commonly a human head is exposed, in vicinity of the transformer station. Two-dimensional and three-dimensional continual distribution of magnetic flux density and electric field strength are given on Figures 2. and 3.

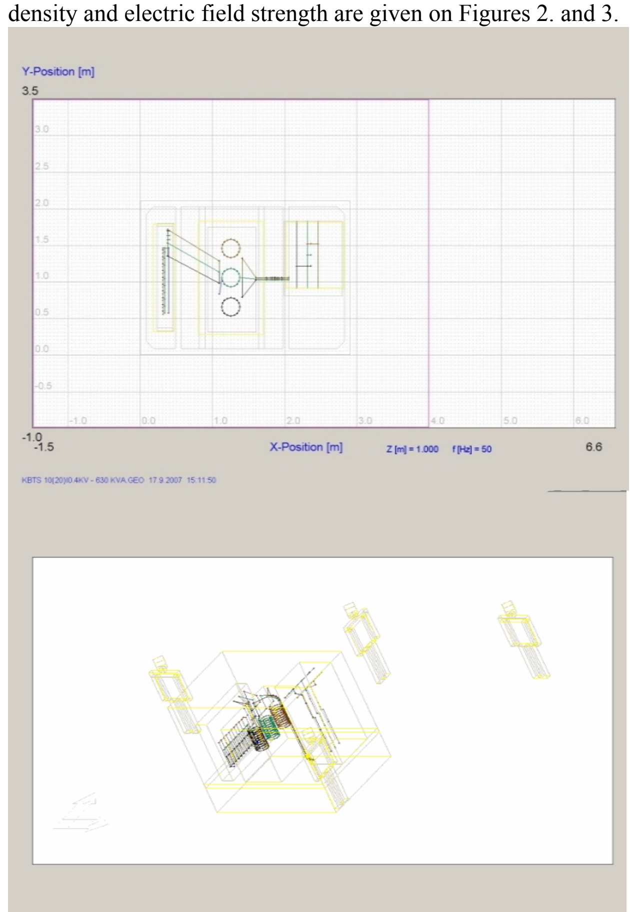
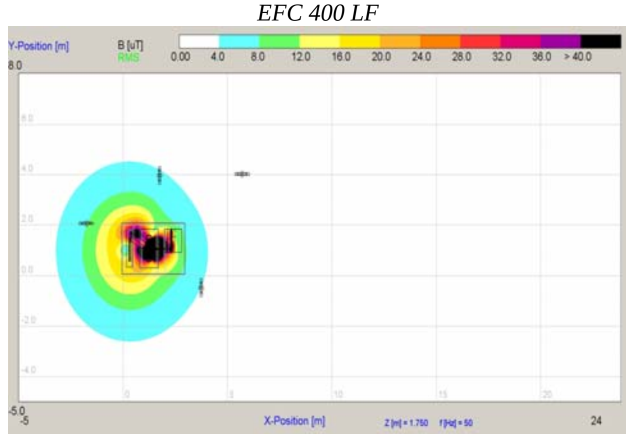


Figure 1. 3D and 2D display of facility disposition by software EFC 400 LF



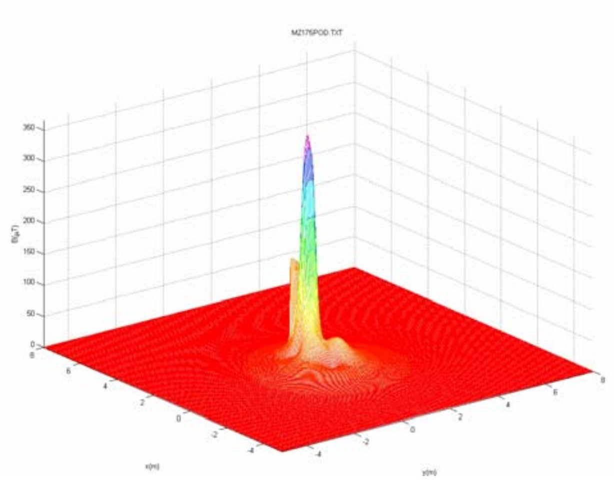
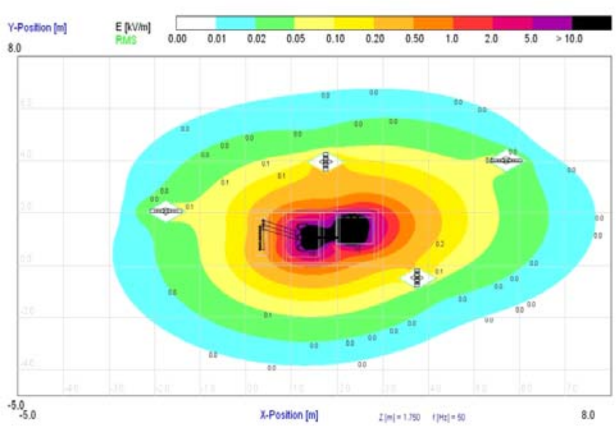


