# Analysis of Eccentric Axial High Voltage Underground Cable

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## Abstract

**Nowadays the electricity energy consumption is rapidly increasing. Along with the growing load demand, the components used in energy systems should be safe, have a long-life and have high quality to ensure energy continuity. The high voltage underground cables (HVUC) that widely used in power systems should be designed for certain criteria. Thus, care must be taken in the design and production of HVUC. For this reason, energy transmission cables should also be safety, long life, high quality, etc. In this study, electric field analysis of a HVUC is carried out. By using Finite Element Method (FEM), an electric field analysis of a 500 kV HVUC is achieved for axial conductor and eccentric axial conductor. In the system simulation, Finite Element Method Magnetics (FEMM) packed software is used.**

## 1. Introduction

HVUCs are basic components used in electricity power systems for energy transmission and distribution [1]. Generally overhead lines are used in transmission systems due to the economic considerations. However, HVUCs are preferred option when there are some restrictions on using overhead transmission lines such as environ-mental conditions, safety, etc.[2]. Especially in transmission and distribution systems of metropolitan areas where overpopulation exists, underground cables are mostly needed. Since it is very hard to maintain the HVUC once it is installed, the cable design and production process become important for energy continuity and reliability.

The layers of an underground cable exposed to electrical stress because of applied high voltage. Thickness of the layers must be calculated to prevent the events as discharge and breakdown due to this stress. Otherwise, there may be a fault in insulation of the cable causing a power outage. When producing a HVUC, it is common to encounter see axially eccentricity in the HVUC which affect also the layer thickness. Therefore, axial eccentricity problem become one of the most important criterion at production process.

## 2. High Voltage Cable Configuration

HVUCs consist of multiple layers as given in Fig.1. The conductor in the center of the cable is the main part that transfers energy and is under applied voltage [3]. In general, copper is preferred for this part. However for some particular circumstances and technical requirements, aluminum is used instead of copper as conductor [4]. The main insulation material of the cable is cross linked polyethylene (XLPE). There is a semi-conductor layer around the copper conductor and XLPE insulation. Semi-conductor layer is used for smoothing the field distortion caused by stranded structure of conductor and roughness of the lead-sheath. The role of the lead- is shielding. The outer layer of the cable is made of high density polyethylene (HDPE) which protects cable from external factors [5].

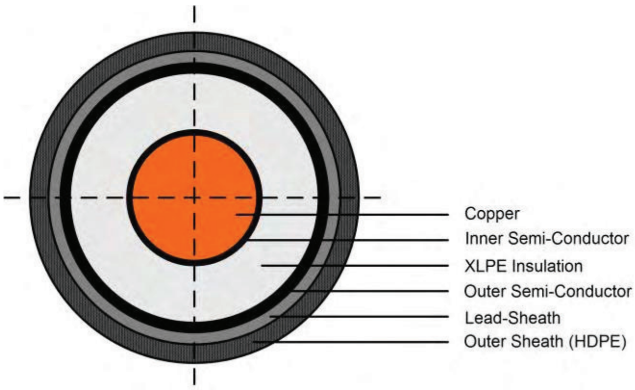


**Fig. 1.** A cross-section view of a HVUC

There are numerous application of HVUC with 380 kV levels. However, 500 kV level is considered as extra-high voltage level. Thus, detailed analysis of the cable structure must be completed for long operation life [4]. Therefore, A lead-sheathed HVUC with copper conductor and 500 kV nominal voltage is selected for analysis. Technical specification of the HVUC is given in Table 1.

**Table 1.** Technical specification of the selected HVUC

| | |
|---|---|
| Nominal Voltage | 500 [kV] |
| Diameter of Conductor, approx. | 72 [mm] |
| Thickness of Insulation | 28,3 [mm] |
| Overall diameter | 161,42 [mm] |
| Thickness of Inner Semi-Conductor | 2,6 [mm] |
| Thickness of Outer Semi-Conductor | 3,32 [mm] |
| Thickness of Lead-Sheath | 6,1 [mm] |
| Capacitance | 0,236 [µF/km] |
| Conductor Resistance at $20^0$C | 0,00589 [ohm/km] |

## 3. Finite Element Method

Basic approach of the FEM is to find the solution that minimizes energy equation. In order to solve a problem of this kind with FEM, five steps should be followed [6],

1. Geometry of problem, materials and boundary conditions must be defined
2. Meshing
3. Writing equations for all elements in mesh
4. Combining all elements in solution domain
5. Solving the acquired equations

Within the scope of this study, V=V(x,y,z) is defined electrical potential, the solution of static electrical field problem requires a quadric homogenous differential solution as in Equation 1. The Equation 1 is defined as "Laplace Equation".

