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ORIGINAL PAPER

MEASUREMENT AND NUMERICAL MODELLING OF ELECTRIC FIELD IN OPEN TYPE AIR SUBSTATION

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Abstract. *The influence of electric field generated by electrical substation and overhead transmission lines represents a thematic of real interest in the domain of transport and distribution of power energy, because it is possible to have an impact on the human body. This paper presents an analogy between measurements and numerical computation of electric field inside of a high voltage 110/20 kV power substation. Measurements that define the behavior of the electric field are analyzed using the ANSYS Multiphysics software package. The article includes electric field measurements in outdoor high voltage 110/20 kV power substation of Targoviste-Aninoasa area. Firstly, a description of the equipment in the open-air type substation, together with the methodology of the electric field measurements in these power stations is discussed. In the second part of the paper there is a numerical modeling of the electric field near the power transformer at the power station. The measured values of electric field were compared with the international standards regarding of safe limits for personnel exposure.*

Keywords: *Electromagnetic compatibility, measurement, numerical simulation, substation.*

1. INTRODUCTION

Electricity produced in power plants is transported from the high voltage power station to the substations through overhead electric lines. The expansion and development of the power systems worldwide, has led to growth the influence of electromagnetic field on the human body but also for the environment. Transport and distribution overhead lines and electric power substations are sources of electromagnetic pollution. These issues were discussed in some publications [1-4].

This influence is more pronounced on personal who have carried and operate in high voltage power station and the overhead lines. Some research has revealed that the electromagnetic field can affect the sensitive parts of the human body [1]. There are many articles [2, 3] in the literature that indicate an increased interest in the electromagnetic fields produced by power lines and power stations. Investigations have shown that significant

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voltages and currents can occur in the conductive elements located in the vicinity of the intense electromagnetic field. There are studies and researches with measurements and electromagnetic field calculations in outdoor and indoor electrical substations of different voltage levels [2-3].

There are studies that highlight the influence of the electromagnetic field on office buildings near the power station [4]. The electric power transmission lines at technical low frequency (50/60 Hz) can interfere with proximity electrical and electronic equipment.

The electric field is caused by the high potential of the conductors. Considering that the power stations operating at high voltages, the electromagnetic pollution the effects increase with increasing voltage. Therefore, it is recommended to caution consider these undesirable effects and any protective measures that may be required especially in the high and very high voltage domain [5-6].

The transition of electricity from the transport network to the distribution network is achieved through substations. These substations reduce the operating voltage and determine the increased current to the distribution network of the electric grid. There are three types of substations, the outdoor, closed and underground type substations. The cost and location will determine what type of substation should be used.

The closed type substations are preferred for limited space, such as in urban areas, where most of the equipment is kept in a building. In cases that substations must have minimum environmental impact, underground substations are preferred. But these types of substations are also the most expensive. Outdoor type substations tend to occupy more space than closed type substations, and since they are cheaper to achieve, they are indicated in the areas where there is space available [7-8]. In open air type substations, the very high voltages and currents generate high electric field that may pose a menace to working personnel and public.

The measurement results were validated by numerical simulation using the finite element method and these results are compared with the limit values of the international standards. Finally, it was possible to make a prediction of the intensity of the electric field for areas in the station with a risk of electric shock. The results are compared to internationally accepted limits. For frequencies of 50 and 60 Hz employed in energy networks, the limits are E = 10 kV/m for professional exposure and E = 5 kV/m, for the general population [9-11].

2. EXPERIMENTAL MEASUREMENTS

The electric field measurements were recorded at an outdoor electric power substation 2x16 MVA, 110/20 kV, located near Targoviste City (Romania). A plan of the Targoviste-Aninoasa substation area is shown in Fig. 1. The substation is about 5400 m^2 in area. Two identical power transformers are installed in the substation area. Each transformer has a nominal power of 16 MVA, a nominal voltage rate of 110/20 kV and it is fed by one of the circuits of a 110-kV double circuit transmission line entering the substation.

The conductors are placed at a height of 6 m above the ground. The substation area is surrounded by a concrete fence which is about 2.2 m higher. Measurements were made in favorable weather conditions at a temperature of 21^oC.