Figure 2. 2D-3D continual distribution of magnetic flux density on XY plain (z=1,75m)

The values of magnetic flux density for z=1,75m, in area 0,5m from the outer transformer sides are in rage from 4,932μT to 18,240μT, in area 1,0m from the outer transformer sides are from 3,125μT to 14,355μT, and in area 1,5m from the outer transformer sides are in rage from 3,041μT to 10,634μT. The magnetic flux density inside a transformer station reaches its maximum values on intersections of XY plain and primary terminals of the transformer and cable connections with medium-voltage and low-voltage buses, in a range from 0,150mT to 0,366mT. The results show that values of magnetic flux density outside of a transformer station do not exceed value of 22,433μT in some points on distance of 0,2m from the north traverse side of a transformer station in a level of transformer box. They are lower than maximum allowable values for increased sensitivity domain (B_{max}=100μT) and even on a distance from 0,5m to 2,0m from a transformer station values are decreasing from 18,240μT to 7,810μT. Calculated values of a magnetic flux density outside a transformer station fulfill border values for occupational exposure domain (B_{max}=500μT).



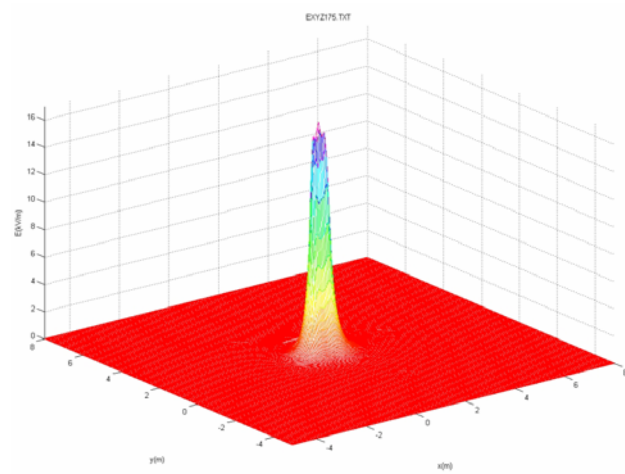


Figure 3. 2D-3D continual distribution of electric field on XY plain (z=1,75m)

In area 0,5m from the transformer sides maximum values of the electric field are in rage from 0,060kV/m to 0,177kV/m, in area 1,0m from 0,023kV/m to 0,081kV/m, and in area 1,5m from 0,019kV/m to 0,061kV/m. Maximum values of the electric field inside a transformer station are visible on intersections of XY plain with a transformer medium-voltage terminals and cable connections of medium-voltage block and primary side of a power transformer, in range from 415,302kV/m to 452,363kV/m, and a transformer box, in range from 2,194kV/m to 16,912kV/m, but outside the equipment boxes they fall on to values 1,00-0,50kV/m. The calculation results show that the value of electric field strength outside of a transformer station on distances from 0,5m to 1,5m do not exceed value of 0,352kV/m and it is much lower than allowed values for increased sensitivity domain (E_{max}=5kV/m) and occupational exposure domain (E_{max}=10kV/m), according to European Union directive 2004/40/EC.

