The Effect of Insulation Defects on Electric Field Distribution of Power Cables

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Abstract: **Electricity transmission with high voltage is usually done with overhead lines by using bare conductors. Population growth in settlements makes it necessary to transmit and distribute electric energy from underground. Insulation is the most important factor in ensuring that electrical energy transmission and distribution with underground cables safely. The insulation problems that may occur in the production of underground cables cause rapidly aging and failures due to partial discharges. In this study, the effect of defects that may occur in the insulation of XLPE insulated cables to electric field distributions in the cable is investigated. In the XLPE insulated cables with 20.3/35 kV, 240 mm^2 and 400 mm^2 conductor cross-sections; electrical field distributions have been investigated by considering problems such as air bubble, water droplets and fiber-like solid particles. Cases of these defects on the surface of the conductor, in the insulator and on the surface of the insulator were considered. The Finite Element Method Magnetics (FEMM) program was used in the analyses.**

I. INTRODUCTION

Due to the increasing population density, demand for electricity is increasing day by day so more power generation, transmission and distribution are needed. New systems are being added day by day to existing systems; ways of power generation and transmission are sought at higher capacities. More power transmission is possible by increasing the value of the voltage. As energy transmission is usually provided by overhead lines, the side effects of the rise of the voltage value are mainly concentrated on noise pollution, safety, electric and magnetic field distributions. However, the physical problems caused by the constrictions in the settlements and the high buildings along the sides during expansion have obliged underground transmission of electric energy with high voltage [1, 2].

Working at high voltage levels reveals insulation problems. For this reason, the production of underground cables should be as careful and high quality as possible.

Defects that occur during the production of underground cables cause partial discharges. Electric fields formed at these points will cause damage due to exceeding breakdown strength. Therefore, life shortens and damages occur on the cables, cable joints and terminations [1, 2].

Studies in the literature have shown that these partial discharges force air bubbles, water droplets and other foreign particles to behave in the form of treeing in the insulator [3, 4]. In addition, it has been found that the movement in the treeing state causes partial discharge again with negative effect on the electric field distribution, and all these events are repeated in the form of a vicious circle shortening the cable's life until the cable is damaged [5, 6].

Finite Element Method (FEM) software is used for electric and magnetic field analysis in underground cables [7, 8, 9].

In this study, the geometrical dimensions of high voltage cables with 20.3/35 kV, single core, XLPE insulated, 240 mm^2 and 400 mm^2 conductors, which are frequently used in electrical power distribution, are used for analyses. Within the cable in different coordinates; the effect of various cable defects on the electric field distribution with different scenarios has been investigated. As a result of the examinations, comparative results were given for each defect relative to the faulty cable and a general evaluation was made for all the scenarios in the related section. In this study, The Finite Element Method Magnetics (FEMM) package program is used for analysis.

II. METHOD

Since the structures of the high-voltage cables are cylindrical, the electric field analysis of a single-core cable can be performed by using the electric field equations of the coaxial cylindrical electrode system in the high-voltage technique. In equation (1), the electric field intensity and in equation (2), magnetic field intensity expressions are given for a coaxial cylindrical electrode system.

$$E = \frac{1}{r}\frac{U_0}{\ln\frac{r_2}{r_1}} \tag{1}$$

Where r is the radius value for the point of electric field to be calculated, r_1 is the radius of the inner conductor, r_2 is the radius of the cable shield, U_0 is the cable phase-neutral voltage or voltage across cable insulation.

$$B = \frac{\mu I}{2\pi r} \tag{2}$$

Where r is the radius value for the point of magnetic field to be calculated, I is the cable rated current, μ is the magnetic permeability. Finite Element Method Magnetics package program is used for analyzing [10, 11].

III. ANALYSIS

In this section, cable geometries are defined on the FEMM package program for 20.3/35 kV, XLPE insulated, stranded copper conductors, 1×240/25 mm^2 and 1×400/35 mm^2, single-

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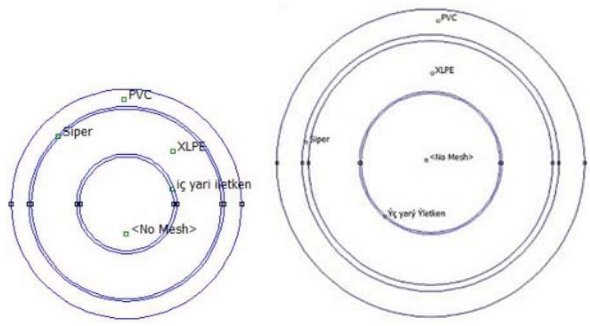
core high voltage cables. Drawings of the cables on FEMM program are given in Fig. 1.



a) 1×240/25 mm^2 b) 1×400/35 mm^2

Figure 1: FEMM drawings of the analyzed cables

The parameters related to the cables to be analyzed and the electrical properties of the materials used in the modeling of cable defects are given in Tables 1 and 2, respectively [8].

