Measurement and Simulation of the Voltage Distribution on an Insulator String

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Abstract: In this paper, the voltage distribution on a porcelain insulator string, which is used for the suspension of 150 kV overhead transmission lines, is investigated. In order to calculate the voltage distribution, a model of the insulator string was set up using OPERA, an electromagnetic analysis program based on the Finite Elements method. Simulation results have been compared with experiments which were carried out in the High Voltage Laboratory of the National Technical University of Athens. The paper highlights the significance of the three-dimensional part of the geometry by comparing OPERA-2d/ST and OPERA-3d/ST results. More significantly, the paper discusses the limitations of an electrostatic solution for this class of problem and presents results from alternative formulations that account for the conducting and dielectric properties of the materials.

1 INTRODUCTION

The insulators, which are used for the suspension of overhead transmission lines, constitute one of the most important parts of the transmission lines as flashover effects in insulators can cause the tripout of a transmission network. Capacitances are developed between each insulator in the insulator string with respect to the high voltage conductor as well as to earth. In addition, stray capacitances between insulators are developed. These capacitances have different values for different positions of the insulators in the string. As a result, the voltage distribution along the insulators is not uniform, with the insulators nearer the conductor are more highly stressed. Several experimental and calculation methods have been developed for the calculation of the voltage distribution over an insulator string and the study of the stray capacitances [1]-[3].

Several experimental and simulation methods have been developed for the computation of electric fields and potentials along an insulator string [4]-[13]. The simulation methods give the possibility to examine the behaviour of models with very complex geometry without using analytical methods or experiments.

In this paper, the potential variation in a porcelain insulator string is thoroughly investigated using modeling tools and experiment. Two and three dimensional modelling results obtained using OPERA, a software suite that uses the finite element method to solve the partia1 differential equations that describe the behaviour of electromagnetic fields, are compared with experimental results. The paper will discuss differences between two and three-dimensional solutions, as well as the limitations of a purely electrostatic solution for this class of problem. Results will be presented from an alternative formulation that accounts for the conducting and dielectric properties of the materials.

2 EXPERIMENTAL PROCEDURE

The aim of the experiments was the study of the voltage distribution on an insulator string. The investigated insulator is of the cap-and-pin type and is used in insulator strings for the suspension of 150 kV overhead transmission lines. Its geometrical characteristics are the diameter, which is 254mm, the height, which is 146mm, and the creepage distance, which is 305mm. The insulator string consists of ten individual porcelain insulators. The test arrangement is shown in Fig. 1.

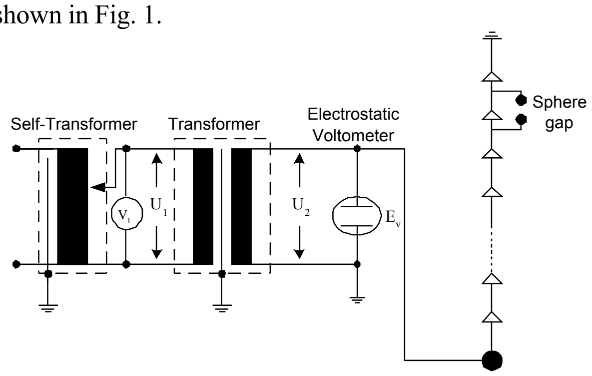

Fig. 1 : Experimental set-up.

A 110V/55kV transformer is fed through a 230V self-transformer. The high voltage U_2 is measured using an electrostatic voltmeter E_v [14] –[15]. At one edge of the insulator string (10th insulator) is connected a transmission line and the other edge (1st insulator) is grounded. In parallel with the *i*-insulator is connected a sphere gap.

By increasing the voltage U_2, the sphere gap critical voltage U_d is being reached. The percentage of the voltage P_i, which is applied in the *i*-insulator, is given by

$$P_i = \frac{U_d}{U_{2i}} \cdot 100\% \qquad (1)$$

Moving the sphere gap in each of the ten insulators and calculating the rates P_i for each insulator the critical voltage of the sphere gap is calculated by the equation

$$\sum_{i=1}^{10} P_i = U_d \quad \sum_{i=1}^{10} \frac{1}{U_{2i}} = 1 \tag{2}$$

The stray capacitances are the reason that the voltage distribution in each insulator is not uniform.

