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The effect of trees on calculation of electric fields near 400 kV transmission lines

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Abstract

In a previous study on electric fields near 400 kV transmission lines it was noticed that the differences in calculations and measurements were caused by trees dampening the electric field. This caused the need for further investigation and dampening measurements. The aim of this study is to model single trees and forest, in the calculation of electric fields using the Finite Element Method (FEM).

International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published guidelines for public and occupational exposure to 50 Hz electric fields caused by power transmission lines. They are 5 kV/m and 10 kV/m, respectively. There are some spans, where guideline for public exposure may be exceeded. Thus it is important to find ways to reduce these fields. The 2D-FEM-model created in a previous study consisted of 20-meter-high forest and conductors but it was noticed that the effect of single trees on electric fields should also be considered. Single spruce tree, one-meter-high grass and 20-meter-high spruce forest were created for the example spans. Results of numerical calculation were compared to measurement results. The maximum value of measurement was 4.38 kV/m and the maximum value of numerical calculation was 5.02 kV/m.

The major difficulty is to find adequate material properties for the mathematical model. Therefore the determination of permittivity and resistivity of living organisms is necessary, which depend on several environmental factors.

1 Introduction

In recent years measurements of electric fields caused by transmission lines have increased due to public concern about possible health risks, and the publishing of guidelines by International Commission on Non-Ionizing

Radiation Protection (ICNIRP) [1]. The guidelines for public and occupational exposure to power frequency (50 Hz) electric fields are 5 kV/m and 10 kV/m, respectively.

Electric and magnetic fields have been studied at the Tampere University of Technology (TUT), Department of Electric Power Engineering since the 1980s. In recent years the study has concentrated on decreasing the fields and improving the field measurements. The research group tries, e.g., to find fast and simple ways to predict and prevent disturbances and problems caused by the fields. Both measurements and calculation have been used in the studies. For example, the extremely low frequency electric and magnetic fields have been measured in different power system environments, e.g., at a 400 kV substation [2, 3, 4]. Calculations have been done, for example, for transmission lines, switching substations, power station bus bars, transformer substations and electric arc furnaces using different methods [5, 6, 7, 8, 9].

In the previous study at TUT on transmission line electric fields, 25 line spans were measured in three regions around Finland in 1998 [5]. The electric fields were also calculated and the results were compared to measurements. In 17 spans calculation gave obviously too high results. It was found that the differences in calculations and measurements were often caused by vegetation dampening the field [10]. The reduction effect of vegetation was not analyzed in these measurements. Because of these results, more exact calculations and consideration of the vegetation dampening the field were needed.

Calculations and measurements in 1999 showed that calculated values were generally too high compared to the measured values. It was noticed that the differences were often caused by vegetation dampening the field. The reduction effect of spruce forest was included in the simulation in 1999, but the results achieved then showed that the effect of single trees should also be considered in the model [13]. The aim of this study is to model single trees and forest, in calculation of electric fields using the Finite Element Method (FEM). Our main tool for numerical calculation was the ANSYS calculation software.

2 Methods

During this project electric field measurements and calculations on 400 kV transmission lines were carried out for transmission line spans where forest and especially single trees were considered to dampen the electric field significantly.

Suitable example spans for numerical and analytical calculations were selected from the measured spans. The calculation was carried out for two example cases.

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2.1 Measurements

The measurements took place in the surroundings of Tampere city, Finland (11 measurements/8 spans). The electric field measurements were carried out for the span according to the IEEE Std 644-1994 standard [11]. Figure 1 presents the measurement points perpendicular and parallel to transmission lines. The measurement height was 1.0 m. In addition, the conductor heights of the line at the midspan were measured with a line height meter. Furthermore, air temperature and humidity were measured. Voltages and powers at both ends of the wire were asked from the control room. A 3-axial Wandel&Goltermann's EFA-3 electric field meter (accuracy ±5%, rms) was used in measurements. Frequency band used in the measurements was 30 Hz-2 kHz.

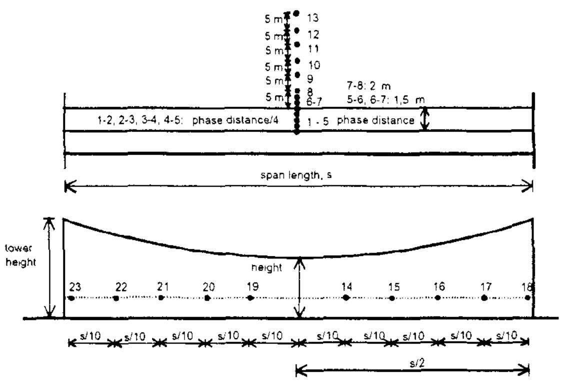

Figure 1: Electric field measurement points perpendicular and parallel to a transmission line span.