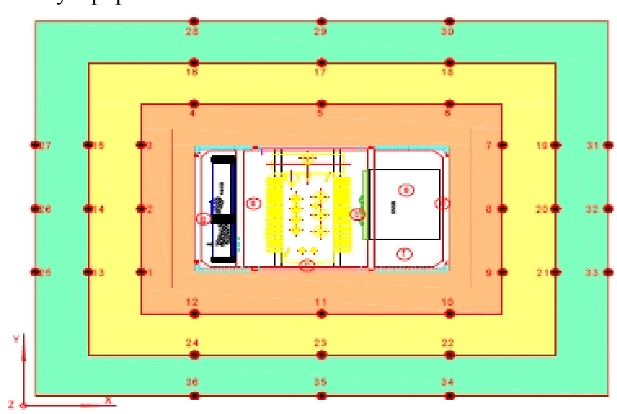
3. MEASURING OF LOW-FREQUENCY MAGNETIC AND ELECTRIC FIELD OF A TRANSFORMER STATION

During measuring preparations, totally 36 measuring points outside and 7 measuring points inside a transformer station were chosen, where the highest values of electric and magnetic field are expected. On distances of 0,50m, 1,0m and 1,5m and height of 1,75m above ground, outside a transformer station 108 measuring points were located. Inside a transformer station, measuring points close to medium-voltage and low-voltage switchgear boxes, transformers and transformers terminals, as well as close to cable connections with medium-voltage and low-voltage buses, were chosen (Figure 6.). Measuring range was related to occupational exposure domain and increased sensitivity domain. Measuring was conducted at air temperature of 20,9^{o}C, relative air humidity of 28,4% in a transformer station and air temperature of 22^{o}C, relative air humidity of

27% outside a transformer station. After locating measuring points, a measuring instrument EFA-300 Field Analyzers was tested, climate conditions were recorded, and after that measuring and analyses of magnetic and electric fields of a transformer station, related to systems of power transmission and distribution, were conducted.

The highest values of magnetic flux density, outside a transformer station on a height 1,75m, are recorded on a wing low-voltage side of a transformer station on distance of 0,5m in a range from 57,699µT to 24,892µT, while increasing a distance from a transformer station to 1,0m-1,5m, those values fall into a range from 27,750µT to 2,897µT, and on distance of 1,5m they fall to 8,378µT. Magnetic flux density measured inside a transformer station reaches its maximum value, on medium-voltage and low-voltage transformer terminals and cable connections with medium-voltage and low-voltage switchgear boxes, in a point „a“ 172,150µT and point „b“ 195,100µT, while on low-voltage switchgear box on height 1,0m above ground, in point „g“ 119,185µT. Measuring of a magnetic flux density outside of a transformer station satisfy border values for a occupational exposure domain (B_{max}=500µT) and increased sensitivity domain (B_{max}=100µT).

Measuring results of the electric field strength outside of a transformer station on distances from 0,5m to 2,0m do not exceed values of 0,176kV/m, and they are much lower than a maximum allowed values for increased sensitivity domain (E_{max}=5kV/m), and occupational exposure domain (E_{max}=10kV/m). Measured results of the electric field inside a transformer station in a transformer box are in points „a“ 8,120kV/m, „b“ 10,155kV/m and „c“ 6,550kV/m, but outside the equipment boxes they fall on to values 0,583-0,087kV/m, and therefore they satisfy condition of occupational exposure domain (E_{max}=10kV/m) to which an employee of the power distribution company can be exposed while manipulating with a facility equipment.



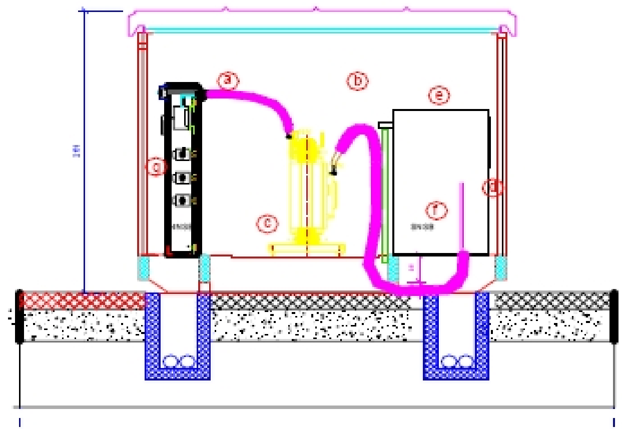


Figure 4. Measuring points of the electric and magnetic field inside and outside of a transformer station