Fifteen series of experiments have been carried out and the average value and the standard deviation have been calculated. The measurements, which were out of the limits given by equation (3), were excluded in order to reduce the measurement error.

$$\mu - 2\sigma \le P_i < \mu + 2\sigma \tag{3}$$

where μ is the average value and σ is the standard deviation.

3 SIMULATION PROCEDURE

The suite of programs for two and three dimensional electromagnetic field analysis, OPERA, uses the finite elements method to solve the partial differential equations (Poisson's, Helmholtz, and Diffusion equations) that describe the field.

The lossy-dielectric solver provides field solution modules that address designs with conducting - dielectric materials and is suitable for the design of electric insulating components. In its simplest form, a combined solution would involve an initial solution of the current flow problem, the output of which is used as a boundary condition for the electrostatic problem.

The electric field intensity **E** is given by [16]-[17]:

$$\mathbf{E} = -\nabla V \tag{4}$$

The divergence of the electric flux density **D** is related to the charge density ρ:

$$\nabla \mathbf{D} = \rho \tag{5}$$

Combining equations (4) and (5) and introducing the dielectric permittivity tensor ε ($\mathbf{D} = \varepsilon \mathbf{E}$) arises the usual Poisson's equation description of the electrostatic potential:

$$\nabla \cdot \varepsilon \nabla V = -\rho \tag{6}$$

A similar equation arises for current flow problems,

$$\nabla \cdot \sigma \nabla V = 0 \tag{7}$$

where σ is the conductivity, and $\mathbf{J} = \sigma \mathbf{E}$.

In time-varying problems, the electric and magnetic fields are normally solved in a coupled manner. Assuming that inductive effects are negligible in semi conducting dielectric problems, the software solves for

$$\nabla \cdot \varepsilon_c \nabla V = 0$$

where,

$$\varepsilon_c = \varepsilon_0 \varepsilon_r - j\frac{\sigma}{\omega}$$

Special routines within OPERA-2d/LD support complex permittivity and thus a complex electric scalar potential.

Tests verified that the SS (Steady-State AC) solution will tend to the ST (Statics) solution as the conductivity approaches zero.

The structural analysis is carried out by separating the region of the model into triangular elements. The density of the finite elements mesh is higher in the critical regions of the insulator than in the rest area around it.

4 RESULTS

4.1. Two dimensional model, electrostatic analysis

The two dimensional model of the insulator string is shown in Fig. 2. The symmetry of the insulator string was exploited when creating the finite element model, resulting in an axi-symmetric two dimensional problem. This arrangement does not, however, account for the three-dimensional topology of the conductor running along one axis of the problem.

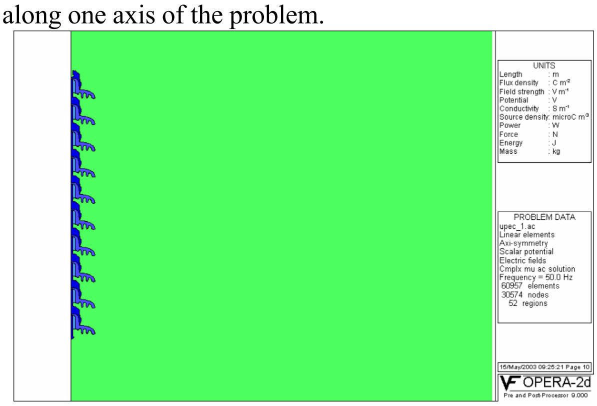

Fig. 2: Two dimensional model of the insulator string.

The OPERA-2d ST (electrostatic solver) has been used in order to calculate the voltage and the electric field distribution. Fig. 3 illustrates the potential distribution along a set of line running parallel and at different distances to the axis of the insulator string. Fig. 4 indicates the electric field distribution along the same lines.