$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \qquad (1)$$

FEM solves this equation by the principle of minimizing the electrical energy equation in solution domain as,

$$W = z\iint \left\{ \frac{1}{2} \left[ \varepsilon_x \left( \frac{\partial V}{\partial x} \right)^2 + \varepsilon_y \left( \frac{\partial V}{\partial y} \right)^2 \right] \right\} dx \cdot dy \qquad (2)$$

The solution that is found in this way is also desired solution of the Laplace equation [6].

In the solution, Cartesian coordinates can be used. Principally, mentioned area is divided into finite elements called "discretizing the area". Generally, triangle finite element is used for discretizing.

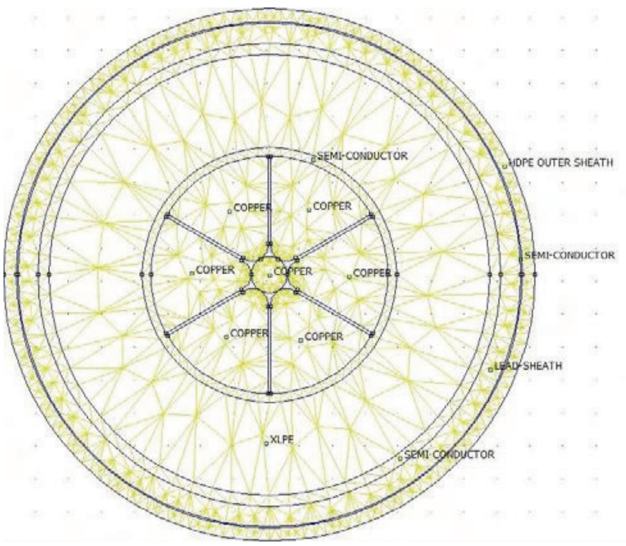


**Fig. 2.** Finite element model of the analyzed HVUC

Thereafter by using boundary conditions, known potentials and material properties, lateral polynomial approach functions, equations of the elements and general equation of the problem is derived. Acquired equation is a big dimensional matrix with many zeros. By solving this linear equation system with an iterative numerical solution method, node potential of triangle elements are obtained. Depending upon potential values and element's potential approach functions, potentials and electrical field values can be calculated in any point of the area. HVUC is modeled as given in Fig. 2. with FEMM software package.

## 4. Modeling and Analysis

For selected 500 kV HVUC, two types of analyze are completed. Primarily, an electric field analysis is carried out for axial cable whose conductor is at the center. Secondly, conductor of the cable is eccentric about 6 mm. In both situations, minimum and maximum electrical field of the layers are calculated and given in Table 3 and 4. In order to solve the problem in FEMM, required data and specification of the system is given in Table 2.

**Table 2.** Data and specifications of the problem

| | |
|---|---|
| Mesh Size | 1 |
| Number of Finite Elements | 21619 |
| Relative Permittivity of Copper | 1 |
| Relative Permittivity of Semi-Conductor | 3,2 |
| Relative Permittivity of XLPE | 2,3 |
| Relative Permittivity of HDPE | 2,3 |
| Boundary Condition of Conductor | $\frac{500}{\sqrt{3}}$ [kV] |
| Boundary Condition of Lead-Sheath | 0 [V] |

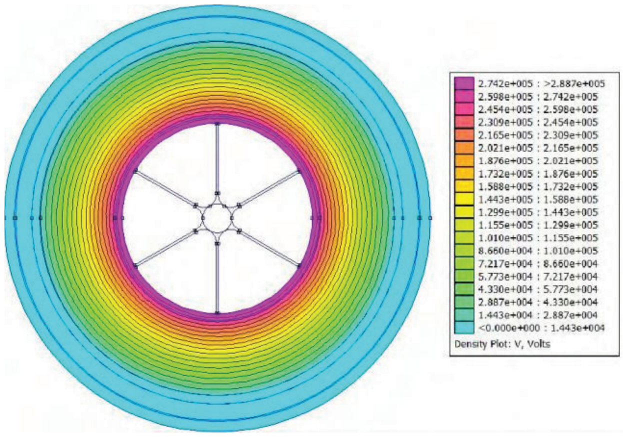


**Fig. 3.** Voltage distribution of a single-core 500 kV HVUC

As seen in Figure 3, when the conductor is at the center of the cable, potential distribution become homogenous as desired. A potential curve between conductor surface and lead-sheath is given in Fig. 4. Although the voltage distribution on the layers are linear, electric field distribution on each layer is varying because of different relative permittivity and radius of materials.