Table 1
The cable parameters

Parameters	Cable240	Cable400
Rated voltage (kV)	36	36
Conductor cross sectional area (mm^2)	240	400
Diameter of conductor (mm)	18,8	23,8
Inner semiconductor diameter (mm)	20	24,4
Outer diameter of insulation (mm)	38	41,9
Outer diameter of sheath (mm)	46	52,7
Shield cross sectional area (mm^2)	25	35
Current carrying capacity (A)	576	697

Table 2
Electrical properties of materials used in analyses

Material	Electric field strength E_d (kV/cm)	Relative permittivity ε_r	Relative permeability μ_r
XLPE	1000	2,3	1
Air	30	1	1
Fiber	150	4	1
Water	-	80	1
PVC	100	3,4	1
Ground	-	-	1

Four different scenarios were identified in the analysis. The flaws in these scenarios and their location in the cable are detailed below.

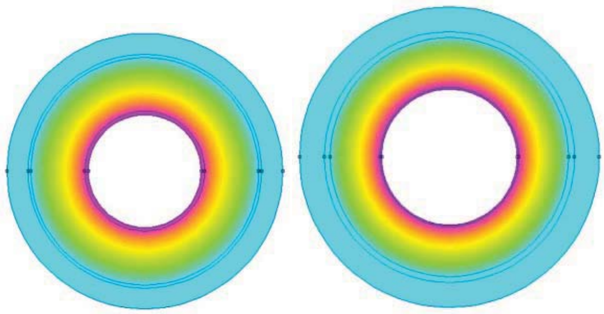
1. Ideal (perfect) cable
2. 0.5 mm diameter air bubble
   a) On the conductor surface
   b) In the insulator
   c) On the insulator surface
3. 0.5 mm diameter fiber
   a) On the conductor surface
   b) In the insulator
   c) On the insulator surface
4. 0.5 mm diameter water droplets
   a) On the conductor surface
   b) In the insulator
   c) On the insulator surface

All the scenarios were analyzed in the cylindrical coordinate system, under the nominal voltage with cable depth of 1000 mm, the nominal current flow from the conductor, and the boundary conditions that would occur if the cable shield was grounded.

A. Scenario 1: Field Distributions for Ideal Cable

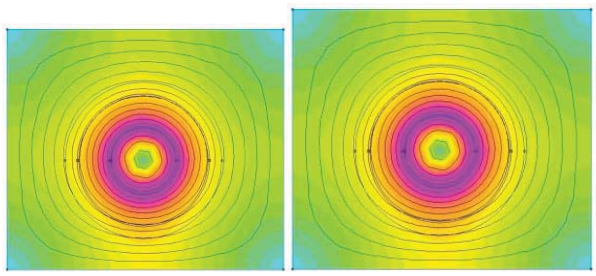
In the high-voltage cable in the absence of any defects (ideal cable) electric field and magnetic field distribution in the cable are shown in Fig. 2 and Fig. 3 respectively.

As can be seen in Fig. 2 and Fig. 3, the electric field and magnetic field distribution decrease logarithmically in inverse proportion to the distance as the distance from the cable axis in the ground is increased.



a) 1×240/25 mm^2 b) 1×400/35 mm^2

Figure 2. Electric field distributions for the ideal cables



a) 1×240/25 mm^2 b) 1×400/35 mm^2

Figure 3. Magnetic field distributions for the ideal cables

The electric field distribution for the ideal cable with 1×400/35 mm^2 cross sectional area is shown in Fig. 4.

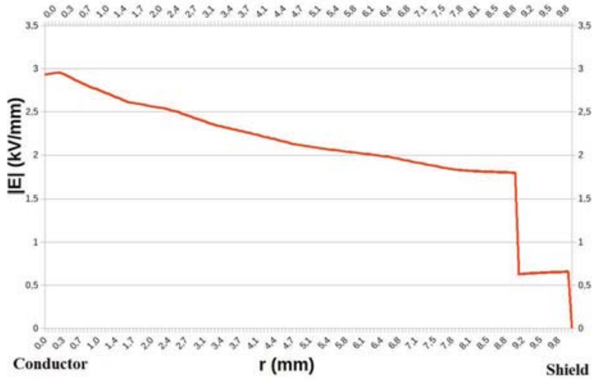


Figure 4. Electric field distribution for 1×400/35 mm^2 cable

The magnetic field distribution for the ideal cable with 1×240/25 mm^2 cross section is shown in Fig. 5.