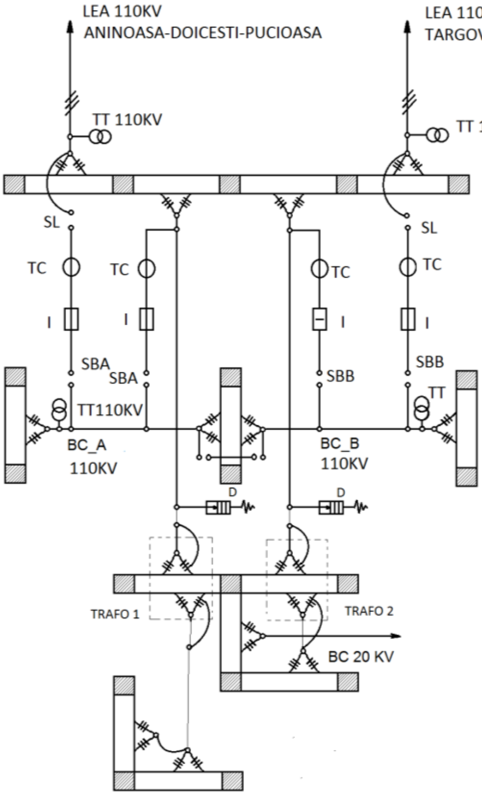

Figure 1. Architectural drawing of the Targoviste-Aninoasa outdoor substation: Switches - I, Power Transformers – TRAFO1 and TRAFO2, Current Transformers – TC, Voltage Transformers - TT, Line Separators – SL, Busbars Separators - SBA and SBB, Arresters – D, Overhead Power Lines Conductors – LAE, HV and MV Busbars.

The six conductors are powered by six circuit breakers, which are used for switching for station maintenance or in case of an electrical fault. Above each phase of the two power lines there is a lightning discharge device to protect the station in the event of overvoltage caused by the lightning strike. These switches connect the conductors into current transformers to regulate the current. The separators can be coupled line at busbar systems. The busbars are separated into two sections, one for each power line, but they can be interconnected through switches.

Figure 2. METRA multimeter and METRA FMA1 adapter.

Measurements were made with the device METRA multimeter to which is attached the METRA FMA1 (Field Measurement Adapter) GOSSEN-METRAWATT GMBH. Measuring values are always displayed by selecting a measuring range from the Meter to ~3V, regardless of the measuring range that has been selected at the field measurement adapter (Fig. 2). To determine the values of the two magnitudes defining the electric and magnetic fields, multiply the value displayed on the multimeter to the corresponding decimal factor (Table 1).

Table 1. Characteristics of the measuring instrument.

Electric-field strength	
Measurement scale	Factor
300 V/m	100/m
3000 V/m	1000/m
30000 V/m	10000/m

In open air substation, the risk of an electroshock during the measurements is higher than that of a closed type air substation, because all the high current and voltage equipments is not encapsulated in insulating materials and gases. For this reason, measurements could not be made in all areas of the station. Measurements were performed in 80 points inside the power substation. Measuring points have been selected near HV switchgear, power transformer, current and voltage surge arresters, and near the cable connections implemented on HV and MV busbars.

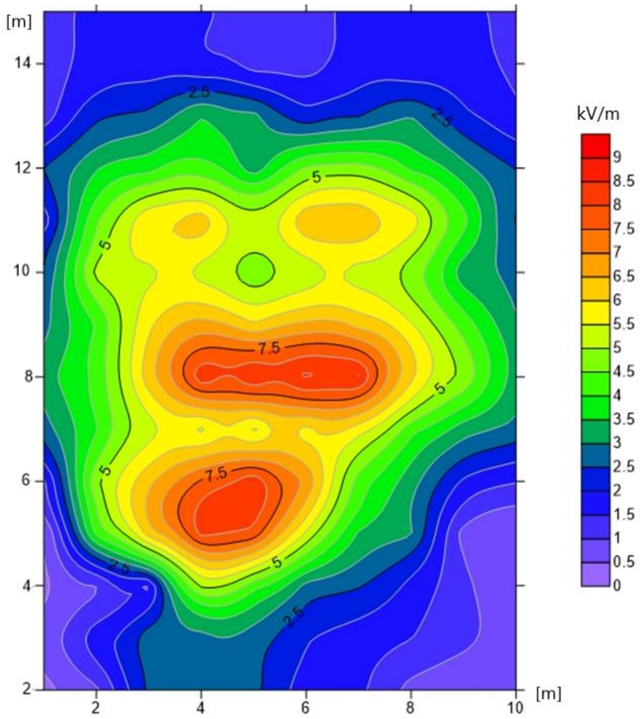

Figure 3. Electric-field strength spectrum inside the substation.

