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Research Article

Analysis of the Effect of Air Gaps on the Electric Field in the Insulation Material of High Voltage Transmission Cables

Yıldırım ÖZÜPAK[1*]

[1] Dicle University, Silvan Vocational School, Electrical Department, Diyarbakır

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Abstract

High voltage (HV) cables are widely used in the transmission and distribution of electrical energy. The design and manufacture of these cables with great precision are of great importance for power systems. Mistakes made during the manufacturing phase and defects that may occur in the structure of the cable material can cause premature aging and continuous malfunctions in the cables. Factors such as air gaps, foreign substances, and moisture in the insulating material may cause punctures and insulation problems in high voltage cables. In this study, the effects of air gaps left as manufacturing defects on the electric field distribution in the insulation of high voltage cables used in power systems were investigated. The effects of 154 kV high voltage cable, the air gap in different coordinates, and diameters in the insulating layer on the electric field distribution in the cable have been investigated. For this analysis, the Finite Element Method (FEM) and ANSYS@Workbench program which realizes a solution based on this method were used. It has been found that the diameter and location of the air gap significantly affect the electric field distribution of the high voltage cable.

Keywords: Electromagnetic field, HV cable, Finite Element Method (FEM), ANSYS.

Yüksek Gerilim İletim Kablolarının Yalıtım Malzemesindeki Hava Boşluklarının Elektrik Alana Etkisinin Analizi

Öz

Elektrik enerjisinin iletimi ve dağıtımında yüksek gerilim (YG) kabloları yaygın olarak kullanılmaktadır. Bu kabloların tasarım ve imalatlarının büyük bir hassasiyetle gerçekleştirilmesi güç sistemleri için büyük önem teşkil etmektedir. İmalat aşamasında yapılan hatalar ile kablo malzemesinin yapısında oluşabilecek bozukluklar, kablolarda erken yaşlanma ve sürekli arızalara neden olabilmektedir. Yalıtkan malzeme içerisinde hava boşlukları, yabancı maddeler ve nem gibi etmenler yüksek gerilim kablolarında delinmeye ve yalıtım sorunlarının meydana gelmesine neden olabilmektedir. Bu çalışmada, güç sistemlerinde kullanılan yüksek gerilim kablolarının yalıtımında, imalat hatası olarak bırakılan hava boşluklarının elektrik alan dağılımı üzerindeki etkileri incelenmiştir. 154 kV'luk yüksek gerilim kablosunun, yalıtkan tabakasında farklı koordinatlarda ve çaplardaki hava boşluğunun kablodaki elektrik alan dağılımı üzerindeki etkileri incelenmiştir. Bu analiz için Sonlu Elemanlar Yöntemi ve bu yönteme dayanarak çözüm gerçekleştiren ANSYS@Workbench programı kullanılmıştır. Hava boşluğu çapının ve konumunun yüksek gerilim kablosunun elektrik alan dağılımına önemli ölçüde etki ettiği görülmüştür.

Anahtar Kelimeler: Elektromanyetik akı, YG kabloları, Sonlu Elemanlar Yöntemi (SEY), ANSYS.

yildirimozupak@gmail.com

1. Introduction

Modern Electricity is the main source of energy today. Without electricity, many daily activities are interrupted. In order to provide the distribution of electricity to consumers without any problem, there is a system that forms the national grid network and is used in transmission and distribution systems. The national network is the system using transmission lines. In this system, different levels of high voltage are coordinated. Transmission lines or power lines are an important part of the power network.

The transmission line provides the basic link between consumers and electricity generation. Electric power transmission is the collective movement of electrical energy from a production area such as a power station to an electrical substation. The interconnected lines that facilitate this movement are known as the transmission network. This is different from the local wiring between high voltage substations and customers and is typically referred to as electrical power distribution. The combined transmission and distribution network is part of the electricity distribution known as the power grid. Efficient transmission involves reducing currents by increasing the voltage before transmission and stepping it down at a substation at the far end. Transformers are used for this purpose in AC power transmission.