Measuring results and calculated values of magnetic flux density and electric field strength in measuring points are given by Table 1. By comparison of calculated and measured results a slight difference is noticed. At the same time it is important to notice the significance of the projection of the most advanced parts of the diagram which connect the points where the magnetic flux density or electric field strength is approximate. That way it is ensured that in any case human bodies are not exposed to magnetic or electric field radiation of values exceeding border values regulated by rule books related to protection from non-ionizing radiation. Beside it is interesting to observe area where a transformer station stops being a significant source of magnetic and electric fields because in that case they can be relieved from some periodic examinations. From a comparison a problem can be seen that is related to measuring of magnetic and electric fields only at a certain height. By measuring an insight of magnetic and electric field values can be obtained only at a certain height. For exact field presentation measuring should be conducted at different heights. Only in that case we can get the results that are relevant for identifying the character and the level of magnetic and electric fields. Beside mentioned, problem of a number of suitable places for measuring occurs. A number of measuring points is restricted, having in mind that sometimes conditions on a field largely complicate the conducting of measuring. Beside this, a measuring of the magnetic field is conducted under certain load of the transformer station that is changed according to daily and annual consumption load diagram, so it emphasizes the measuring of the electric field that is more or less constant. On Figures 7-10, calculated and measured values of the electric field in and outside a transformer station are shown, as well as the errors between the measured and the calculated values of magnetic and electric fields.

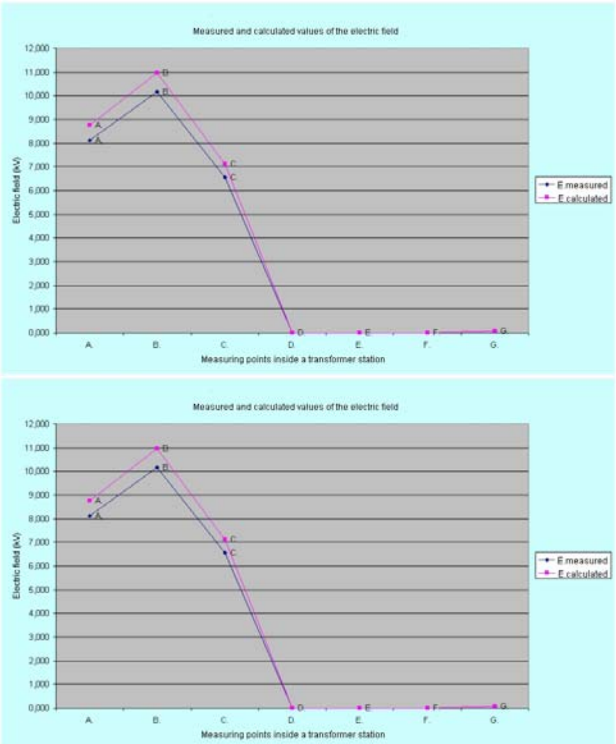


Figure 5. Calculated and measured values of the electric field in and outside a transformer station

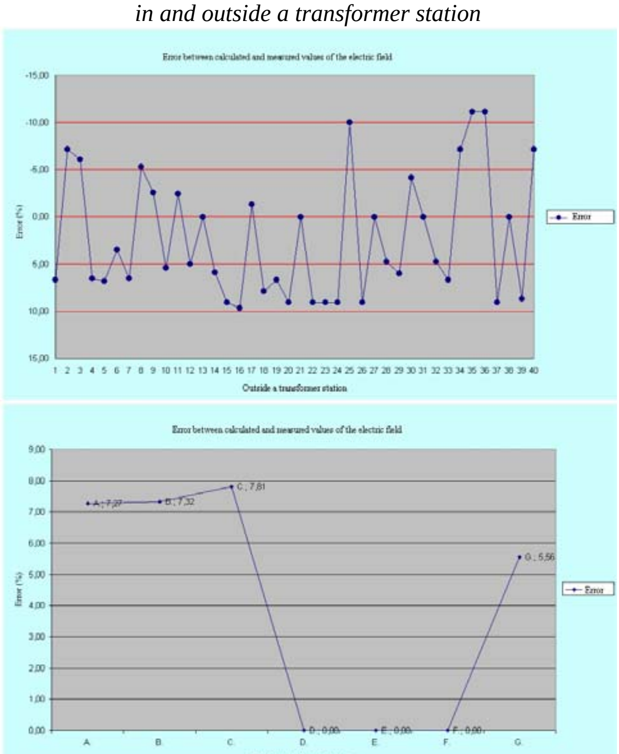


Figure 6. Error between calculated and measured values of the electric field in and outside a transformer station