Outdoor measurements may be affected by errors. The most likely sources of major errors are reading errors, difficulty in positioning the meter, observer proximity effects and temperature effects. To increase the accuracy of the measurements, the probe should be oriented to read the vertical E-field and the distance between the measuring instrument and the operator must be less than 2.5 m. Since there was no possibility of remote reading of the data, the distance between the operator and the measuring device was 1.2 m. If the proximity effects are considered acceptable, the observer's distance may be reduced. The actual value will depend on the geometry of the observer-measuring device. The values of electric-field strength at selected positions were measured at a head height about 1.8 m above the ground level. The device used to measure the electric field strength was set on a wooden tripod. Our measurement procedures were in accordance with the guideline’s procedures prescribed in IEEE Standard 644-1994 [9-11].

Fig. 3 shows the measured electric-field strength at selected points inside the substation. All the electric field strength is lower than 9 kV/m and the maximum electric field strength of 8.76 kV/m was recorded near the high voltage busbars where are the HV switchgears and arresters. The electric fields where the 110 kV power conductors are situated, are relatively high due to the very high voltages that exist along their, and reach values close to the IEEE Standard. Intense electric fields were also recorded around the voltage transformer and the power transformer. In this region the maximum value of 8.36 kV/m was measured.

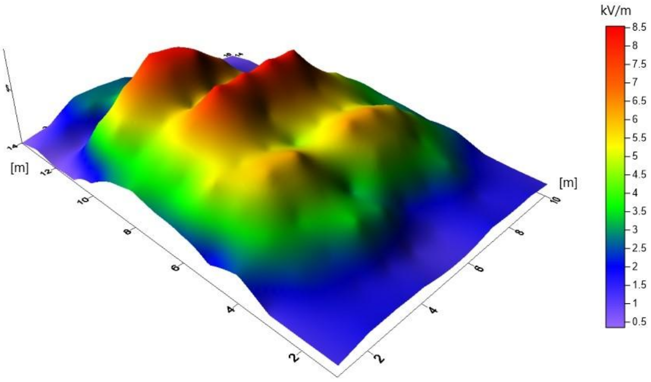

Figure 4. Contour and surface maps for the electric field strength throughout all the substation area.

On the station side paths, the electric field does not exceed the value of 3.5 kV/m. Near the fence around the station the values of the electric field are between 2.1 kV/m and 0.3 kV/m. These values are lower than the occupational exposure limit of 10 kV/m. Diagrams are given in Fig. 4 showing contour and surface maps for the electric-field strength throughout all the substation area. In Figs. 3-4 are presented the distributions of the electric field strength in the active area of the station at a distance from the fence. When the distance is larger than 6 m, all the measured field values are below 1 kV/m and descend slowly.

3. NUMERICAL ELECTRIC FIELD COMPUTATION

There are different approaches to calculating the electric field produced by high-voltage overhead lines. Depending on the geometric complexity of models, problems can be two-dimensional or three-dimensional. The most common calculation methods in the literature are Charge Simulation Method (CSM), Boundary Element Method (BEM) or Finite Element Method (FEM). These papers propose a technical suggestion, analytical expressions that could be programmed on hand-held calculators or using computerized techniques and computer software [12-15]. Hybrid of CSM and FEM is presented in [9] where the adopted algorithm allows to determine the optimal position and the number of fictitious charges for overhead power lines. Calculation of electric field depending on the arrangement of the conductors was made in [13] using also the Method of Images. In this papers, the proposed calculations are validated by the numerical modeling of the electric field in COMSOL Software. In another study[17, 20], the authors use the CSM to calculate the electric field, which is simulated by a few discrete simulation charges located in the conductors. Values of simulation charges are obtained by satisfying the boundary conditions at several contour points selected at the conductor surfaces. Once the values of simulation charges are determined, using the superposition principle can be calculated the potential and electric field of any point in the region outside the conductors. The analytical calculation model is confirmed by FLUX3D Software [14].