Generally, common events occurring in the transmission line are electric field and magnetic field. The electric field is proportional to the voltage (Özüpak, 2021). If the voltage levels rise, the electric field also increases rapidly. Electric field occurs in every transmission line under-voltage, and this field exists even when there is no current. The magnetic field is directly related to the current.

Since energy production facilities and consumption facilities are generally distant from each other, high voltage is required in order to make the energy transmission technically and economically in the most appropriate way (Boggs, 2012). Efficient transport of high-level powers over long distances can only be achieved with high voltage. For this reason, high voltage equipment used in power systems is the backbone of all modern systems. Energy transmission with high voltage is generally done by overhead lines. However, high voltage cables are preferred in cases where there are some physical and environmental imperatives (visual pollution, security, space constraints, etc.). It provides great convenience, security, and energy continuity in situations where energy needs to be transported, especially in residential areas with a dense human population. In order to use high voltage cables in a healthy way, the main insulation material must be produced of high quality (Aaron at al., 2013).

The main insulation layer is the most important layer of the high voltage cable and the quality of this material directly affects the life of the cable (Kocatepe and Arıkan, 2012). In addition, it is known that foreign materials, voids in the insulation, and partial discharges due to these have an effect on the life of the cable (Lachini at al., 2010; Phung at al., 2016; Özüpak, 2021). In many studies in the literature, the effects of the gaps in the insulation on partial discharge and cable life have been examined. Partial discharge occurs when the electric field exposed to the air gaps in the cable exceeds the puncture resistance of the air. This discharge may cause the insulation material to deteriorate and, consequently, to complete perforation that can pose a danger to the entire system (Özüpak at al., 2019; Chengaiah and Satyanarayan, 2012). Magnetic materials were examined in the study named Reliable mechanical connector design and resistance control analysis for high voltage cables (Feyzioğlu, 2021).

In this study, electric field analyzes were carried out for different coordinates and diameters of air gaps in the main insulation of a single-core high voltage cable with a nominal voltage of 154 kV. For this analysis, the Finite Element Method and ANSYS@Workbench program which realizes a solution based on this method were used.

2. Material and Methods

A. Analytical Method

One of the most important problems in analytical solutions used in high voltage technique is the electric field analysis that requires the solutions of Laplace and Poisson equations (Kocatepe and Arıkan, 2012). Especially in cases with complex geometry, analytical solutions become very difficult. High voltage cables have a cylindrical structure and field equations of the cylindrical electrode system are used for their analysis. The electric field expression for the cylindrical electrode system is given in Equation (1).

$$E = \frac{1}{r}\frac{U_0}{ln\left(\frac{r_2}{r_1}\right)} \tag{1}$$

Here r is the radius of the electric field value to be calculated, r_1 is the conductor radius, r_2 is the radius of the cable shield, and U_0 is the voltage between the cable shield (ground). The air gap in the insulation material is generally spherical. Therefore, the calculation of the electric field in the air gap requires the solution of the Laplace equation in spherical coordinates.

As it is known, the Laplace equation in spherical coordinates depends on r, θ, and Φ. Here r is the radius of the sphere, and Φ is the axial angle changes. However, the air gap diameter is considerably smaller than the axially symmetrical cable diameter. Therefore, the Laplace equation in spherical coordinates transforms into a two-dimensional Laplace equation that depends only on r.

$$\nabla^2 = \frac{\partial}{\partial r}\left(r^2 \frac{\partial V}{\partial r}\right) + \frac{1}{sin\theta}\frac{\partial}{\partial \theta}\left(sin\theta \frac{\partial V}{\partial \theta}\right) = 0$$

(2)

As can be seen, an analytical solution of the two-dimensional Laplace equation given above is difficult. However, the expression that approximates the electric field value in the air gap is given in equation (3) (Kocatepe and Arıkan, 2012).

$$E_c = \left(\frac{3.\varepsilon_d}{\varepsilon_c + 2.\varepsilon_d}\right).E_d \tag{3}$$

Here, E_c is the electric field in the cavity, E_d is the electric field in the insulating material, ε_d is the relative dielectric constant of the insulating material and ε_c is the relative dielectric constant of the material in the cavity.