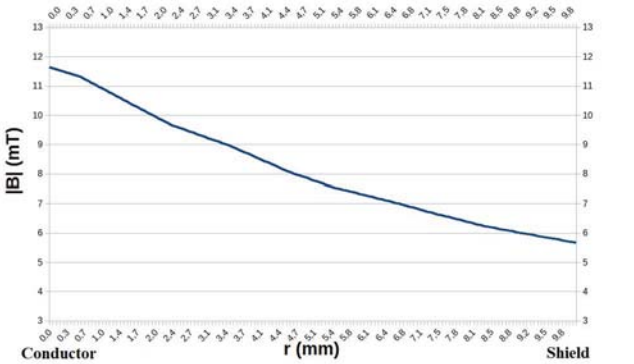


Figure 5. Magnetic field distribution for 1×240/25 mm^2 cable

B. Scenario 2: Field Distributions in the Case of a 0.5 mm Diameter Global Air Bubble Defect in the Cable

The presence of air bubble with a diameter of 0.5 mm in the cable is investigated in the cases of on the conductor surface, in the insulator and on the insulator surface.

Electrical field distributions for air bubble in all locations compared to the ideal cable are also shown in Fig. 6.

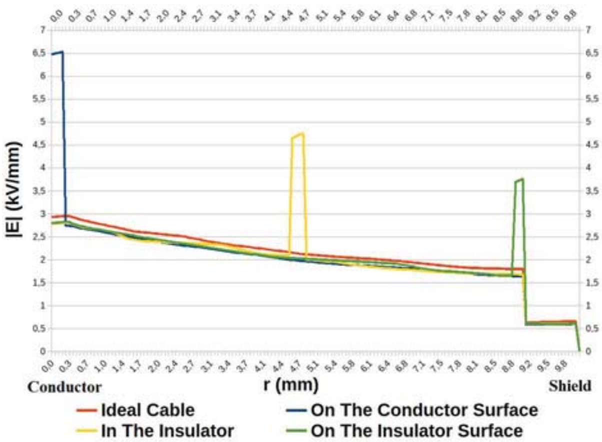


Figure 6. 1×400/35 mm^2 comparative electric field distributions in case of cable 0.5 mm air bubble

C. Scenario 3: Field Distributions in the Case of a 0.5 mm Diameter Fiber Particles Defect in the Cable

The presence of fiber particles with a diameter of 0.5 mm in the cable are investigated in the cases of on the conductor surface, in the insulator and on the insulator surface.

Electrical field distributions for fiber particles in all locations compared to the ideal cable are also shown in Fig. 7 for 1×240/25 mm^2 cable.

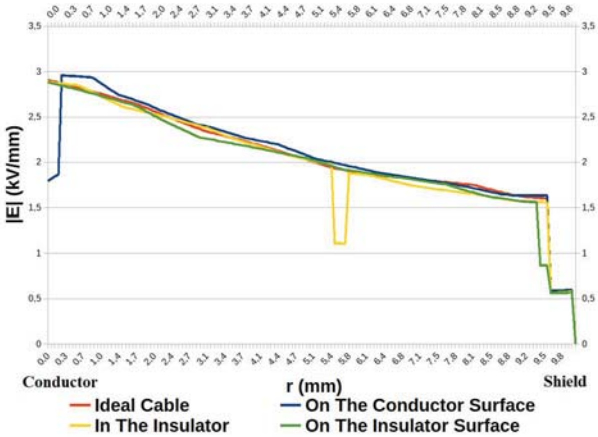


Figure 7. 1×240/25 mm^2 comparative electric field distributions in case of cable 0.5 mm fiber particle

D. Scenario 4: Field Distributions in the Case of a 0.5 mm Diameter Water Droplet Defect in the Cable

The presence of water droplet with a diameter of 0.5 mm in the cable is investigated in the cases of on the conductor surface, in the insulator and on the insulator surface.

Electrical field distributions for water droplet in all locations compared to the ideal cable are also shown in Fig. 8 and Fig. 9 for 1×240/25 mm^2 and 1×400/35 mm^2 cables.