This part of the paper is based on a numerical modeling of the electric field derived from measurements presented in experimental measurements section, in order to validate the experimental results and to obtain electric field values in areas where it is dangerous to make measurements. Numerical modeling was performed near the power transformer, 9 m in length and at different heights (1 m, 1.5 m and 1.8 m), heights representing vital human points (head, heart and pelvis) [1]. High voltage transformer is one of the most powerful electrical equipment inside the power station, which produces an intensives electric field of low frequency. Hence, the electric field must be investigated in close to the 16 MVA power transformer with narrowly.

Software package ANSYS Multiphysics can be used for modeling the main characteristics of electric field (electric field strength, electric flux density and potential difference) in and around different electric installation. This simulation package solves linear and nonlinear equations, systems in one-, two- or three- dimensional domain. Physical phenomena of electromagnetic nature are mathematically described by Maxwell's equations [16]. The problem solution of a given package is based on the Finite Element Method (FEM). Generally, the finite element approximation is based on partial differential equations as expressions of the solutions defined by a partition of the field study in disjoint elements, called "finite elements", giving the name of the method [17].

Steps to solve an electrostatic field problem are: create the physics environment, define element types and options, define element coordinate systems, set real constants and define a system of units, define material properties, build and mesh the model and assign physics attributes to each region within the model, apply boundary conditions and loads (excitation), obtain the solution, review the results [16].

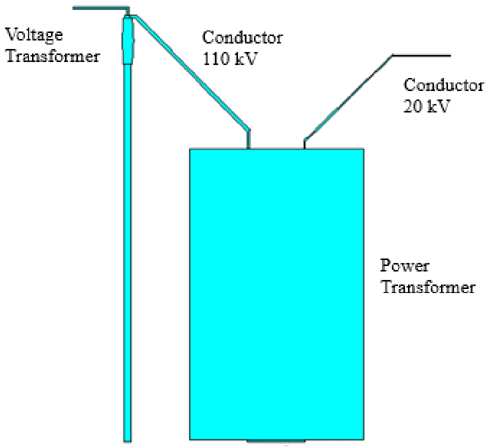

Figure 5. The physical model subjected to modeling.

In Fig. 5 is presented the physical model subject to modeling, which includes: power transformer, voltage transformer and conductors [18]. The power lines 110 kV are the conductors of Aluminum Conductor Steel Reinforced (ACSR) type and lines are 20 kV bare conductors of aluminum. For electrostatic fields, the relative permittivity for a metal is very high, close to infinity. In ANSYS, it is required to define relative permittivity of material used and considered value $\varepsilon_r = 10^5$ and conductivity for aluminum $\sigma = 3.77\times10^7$ S/m. The voltage transformer has ceramic insulation (ε_r=25) and is placed on a concrete support (ε_r=4.5). The power transformer dimensions are 3 m × 5 m and has a galvanized steel coating, with oil insulation (ε_r=2.1). For air, relative permittivity is ε_r=1.

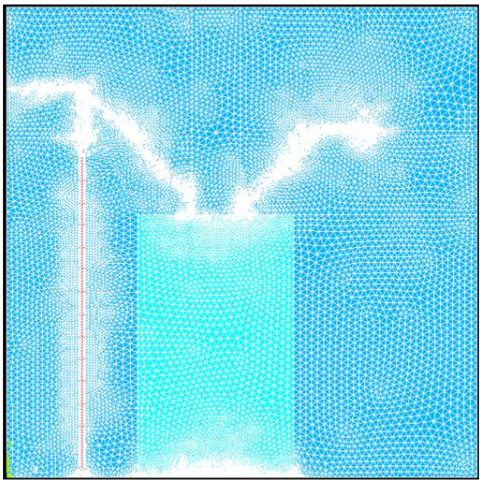

Figure 6. The physical model meshed into finite elements.

The next step in the preprocessor phase is mesh generation and load applying upon the elements. It been used a mesh with 37310 nodes and 75101 triangular elements. Finite element mesh selected automatically generated, so all elements of the modeled shape adapt to and shape real domain. Finite element mesh model is shown in Fig. 6.