B. Finite Element Method

The finite element method is a numerical method used to obtain approximate solutions to boundary value problems of physical mathematics. This method is based on the principle of minimizing the energy in the region whose electric or magnetic field is to be examined. The area within the zone can be an electric or magnetic field of the Laplace and Poisson type. In the finite element method, as in other numerical methods, the method of finding a finite number of unknown sizes of a system in terms of the known sizes of the system is followed. The solution of any problem with the finite element method is accomplished in the following five steps (Chengaiah and Satyanarayan, 2012):

- Determining the problem geometry, material properties, and boundary conditions,

- The separation of the solution area into finite elements or sub-regions,
- Writing basic equations for each element,
- Combining all the elements in the solution area,
- Solution of the obtained equation system

3. Results and Discussion

In this section, electric field analyzes have been carried out using the FEM package program. For the analysis, XLPE insulated single-core high voltage cable with a nominal voltage of 154 kV was used.

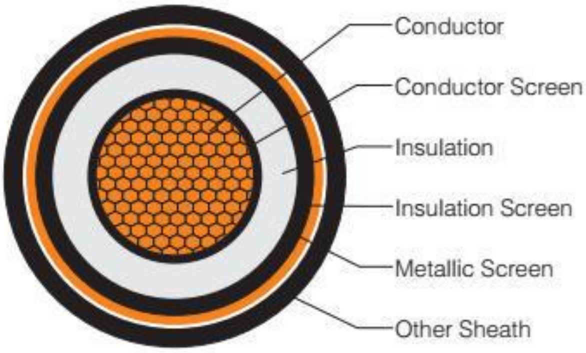

Figure 1. The sectional view of the analyzed cable

The section view of the analyzed high voltage cable is given in Figure 1 and the technical data of the cable are given in Table 1.

Table 1: Cable parameters used in the study

XLPE Materials	Value
Rated voltage *(kV)*	154
Solid conductor radius *(mm)*	53.5
Solid conductor thickness *(mm)*	8.9
Insulation thickness *(mm)*	20
Permittivity	5
Conductivity *(S)*	0
Resistance *(Ω)*	0,00903Ω/km

Analysis of the high voltage cable was carried out in two different ways. First, the radius of the airspace was fixed, and the void position was analyzed when it was variable. Then, the radius of the air gap was analyzed while it was variable.

The section view of the cable to be used for both scenarios and the air gap in the cable is given in Figure 2.

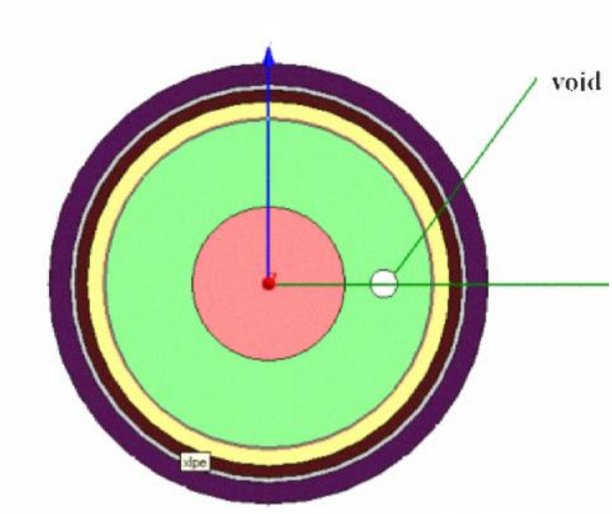

Figure 2. The sectional view of the cable used in the study

The electric field distribution obtained when there is no air gap in the insulation of the high voltage cable is given in Figure 3.