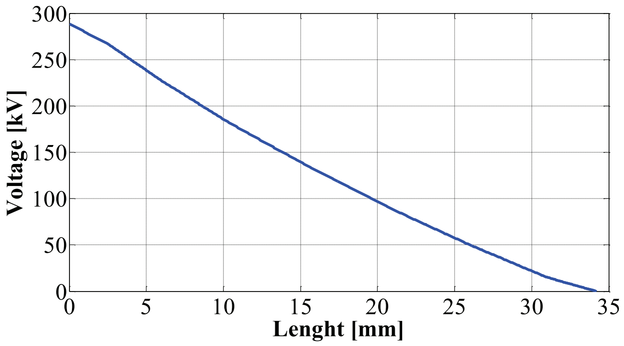


**Fig. 4.** Voltage distribution of a single-core 500 kV HVUC between conductor and lead-sheath

To get a regular electric field distribution, the condition in the Equation 3 should be satisfied [1].

$$\varepsilon_1 \cdot r_1 = \varepsilon_2 \cdot r_2 = ........... = \varepsilon_n \cdot r_n \quad (7)$$

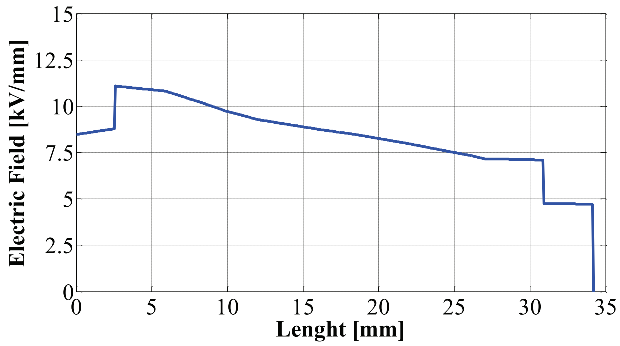


**Fig. 5.** Electric field distribution of a single-core 500 kV HVUC between conductor and lead-sheath

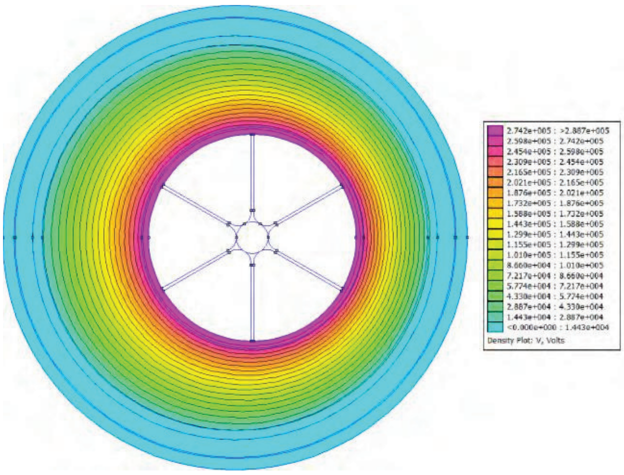

**Fig. 6.** Voltage distribution of a single-core 500 kV HVUC with eccentric conductor

In Fig. 6, potential distribution of 500 kV HVUC is given while the conductor is eccentric about 6 mm. the potential of the narrow side of the cable is raised and voltage distribution become inhomogeneous.