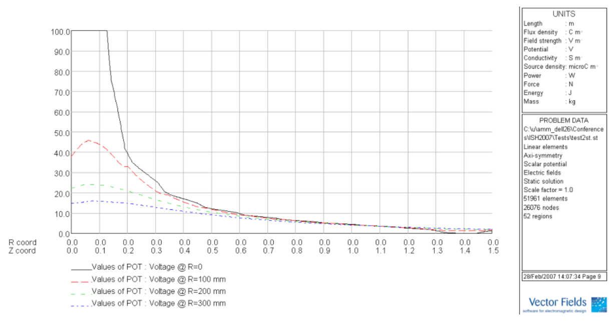

Fig. 3: Potential along lines parallel to the axis of the insulator string.

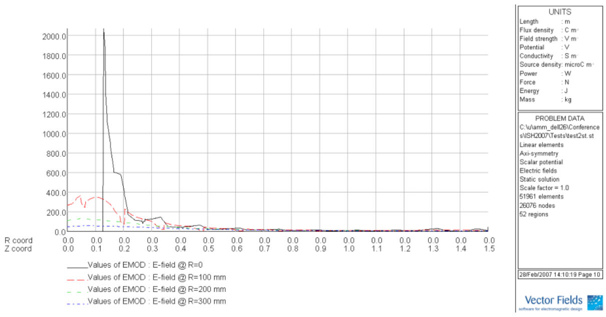

Fig. 4: Electric field along lines parallel to the axis of the insulator string.

4.2. Three dimensional model, electrostatic analysis

The axi-symmetry of the problem is destroyed by the existence of excited and ground conductors which must be included in the three-dimensional model to correctly represent the device. Hence, the cap-and-pin insulator string structures were also simulated using OPERA-3d ST (static solver). The three dimensional model of the investigated insulator string is shown in Fig. 5. In this model, a section of the transmission line is included. The length of the conductor included in the model was set to be approximately equal with the length of the insulator string [6]. The conductor is sited along the X-axis while the insulator string is sited along the Z-axis.

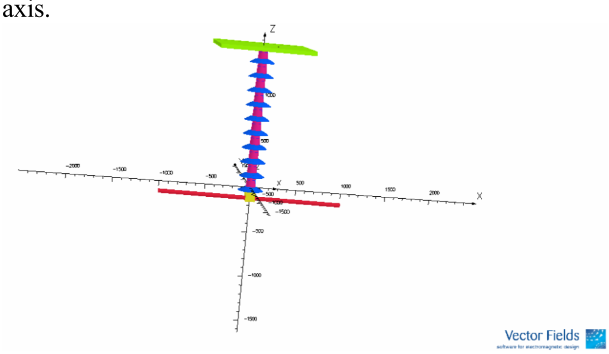

Fig. 5: Three dimensional model of the insulator string.

Recognising the limitations of the electrostatic models in representing the true conducting properties of the materials, the permittivity of metallic parts was significantly increased, in an attempt to better represent its behaviour. A better approach to the problem is the implementation of a true lossy –dielectric solver, as discussed in the following section.

Figs. 6 and 7 represent the potential and the electric field distribution, respectively, along a set of lines running parallel to the axis of the insulators (Z-axis) and at different distances from it. The above lines are vertical to the conductor (X-axis).

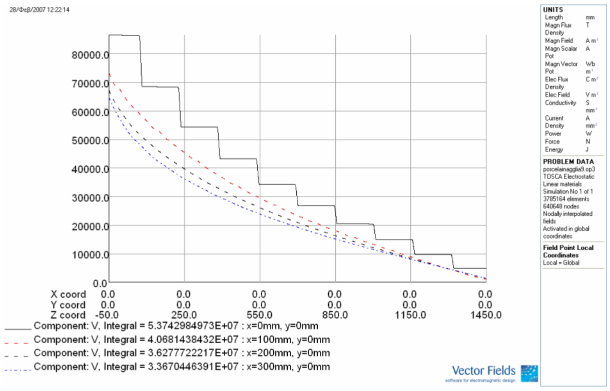

Fig. 6: Potential along lines parallel to the insulator axis and at different distances from this along the X-axis.