2.2 Numerical calculations

ANSYS 5.5 -program was used in numerical calculation of electric fields of 400 kV transmission lines. ANSYS is based on Finite Element Method (FEM). Finite element method provides a greater flexibility to model complex geometry than, e.g., finite difference method. It has been widely used in solving structural, mechanical, heat transfer, and fluid dynamics problems as well as problems of other disciplines. Calculation was carried out in three dimensions (3D). An electrostatic steady state analyses was used. For calculating electrostatic field the LaPlace/Poisson equation was used.

$$\nabla^2(\varepsilon V) = -\rho \qquad (1)$$

where ε is permittivity, V is electric potential and ρ is charge density. The sequences of the calculations are presented below.

2.2.1 Creating the model

The model consisted of three phase wires, two lightning wires, single tree and spruce forest. The calculation area was built of rectangles of different

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sizes and the cross-section area of wires was created with blocks. The volumes in which the phase and lightning wires were located was defined so that the volumes of wires were subtracted from this volume. Building a finite element model requires more of an ANSYS user's time than any other part of the analysis. Preprocessor is used to define the element types, element constants, material properties, and the geometry.

There are two methods to create the finite element model: solid modelling and direct generation. With solid modeling, geometric shape of the model is described, and then the program automatically meshes the geometry with nodes and elements. The size and shape of the elements can be controlled. With direct generation, the location of each node and the connectivity of each element are "manually" defined. Several convenience operations, such as copying patterns of existing nodes and elements, symmetry reflection, etc. are available. In the example calculations solid modeling was chosen. For example, the conductors were modelled with blocks. Solid model can be "sculpted" by using intersections, subtractions, and other Boolean operations. Booleans allow you to work directly with higher solid model entities to create complex shapes. The overlap and value operations were very important because they also allow the different volumes to "communicate with each other" to find a solution.

2.2.2 Defining the material properties

Most element types require material properties. Depending on the application, material properties may be: linear or nonlinear, isotropic; orthotropic, or anisotropic; constant temperature or temperature-dependent.

As with element types and real constants, each set of material properties has a material reference number. The most difficult part was to set the permittivity of the trees. There was not any information about the electro-static attitude of natural vegetation. The permittivity of spruce tree was approximated as 12. After setting material properties the assignment to the different volumes is necessary.

Another problem was material properties of spruce forest. Dielectric constant for dry trees is 3...7, but for living trees the dielectric constant is considerably higher. Furthermore, humidity affects the permittivity of the spruce, because the tree settles in chemical balance with the environment. These material properties could not be defined directly for the forest because the material composition of the forest is heterogeneous. In addition, there is air and additional vegetation between the trees as well, the humidity of the forest and land may vary.

2.3.3 Creating the mesh

After defining the material properties, a mesh was created. The mesh contained rectangular elements. It is essential to generate a suitable mesh regarding to accuracy and speed during the solution process. The mesh was refined in those areas where more accurate results were needed. ANSYS 5.5

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calculates values for electric field in the nodes of the mesh. The default mesh controls that the program produces a mesh that is adequate for the model.

The limit of the elements, which can be created, is 32.000 on ANSYS 5.6 on the local server and 128.000 on ANSYS 5.5 on server in Helsinki. After creating the mesh network the solution procedure can be started.

2.2.4 Setting the loads

For electrostatic analysis with the element type SOLID123 the only boundary condition which is needed is VOLTAGE. Boundary conditions were set on the areas of the conductors and the ground area.

After creating the mesh, the voltages were calculated. The voltages and powers at both ends of the wire were asked from the control room when measuring the fields. The average of the voltage was then calculated. Calculations were made with complex voltages. The main voltages were changed to phase voltages and 120 degree phase difference was applied. Potential on the ground was set to zero, as well as potential on the surface of lightning wires. The calculated potentials were applied on the surface of the phase wires.

2.2.5 Solution

After the mesh network was created and all boundary conditions were set the solution procedure could be started. The calculation time depends on the number of elements. In these models it took about 20 minutes. The path operation to compare the measured data with calculation results was obtained. The solution was calculated and the path for data was defined on the working plane. The list of electric field values was transferred into MS Excel format. In Excel the magnitude of the electric field was calculated with the formula:

$$E = \sqrt{E_{\mathrm{Re}}^2 + E_{\mathrm{Im}}^2} \quad (2)$$

where E_{Re} is solution with real part of voltages and E_{Im} is solution with imaginary part of voltages. In figure 2 a vector plot of the electric field can be seen.