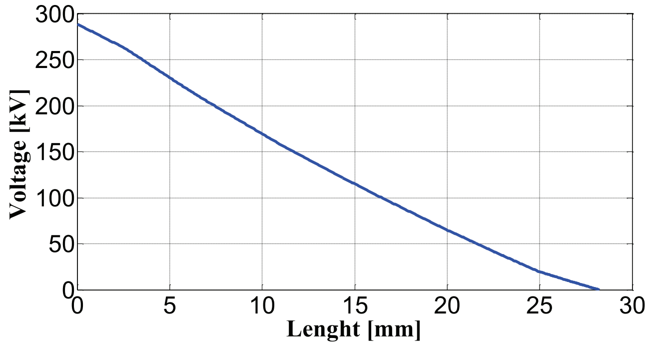


**Fig. 7.** Voltage distribution of a single-core 500 kV HVUC between conductor and lead-sheath with eccentric conductor

In addition to this, electric field stresses on the layers are increased to a high level. The electrical field stress between conductor and lead-sheath can be seen in Fig. 8.

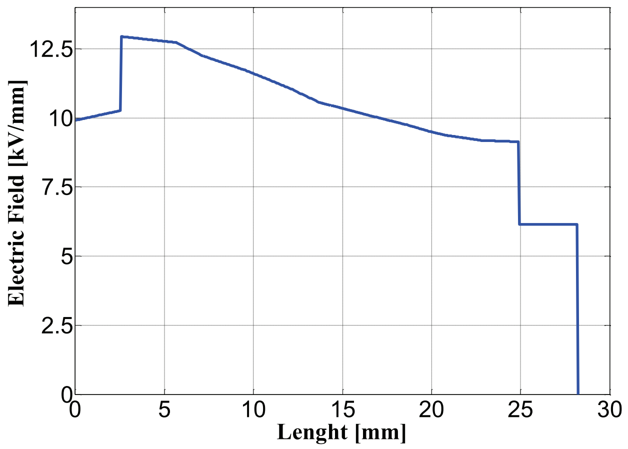


**Fig. 8.** Electric field distribution of a single-core 500 kV HVUC between conductor and lead-sheath with eccentric conductor

In accordance with the obtained result, electric field stress in eccentric cable is much higher than the normal situation. The criterion for eccentricity of HVUCs is indicated in IEC 62067 standard as given below [8].

$$t_{\min} \geq 0{,}90 \cdot t_n \quad (4)$$

$$\frac{T_{\max} - T_{\min}}{T_{\max}} < 0{,}1 \quad (5)$$

where Tmax is the maximum thickness, Tmin is the minimum thickness and $t_n$ is the nominal thickness in millimeters [3]. When the result of the Equation 5 is bigger than the standard value, this cable is technically unacceptable for production.

## 5. Conclusion

In this study, electric field analysis of a 500 kV nominal voltage underground cable is carried out with FEM for axial and eccentric axial cable. Although the field analysis of coaxial cylindrical systems can be easily made, it is hard to make analysis of an eccentric axial cylindrical system. FEM makes it easy for analyzing of eccentric axial cylindrical systems. For this reason, analysis of the problem is made by FEM.

**Table 3.** Electric field values of layers calculated by FEMM for normal cable

| Layers | $E_{min}$ [kV/mm] | $E_{max}$ [kV/mm] | $E_{avg}$ [kV/mm] |
|---|---|---|---|
| Inn. Semi-Conductor | 8,79 | 8,47 | 8,63 |
| XLPE Insulation | 9,09 | 11,08 | 7,1 |
| Out. Semi-Conductor | 4,72 | 4,75 | 4,69 |

**Table 4.** Electric field values of layers calculated by FEMM for eccentric cable

| Layers | $E_{min}$ [kV/mm] | $E_{max}$ [kV/mm] | $E_{avg}$ [kV/mm] |
|---|---|---|---|
| Inn. Semi-Conductor | 9,90 | 10,27 | 10,09 |
| XLPE Insulation | 9,14 | 12,94 | 11,04 |
| Out. Semi-Conductor | 6,14 | 6,15 | 6,14 |

There are different layers in a HVUC. These layers are exposed to a certain electric field stress. In addition to this, dielectric strength of each layer must be higher than the exposed maximum electric field. Otherwise, discharge and breakdown events can be probably seen on the cable.

The calculated maximum, minimum and average electric field values of layers is given in Table 3 and 4. In eccentric axial cable, it is clearly seen that the electric field stress on the layers have a higher value in comparison with axial cable. For this reason, to prevent discharge and breakdown events, the production must be done conscientiously.

Consequently, in eccentric axial cable, electric field distribution is not regular. To come over and analyze this problem clearly, FEM can be used to make the analysis easily.

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