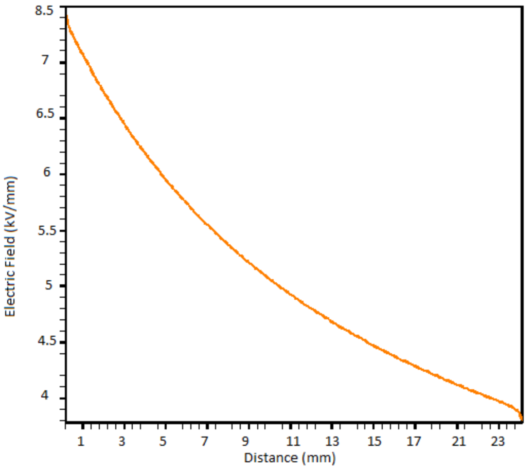

Figure 3. An electric field without an air gap

As can be seen from Figure 3, the electric field distribution in a high voltage cable is linear. The electric field strength in the insulation varies inversely with the radius.

A. Electric Field Caused by an Air Gap at Different Distances From The Conductor

In this part, the electric field distribution in the case of an air gap of constant diameter and in different coordinates within the cable insulation has been investigated. In Figure 4, the area distribution when the air gap center is 2 mm away from the conductor is given. While the field distribution continued linearly, the linearity in the air gap was distorted and the electric field strength reached the value of 9.05 kV/mm in the air gap. The reason for this increase is that the relative dielectric constant of air is much lower than XLPE material. The maximum electric field strength in the air gap is considerably greater than the puncture field strength of the air. Therefore, a partial discharge will occur in the air gap in the insulation and the electric field value will decrease to zero. In this study, since it is aimed to determine the electric field strength in the air gap, partial discharges that may occur in the vacuum are ignored.

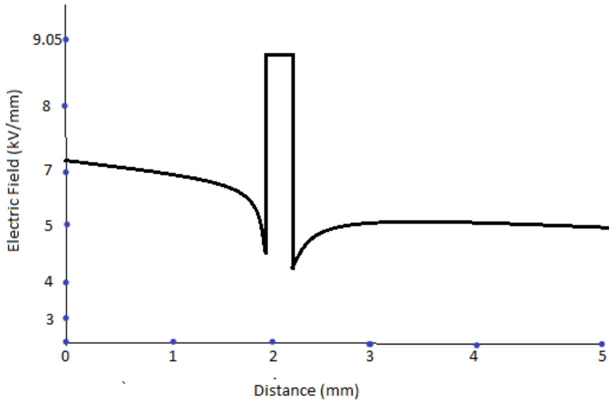

Figure 4. Electric field distribution for the air gap 2 mm from the conductor

The electric field distribution in the case that the air gap of the same diameter is at a distance of 17 mm from the conductor is given in Figure 5.

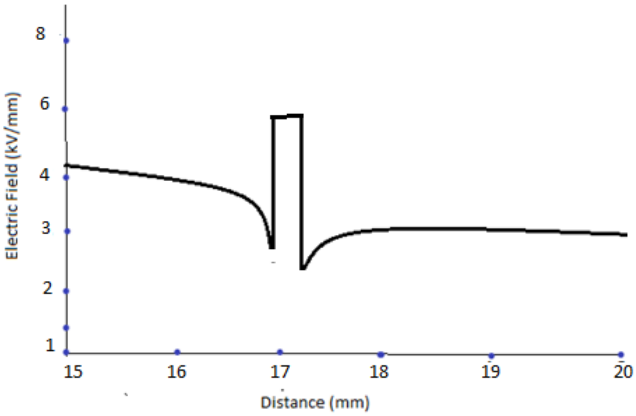

Figure 5. Electric field distribution for the air gap 17 mm from the conductor

As seen in Figure 5, the electric field intensity value in the air gap at a distance of 17 mm from the conductor has reached 6.03 kV / mm. This value is greater than the puncture field strength of the air. The maximum electric field strength values obtained in the case of air gaps of fixed diameter and different coordinates in the insulation are given in Table 2.