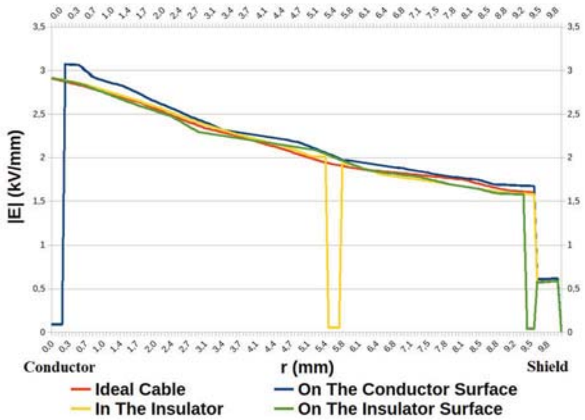


Figure 8. 1×240/25 mm^2 comparative electric field distributions in case of cable 0.5 mm water droplet

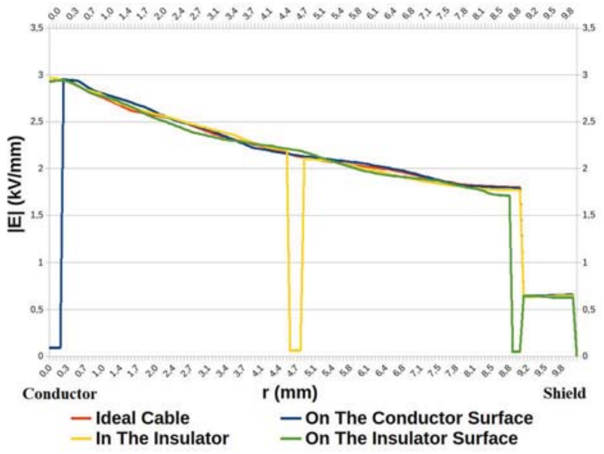


Figure 9. 1×400/35 mm^2 comparative electric field distributions in case of cable 0.5 mm water droplet

IV. DISCUSSION AND CONCLUSION

In this study, the effects of defects that may occur during the production phase of power cables on electric and magnetic field distributions are investigated. These distributions are given for four different scenarios respectively; ideal cable, cable with 0.5 mm air bubble, cable with 0.5 mm water droplet and cable with 0.5 mm fiber particles. Since the magnetic permeability is taken same for all materials, defects have no effect on magnetic field distribution. This is shown in the first scenario, the ideal cable review, and the magnetic field distributions for the other scenarios are not given.

In the first scenario, the electric field value in the ideal cable decreases logarithmically from 3 kV/mm to 0 kV/mm.

In the second scenario, when 0.5 mm diameter air bubble on the conductor surface in the cable, the electric field value increased by 133% from 3 kV/mm to 7 kV/mm. When 0.5 mm diameter air bubble in the insulator in the cable, the electric field value increased by 120% from 2 kV/mm to 4.4 kV/mm. When 0.5 mm diameter air bubble on the insulator surface in the cable, the electric field value increased by 133% from 1.5 kV/mm to 3.5 kV/mm.

In the third scenario, when 0.5mm diameter fiber particles on the conductor surface in the cable, the electric field value decreased by 40% from 3 kV/mm to 1.8 kV/mm. When 0.5 mm diameter fiber particles in the insulation of the cable, the electric field value is decreased by 42.5% from 2 kV/mm to 1.15 kV/mm. When 0.5mm diameter fiber particles on the insulator surface in the cable, the electric field value is decreased by 46.66% from 1.5 kV/mm to 0.8 kV/mm.

In the fourth scenario, when 0.5mm diameter water droplet on the conductor surface in the cable, the electric field value decreased by 96.66% from 3 kV/mm to 0.1 kV/mm. When 0.5 mm diameter of water droplet in the insulation of the cable, the electric field value is decreased by 95% from 2 kV/mm to 0.1 kV/mm. When 0.5mm diameter water droplet on the insulator surface in the cable, the electric field value is decreased by 93.33% from 1.5 kV/mm to 0.1 kV/mm.

As can be understood from the variation of the electric field values, the change of the electric field has the most negative effect in case of air gap in the cable. The obtained results show the negative effects of defects that may occur in the cable.

The presence of defects in the cable caused a serious change in the electric field. If the electric field value changes at these ratios, the effect of the fault current may cause the cable to be damaged. Partial discharges that may occur due to electric field changes may cause foreign matter to move in the form of tree branches.

It would be beneficial to make similar analysis in cable design and go to the production stage. Similar analyzes should be done for cable joints and terminations to determine the effect of defects that may occur.

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