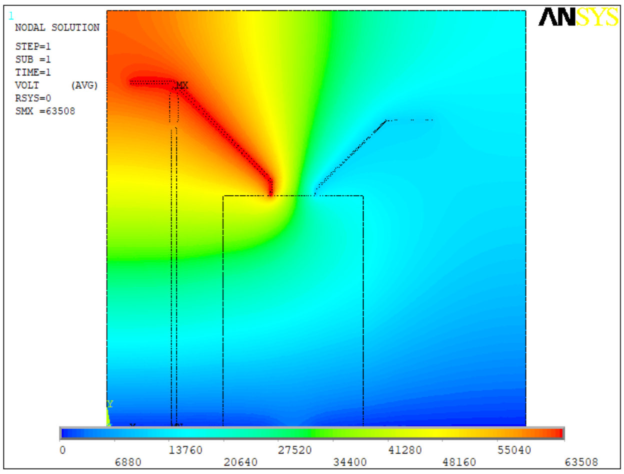

Figure 7. Electrical potential distribution near the power transformer, in V.

The electrical potential V and the intensity of the electric field vector can be expressed at a certain point at a distance *r* by the expressions [19]:

$$V = \frac{q}{4\pi\varepsilon r} \quad [V] \tag{1}$$

$$\vec{E} = -gradV = \frac{q}{4\pi\varepsilon r^2}\cdot\vec{e_r} \quad [V/m] \tag{2}$$

where q is electric charge [C], ε is the electrical permittivity of the environment [F/m], r represents the distance between the location of the electrical charge [m] and $\overrightarrow{e_r}$ is oriented vector of field lines.

The dependence between the vector electric field strength and the electric flux density is given by the relationship.

$$\vec{D} = \varepsilon\vec{E} = \varepsilon_0\, \varepsilon_r\vec{E} \qquad [C/m^2] \tag{3}$$

where ε_0 is electric vacuum permittivity ε_0=8.854$\cdot 10^{-12}$ [F/m] and ε_r is the relative electrical permittivity.

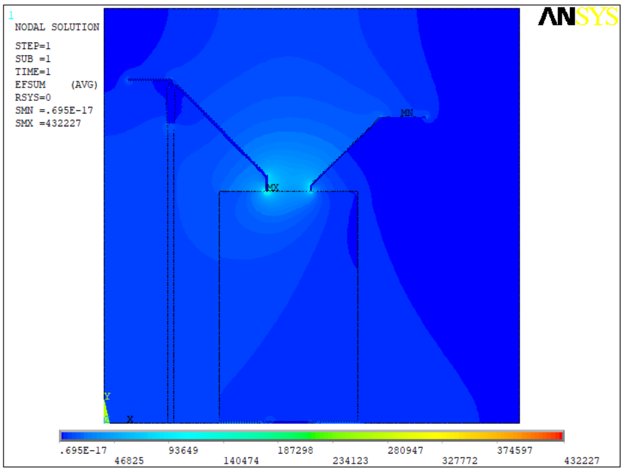

Figure 8. The electric field strength distribution in the environment around the power transformer, in V/m.

The conductors are at potentials of 110 kV, respectively 20 kV and earth are at the reference electric potential 0 V. Fig. 7 shows the distribution of the electrical potential. Line voltages applied in numerical modeling are 110/√3 kV, respectively 20/√3 kV.

In ANSYS software, there is a graphical program which displays the resulting fields in the form of contour and density plots. The program also allows user to evaluate the measurements that characterize the electric field at random points. In order to compute different integrals and plot various electrical quantities the graphical program also can be used [16]. The electric field strength distribution in the environment around the power transformer is shown in Fig. 8 and the electric flux density distribution is presented in Fig. 9.