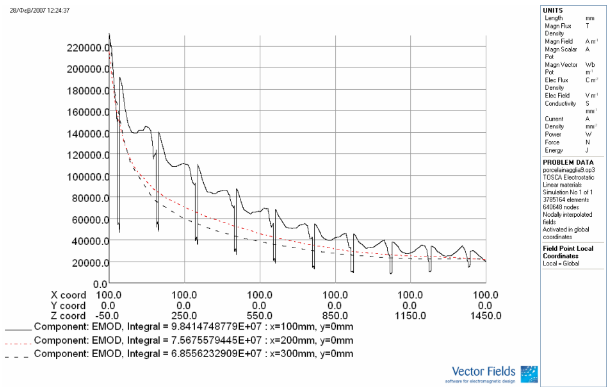

Fig. 7: Electric field along lines parallel to the insulator axis and at different distances from this along the X-axis.

Figs. 8 and 9 illustrate the potential and the electric field distribution, respectively, along a set of lines running parallel to the Z-axis and perpendicular to the Y-axis (away from the conductor).

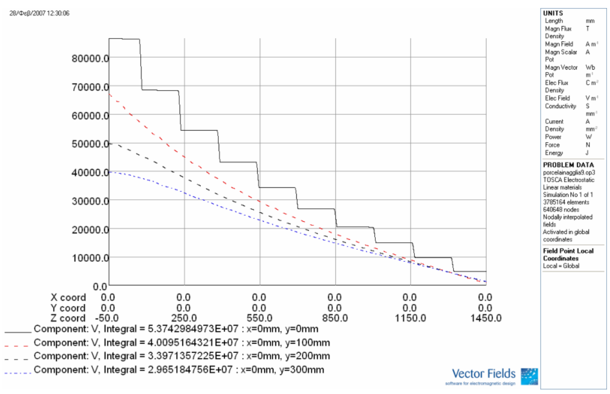

Fig. 8: Potential along lines parallel to the insulator axis and at different distances from this along the Y-axis.

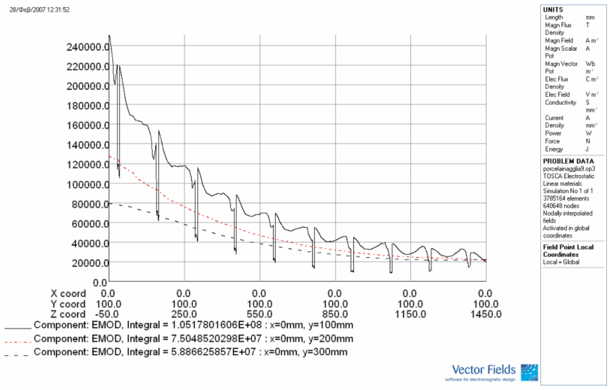

Fig. 9: Electric field along lines parallel to the insulator axis and at different distances from this along the Y-axis.

The results in Figs. 6 – 9 have been arisen from the electrostatic solution, but with an attempt to account for the conductivity of metallic parts through adjustment of its dielectric properties. Comparing the values of the potential and the electric field that have been arisen from Figs. 6 and 7 with the respective values of Figs. 8 and 9, the potential and the electric field levels of Figs. 6 and 7 are higher as the lines are sited nearer the excited conductor. This variation in the field around the azimuth of the insulator strings cannot be calculated using a two-dimensional model.

4.3. Two dimensional model, lossy dielectrics ac analysis

The permittivity and conductivity of all materials, including the cement, porcelain and iron, can be accounted for using a full lossy dielectrics solver – OPERA-2d/LD. The results that were obtained using the lossy dielectrics ac analysis are presented in Figs. 10 and 11.