Table 2. Electric field strength distribution depending on the distance

Distance *(mm)*	2	5	8	12	17	20
Electric Field *(kV/mm)*	9.05	8.44	7.84	6.63	6.03	5.42

Considering the simulation results, it was determined that the electric field strength in the air gap is higher near the conductor and lower at the points farther from the conductor. However, even in the farthest case, partial discharges occur in the air gap that can result in complete perforation. For this reason, the location of the air gap in the insulation is of great importance.

B. The Effect of Change of The Radius of The Air Gap On The Electric Field

In this section, a fixed point in the cable insulation has been chosen and the electric field distributions have been examined by changing the diameter of the air gap. The distance of the air gap to the conductor is chosen as 7 mm. Similar to previous analyzes, the perforation strength of the air has been exceeded here, too. For this reason, the insulation material should be as homogeneous as possible and the gap diameters in it should be as small as possible during the manufacturing phase. Otherwise, heating, puncture, and premature aging events may occur in the insulation material.

In the case where the radius is r = 0.35 mm, the maximum electric field strength in the air gap is calculated as 8.81 kV/mm. This electric field value is very close to the value in the initial case where the radius is smaller. Therefore, the effect of the radius change on the maximum field strength in the air gap is very small. However, the point to be considered here is that the volume of partial discharge increases with the increase of the radius. Partial discharge occurring in larger radii causes the material to deteriorate and age in a shorter time. In Table 3, values of maximum electric field strength in fixed point and air spaces with different radius are given.

Table 3. Electric field distribution depending on the radius of the cavity

Radius *(mm)*	0.06	0.22	0.35	0.52
Electric Field *(kV/mm)*	8.71	8.76	8.81	8.90

As seen in Table 3, the maximum field intensity in the air gap increases slowly with the radius change. The reason for the low increase is that the dimensions of the air gap are very small compared to the cable sizes. The geometry of the analyzed high voltage cable and the air gap is given in Figure 6.

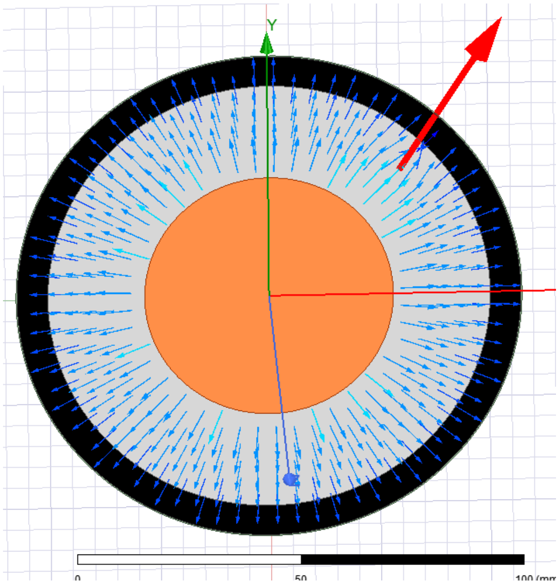

Figure 6. The geometry of the analyzed high voltage cable and the air gap

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4. Conclusion

In this paper, electric field analysis was performed for a single-core XLPE insulated high voltage cable with a nominal voltage of 154 kV. The study was carried out for the presence of air gaps in different coordinates and diameters in the cable insulation. As a result of the analysis, it was seen that the field strength in the air gap changes depending on the distance from the conductor. It was determined that the field strength in the cavity is higher at the points close to the conductor, and lower at the far points. However, the value of the field strength in the vacuum is also important. The maximum electric field strength value in the cavity should be less than the puncture resistance of the cavity material. Otherwise, partial discharge and consequently heating, perforation, and premature aging events occur in the space. Air gap diameter also has an effect on material life. The gap diameter does not affect the maximum field strength value very much. However, the large diameter of the cavity causes the partial discharge to destroy a larger area and consequently the rapid aging of the material. As a result, the production of high voltage cable insulations and insulating materials exposed to high voltage should be made with care.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

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