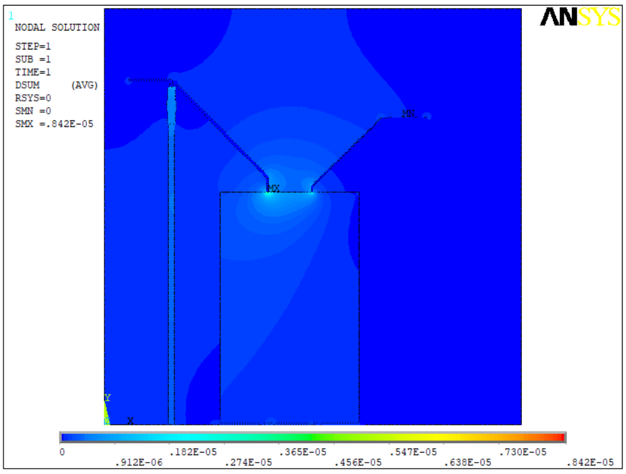

Figure 9. The electric flux density distribution in the environment around the power transformer, in C/m^2.

The electric field strength increases in the 110 kV conductor areas. under 110 kV conductor and voltage transformer the maximum values of the electric field are 8.40 kV/m at distance of 1 m, 8.52 kV/m at the distance of 1.5 m and 8.62 kV/m at distance of 1.8 m. Theoretically, field strengths are inversely proportional to the distance from the source. The values of the electric field for the three levels are presented graphically in Fig. 10.

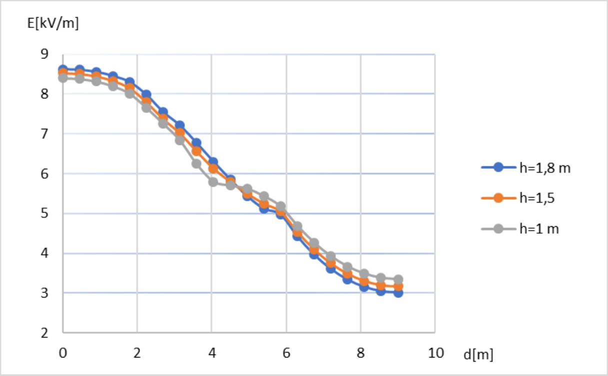

Figure 10. The electric field strength chart for the three levels.

The highest value of the electric field is 187.52 kV/m obtained a follow-up numerical modeling over the power transformer, around the 110 kV insulators at 5 m above the ground. This value could not be confirmed by measurements because could not be made in that space due to the danger of electric shock [20].

This calculation model can be used for insulation distance estimation in the design of a transmission power lines. Furthermore, this method of numerical simulation approach can be used to predict the electric field generated by high voltage overhead power lines, in areas where measurements cannot be made for security reasons.

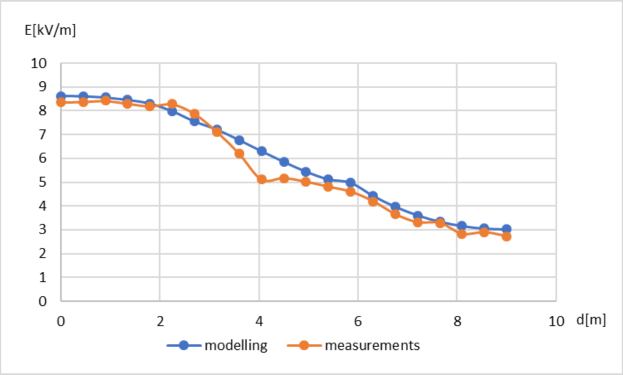

Figure 11. Comparison of the experimental and numerical values for electric field strength.

Fig. 11 show a slight difference between the experimental and numerical values, this difference should be attributed to the model of physics subjected to modeling, but also to measurement errors.

4. CONCLUSIONS

Measurements of the electric and field were performed inside a 110-kV station in the vicinity the town of Targoviste, Romania. Moreover, the numerical calculations were performed in a narrow domain of the station, exactly near the power transformer using FEM. There have been several experimental characterizations of electrical magnitudes at different distances of 1 m, 1.5 m and 1.8 m affecting the sensitive parts of the human body when exposed to high frequency fields. The numerical results were, in principle, consistent with the measured results. Inside power station, important electromagnetic phenomena exist under of high voltage power lines, and it requires several measures to protect of workers and the environment against any type of undesirable and dangerous effects. These measures should be considered, from the design stage up to the service stage. It may be required to adapt special solutions for a safer, cleaner environment, screens to reduce the electrical field, like as higher overhead power lines, etc. In future research we are considering the experimental and numerical evaluation of the magnetic field in the electric stations.

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