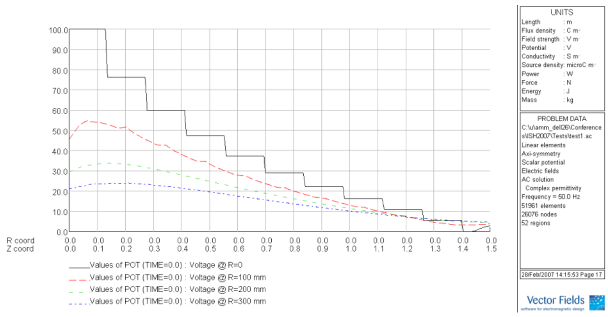

Fig. 10: Potential along lines parallel to the axis of the insulator string.

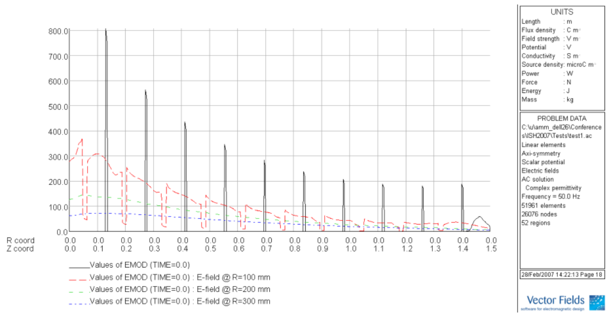

Fig. 11: Electric field along lines parallel to the axis of the insulator string.

5 DISCUSSION

Fig. 12 presents a comparison of two and three-dimensional simulated results obtained by electrostatic (ST) and ac lossy dielectrics (LD) analy sis of the insulator string voltage distribution with experiment. It is significant to note the following:

- OPERA-2d Static results were produced using the true dielectric properties of materials.
- OPERA-3d Static results were produced to account for the three-dimensional aspect, and also account for the high iron conductivity by suitably adjusting its dielectric properties.
- OPERA-2d/LD results were obtained by implementing the full lossy-dielectric solver and accounting for the true conducting & dielectric properties of all materials.

A very good agreement has been ascertained, when comparing the experimental results with simulated OPERA-3d adjusted electrostatic results and with OPERA-2d ac lossy dielectrics results. On the contrary, OPERA-2d electrostatic results show a significant deviation from experiment. The reason of this disagreement is attributed to the fact that the two-dimensional model cannot correctly represent the true conducting properties of each material. In addition, the geometry of the excited and earth conductors significantly alter the axi-symmetry of the problem.

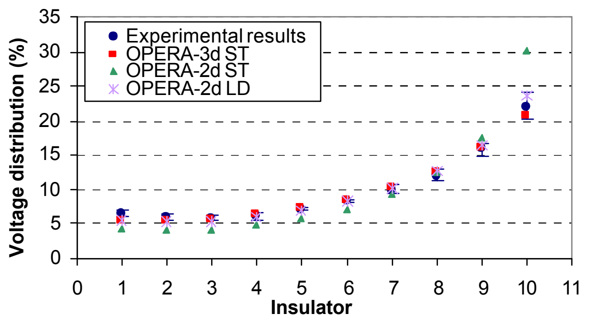

Fig. 12: Comparison of the results for the voltage distribution of the insulator string.

6 CONCLUSIONS

The studied approach is applicable to any insulator type, leading to reliable results in a very fast and economic way, helping the HV overhead line planners to the selection of the right insulator type. A very good agreement has been ascertained, when comparing experimental results with results from simulations using OPERA-3d ST (with adjusted properties for the conducting iron) or OPERA-2d/LD. Two-dimensional model electrostatic results deviate from experiment, due to the lack of correct representation of conducting material properties as well as the presence (and significance) of the non-symmetric parts of the device (i.e. the transmission line and ground). Having optimized the setup and the mesh of the true three-dimensional geometry, it is now intended to exploit new lossy-dielectric solvers in OPERA-3d to account for the conducting as well as the dielectric properties of the materials in a correct geometric representation.

7 ACKNOWLEDGMENT

This work was supported by the National Research Program, EPEAEK Pythagoras II. This Project is co-funded by the European Social Fund (75%) and National Resources (25%).

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