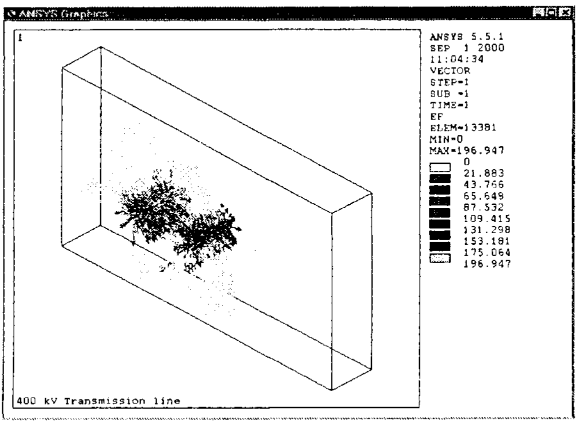

Figure 2: Vector plot of the electric field.

3 Calculation example 1

Height of the spruce forest was 20 meters and the edge of the forest was 20.8 meters from the center phase. Along the perpendicular measurement distance between the origin and forest were five trees of different sizes from 1 to 4 meters. The FEM calculation model was created based on these measures.

3.1 Results for example 1

The highest value in example 1 with numerical calculation was 5.02 kV/m and with analytical calculation 4.04 kV/m. The maximum measured value was 4.38 kV/m. Calculation and measurement results are presented in Fig. 3.

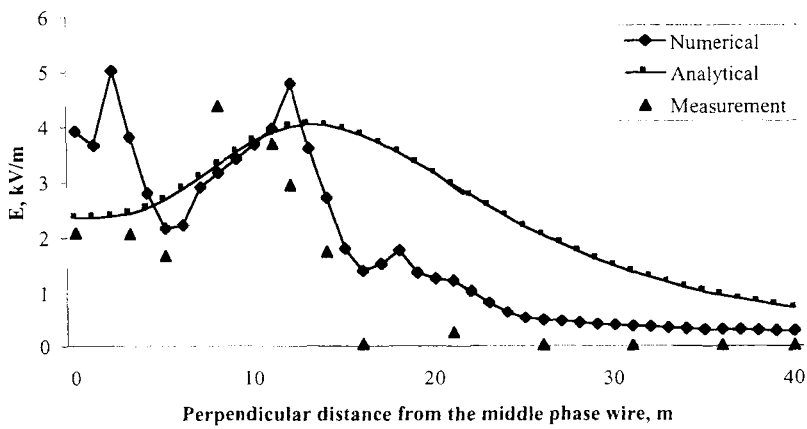

Figure 3: Calculation and measurement results for span example 1.

Several single trees were included in the model. This model is not good enough, because there is a sharp peak near the origin. It is due to defects in meshing procedure. Numerical calculation in this example gives results closer to measured values than analytical calculation apart from the sharp peak near the middle conductor. The measurement results in the forest are very low. 3D FEM model cannot reach similar results since the permittivity of the forest is only an approximation of the real situation. Between the middle conductor and the edge of the forest the results of numerical calculation are closer to measured results than with analytical calculation.

4 Calculation example 2

In example 2 the height of the spruce forest was 20 meters and the edge of the forest was 22 meters from the middle phase. The geometry of this example is presented in figure 4. In the point 14 meters from the middle

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phase there was a small tree nearby. The tree considered was 3-meter-high willow bush. It is notable that height of the bush is an approximation. In the figure there is one-meter-high vegetation under the wires. The FEM calculation model was created based on these measures.

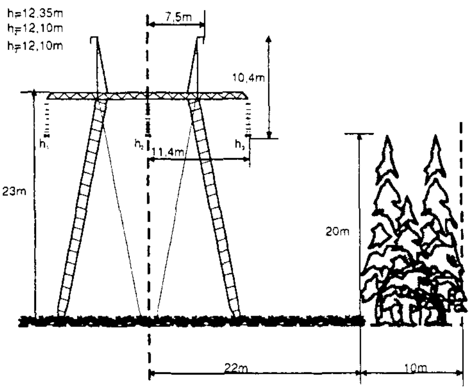

Figure 4: Geometry of the tower in example 2. Conductor heights are h_i. (The figure is not in scale.)

4.1 Results for example 2

The maximum value of numerical 3D calculation is 4.26 kV/m at 10 m distance. The highest values in numerical 2D and analytical calculations occurred nearly at the same distance, 12 m and 13 m. The highest measured value was 3.51 kV/m at 11 m distance. Calculation and measurement results are presented in figure 5.