Tabel 1. Results of measuring and calculated values of magnetic flux density and electric field strength

Mark of the measuring point outside a transformer station			Calculated value	Measured value	Error (%)	Calculated value	Measured value	Error (%)
			B(µT)			E (kV/m)		
1.	x=-0.50m	y=0	15,183	14,304	5,79	0,015	0,014	6,67
2.	x=-0.50m	y=1.05m	16,853	15,720	6,72	0,028	0,030	-7,14
3.	x=-0.50m	y=2.10m	15,533	14,570	6,20	0,033	0,035	-6,06
4.	x=0	y=2.60m	13,219	12,376	6,38	0,046	0,043	6,52
5.	x=1.450m	y=2.60m	9,989	9,263	7,27	0,176	0,164	6,82
6.	x=2.90m	y=2.60m	5,236	4,897	6,47	0,057	0,055	3,51
7.	x=3.40m	y=2.10m	4,932	4,613	6,47	0,046	0,043	6,52
8.	x=3.40m	y=1.05m	6,001	5,607	6,57	0,057	0,060	-5,26
9.	x=3.40m	y=0	5,275	4,954	6,09	0,039	0,040	-2,56
10.	x=2.90m	y=-0.50m	5,845	5,492	6,04	0,037	0,035	5,41
11.	x=1.45m	y=-0.50m	10,297	9,644	6,34	0,083	0,085	-2,41
12.	x=0	y=-0.50m	13,700	12,801	6,56	0,020	0,019	5,00
13.	x=-1.0m	y=0	12,073	11,464	5,04	0,010	0,010	0,00
14.	x=-1.0m	y=1.05m	14,355	13,644	4,95	0,017	0,016	5,88
15.	x=-1.0m	y=2.10m	11,755	11,246	4,33	0,022	0,020	9,09
16.	x=0	y=3.10m	9,067	8,514	6,10	0,031	0,028	9,68
17.	x=1.45m	y=3.10m	7,494	6,942	7,37	0,079	0,080	-1,27
18.	x=2.90m	y=3.10m	4,361	4,087	6,28	0,038	0,035	7,89
Mark of the measuring point outside a transformer station			Calculated value	Measured value	Error (%)	Calculated value	Measured value	Error (%)
			B(µT)			E (kV/m)		
19.	x=3.90m	y=2.10m	3,825	3,565	6,80	0,030	0,028	6,67
20.	x=3.90m	y=1.05m	4,373	4,147	5,17	0,033	0,030	9,09
21.	x=3.90m	y=0	4,031	3,822	5,18	0,025	0,025	0,00
22.	x=2.90m	y=-1.0m	4,867	4,516	7,21	0,022	0,020	9,09
23.	x=1.45m	y=-1.0m	8,347	7,886	5,52	0,033	0,030	9,09
24.	x=0	y=-1.0m	9,985	9,296	6,90	0,011	0,010	9,09
25.	x=-1.50m	y=0	9,186	8,731	4,95	0,010	0,011	-10,00
26.	x=-1.50m	y=1.05m	10,630	9,980	6,11	0,011	0,010	9,09
27.	x=-1.50m	y=2.10m	8,863	8,378	5,47	0,001	0,001	0,00
28.	x=0	y=3.60m	6,540	6,125	6,35	0,021	0,020	4,76
29.	x=1.45m	y=3.60m	5,690	5,277	7,26	0,050	0,047	6,00
30.	x=2.90m	y=3.60m	3,667	3,426	6,57	0,024	0,025	-4,17
31.	x=4.40m	y=2.10m	3,041	2,895	4,80	0,020	0,020	0,00
32.	x=4.40m	y=1.05m	3,352	3,158	5,79	0,021	0,020	4,76
33.	x=4.40m	y=0	3,170	3,028	4,48	0,015	0,014	6,67
34.	x=2.90m	y=-1.50m	4,690	4,386	6,48	0,014	0,015	-7,14
35.	x=1.45m	y=-1.50m	6,372	6,013	5,63	0,018	0,020	-11,11
36.	x=0	y=-1.50m	7,305	6,802	6,89	0,009	0,010	-11,11