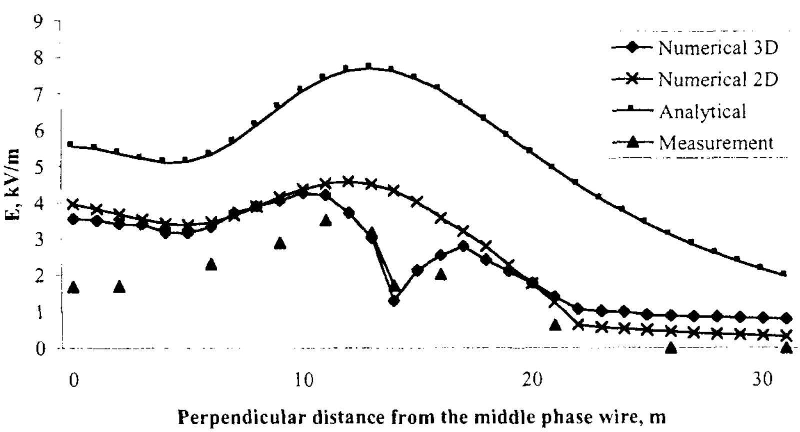

Figure 5: Calculation and measurement results for span example 2.

In the measurements at the point 14 meters from the middle phase, the value of the electric field falls deeply downwards. There was the willow bush

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near this point, which was included in the 3D model. The 2D model does not take into consideration this individual tree, which can be seen from the figure 5. 3D model represents the real situation relatively well, because there is a tolerable difference between measured and calculated values.

Figure 6 presents the results of the 3-meter-high willow bush dampening calculation. It can be seen from the figure that numerically calculated values represent measured values quite well. The maximum percentage difference (16.5%) is at 9 meter distance from the willow bush.

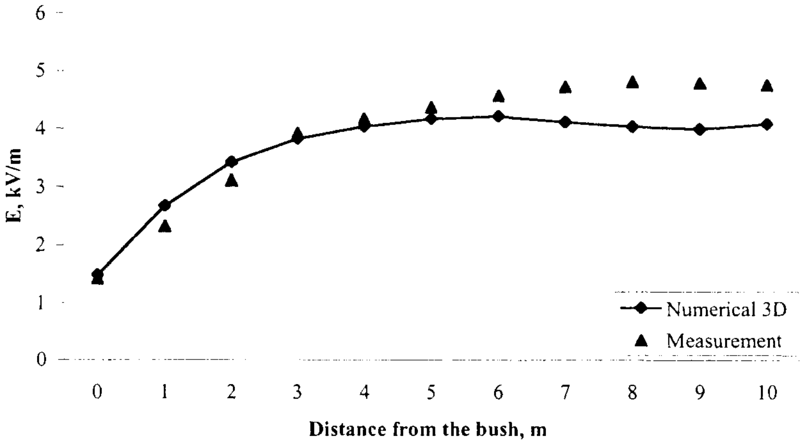

Figure 6: Calculated and measured electric field near 3 m willow bush nearby the span of the example 2.

5 Discussion

In this study the effect of forest and single trees on the calculation of electric fields from 400 kV transmission lines has been modeled. The curve forms representing the calculated values adapt the same curve forms representing the measured values relatively well. However, the calculated values are generally higher than the measured values. When comparing the measured values, numerically calculated values and the analytically calculated values from the figures, the effect of the spruce forest and single trees on the electric field can be seen. Analytical calculation does not consider the dampening caused by vegetation. The created calculation model can be considered moderate, because the maximum value of the electric field is at about the same location on both curves.

The calculation models do not consider the variation of ground height. This could be considered in numerical calculation. However, that would require more exact metering of ground heights around the transmission lines. Preparing a calculation model for electric fields is difficult because of changes in ground height and especially material properties limit the accuracy of the model, since the permittivity has to be approximated for heterogeneous forest. Furthermore, air humidity affects the permittivity. Modeling of single trees was included in modeling to get more accurate results.

Calculations and measurements presented in this paper show, that single trees and forest cause considerable reduction of electric field in the nearby environment. Forest or single trees could be planted at both sides of transmission lines in areas, where reduction of electric field would be needed.

6 Conclusion

As a conclusion it can be stated that forest and single trees do dampen the electric field considerably. Dampening of the electric field near high spruce forest is obvious. However, attention must also be paid to the effect of low vegetation on the field. More detailed modeling and measuring are needed to model the effect of single plants or trees on electric fields. This is important because electric fields of 400 kV transmission lines exceed ICNIRP guidelines for the public (5 kV/m) in some cases. Vegetation might be a possible way to reduce the electric fields, but this requires further investigation. In this study numerical calculation was only done on two spans, so more results would be required to get statistically reliable results.

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SECTION 9

Computational and analytical methods