Mark of the measuring point inside a transformer station				Measured value	Calculated value	Error (%)	Measured value	Calculated value	Error (%)
				E (kV/m)			B(µT)		
A.	x=1.30m	y=1.10m	z=1.75m	8,120	8,757	7,27	172,150	183,498	6,18
B.	x=1.70m	y=1.10m	z=1.75m	10,155	10,957	7,32	195,100	211,018	7,54
C.	x=1.45m	y=0.30m	z=0.30m	6,550	7,105	7,81	5,876	6,385	7,97
D.	x=2.80m	y=1.00m	z=1.00m	0,001	0,001	0,00	17,152	18,401	6,79
E.	x=2.50m	y=1.05m	z=2.15m	0,001	0,001	0,00	5,858	6,355	7,82
F.	x=2.50m	y=1.00m	z=1.50m	0,001	0,001	0,00	16,155	17,304	6,64
G.	x=0.15m	y=1.05m	z=1.00m	0,085	0,090	5,56	119,185	129,367	7,87

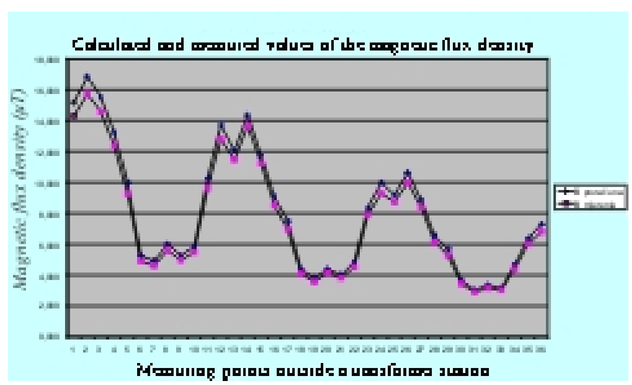


Figure 7. Calculated and measured values of the magnetic flux density in and outside a transformer station

It is clearly visible from diagram that values of magnetic field density gained by calculation are following, in appropriate manner, the changes of measured values. Used calculation gives percentage error, for some measuring points, between measured and calculated values within limits from 4,33% to 7,26% outside a transformer station, apropos from 6,18% to 7,97% inside a transformer station. Calculation results have, for some measuring locations, in respect of measured values percentage error inside limits from -11,11% to 9,68% outside a transformer station, apropos to 7,81% inside a transformer station.

4. CONCLUSION

Calculation and measuring of low-frequency electric and magnetic fields, as well as their correlation, are the basic problems in transmission and distribution of electric power in conditions of standardized electromagnetic compatibility and exposure of humans to no-ionizing electromagnetic radiation. Resolution of these problems corresponds to solving nonlinear differential equations by modeling and applying the numeric methods, as well as by experimental measuring of low-frequency of electric and magnetic fields. Original scientific contribution of conducted research represents determination of three-dimension (3D) distribution of low-frequency electric and magnetic field, their interaction in conditions of complex geometry of transformer station and standardized electromagnetic compatibility (EMC) in area of biologic influence of electromagnetic fields. Obtained three-dimensional (3D) mathematical models are representing very complex functional dependence of electric and magnetic field distribution, as a base for objectified physical measurements in order to create optimal versions for solving electromagnetic compatibility (EMC) in existing and new power facilities. Satisfying accuracy of results gained by calculations comparing to experimental measuring values with EFA-300 Field Analyzers instrument is confirmed, indicating that initiation and developing such calculations for designing of constructive solutions for transformer station is reasonable. From the economic point of view, such way of calculation can reduce the requirements for expensive experimental measurements and substation reparations, indicating that complex theoretical researches are resulting in appropriate constructive solutions. Introduced mathematical models, calculations, measuring and three-dimensional visual distribution of magnetic field, are representing the real assumption for researching of interaction between electromagnetic fields and human body on macroscopic and static level, revealing optimization criteria in aim to create a new technological solutions and methods for designing. The research results are important from scientific point of view, as well as, a possibility for practical implementation.

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