ISSN 2706-655X Vol.6, Issue 5: 25-31, DOI: 10.25236/IJFET.2024.060504

Finite element simulation of multi physical field coupling inside high-voltage XLPE cables

Shaoting Yuan[1], Lingxin Zeng[2]

[1]School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou, 730070, China
[2]School of Electronic, Electrical Engineering and Physics, Fujian University of Technology, Fuzhou, 350108, China

Abstract: *Crosslinked polyethylene (XLPE) cables have good voltage resistance, excellent high-temperature resistance, and good mechanical strength, and are widely used in power systems. This article takes 10 kV XLPE cable as the research object and conducts finite element simulation under temperature electric field coupling. A 2D model of XLPE cable was established using COMSOL Multiphysics finite element software, and relevant electric and temperature field simulation calculations were carried out. The electric field and temperature in XLPE cables were simulated, and the distribution characteristics of electric field and temperature were obtained through finite element calculation when multiple physical fields were coupled inside XLPE cables. The differences in distribution characteristics were simulated when only electric field, temperature, and electric field coupling existed. The research results will provide some reference for the safe operation of XLPE cables.*

Keywords: *XLPE cable, finite element simulation, electric field temperature field coupling, temperature*

1. Introduction

Due to its excellent electrical, mechanical, and heat resistance properties, cross-linked polyethylene (XLPE) cables have become the preferred type of medium and high voltage power cables in China, and are widely used in the power transmission and distribution network. XLPE cable, as the most widely used cable nowadays, generates a large amount of heat under the action of strong current during operation, which will have a huge impact on the lifespan of the cable.

In order to investigate the effects of field strength and temperature on XLPE cables, many scholars have conducted research, David E et al. studied the relationship between the dielectric properties and elongation at break of XLPE insulation under thermal radiation, and found that the dielectric constant of 100kHz XLPE cables gradually increases with aging time, showing a negative correlation with the change in elongation at break [1]. El Kady et al. investigated the effect of geometric coefficients on heat transfer of cables with different numbers and arrangements using numerical calculation methods [2]. Xu Jun and others conducted thermal aging and physical and chemical performance tests to analyze the impact of thermal aging on the physical and chemical properties of XLPE insulation. It was found that as the aging degree deepened, the carbonyl index in cross-linked polyethylene materials gradually increased, while cable insulation materials were mainly subjected to thermal cracking during high-temperature thermal aging [3]. Jin Tianxiong, Liu Fei, and others conducted accelerated thermal aging experiments on the insulation of 3.3kV grade XLPE cables at 105 ℃, 120 ℃, 135 ℃, and 150 ℃, respectively, and studied the Weibull distribution of insulation breakdown voltage at different aging stages and temperatures [4].

Although many scholars have conducted research on the effect of field strength and temperature on XLPE cables, there is a lack of systematic simulation of the electric field temperature field inside XLPE cables. In response to the shortcomings of existing research, this paper conducts a systematic study on the electric field and temperature field inside XLPE cables. The finite element method is used to analyze the distribution of the electric field and temperature field, and to intuitively simulate the operation of power cables under various working conditions and environments. Taking cross-linked polyethylene (XLPE) cables widely used in 10 kV AC distribution networks as an example, the temperature field coupling simulation model of XLPE cables under different conditions is established using the multi physics field coupling simulation software COMSOL Multiphysics. The distribution characteristics of the temperature field and electric field distribution of the cables are studied. Based on the coupling

ISSN 2706-655X Vol.6, Issue 5: 25-31, DOI: 10.25236/IJFET.2024.060504

formula of relative dielectric constant and temperature, the temperature and electric field distribution characteristics inside XLPE cables are simulated using the finite element method.

2. Establishment of simulation models

2.1 Establishment of 2D model for XLPE cable

Applying voltage to the cable conductor will generate an electric field around the conductor. Due to the slow change of the electric field over time under power frequency voltage, the calculation can be analyzed based on the electrostatic field. Single core cross-linked polyethylene DC cables are generally extruded into a 5-layer structure consisting of a copper conductor, a semi conductive layer, XLPE insulation layer, a semi conductive layer, a water blocking tape, and a wrinkled aluminum sheath, as shown in Figure 1. Based on the actual size model of the cable, a two-dimensional coaxial cross-linked polyethylene cable simulation model is established in COMSOL to study its electric field strength in steady-state in an electrostatic field. The two-dimensional model is shown in Figure 1, and the calculation equation system for the electrostatic field is shown in equations (1) and (2).

$$\nabla \bullet D = \rho v \tag{1}$$

$$E = -\nabla V \tag{2}$$

The radius of the wire core in Figure 1 is 10mm, the thickness of the semi conductive layer is 2mm, and the thickness of the XLPE insulation layer is 18mm.The thickness of the aluminum adhesive sleeve layer is 3mm.

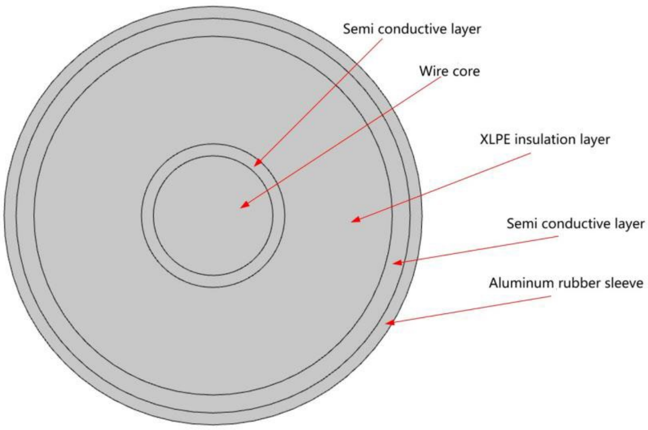

Figure 1: 2D cross-sectional view of the cable

2.2 Simulation parameter settings

In order to simulate the distribution characteristics of electric field strength inside actual cables, after consulting literature, the simulation parameters of different materials of XLPE cables are shown in Table 1.

Table 1: Relative Dielectric Constants of Cable Materials

part	material	conductivity(S/m)	Relative dielectric constant
Copper conductor	Copper	5.998e7	10000
Semi conductive layer	Semi conductive paper tape	10	12
XLPE insulation layer	XLPE cross-linked polyethylene	1e-16	2.35
Aluminum rubber sleeve	Aluminium	3.774e7	0.0001

ISSN 2706-655X Vol.6, Issue 5: 25-31, DOI: 10.25236/IJFET.2024.060504

3. Simulation results and analysis

3.1 Only consider the simulation results of the electric field

This article uses electric field simulation software based on finite element method to simulate XLPE electric field. The simulation results of electric field considering only electric field and not temperature coupling are shown in Figure 2. During the electric field simulation process, a 10kV voltage is applied to the copper core of the cable, and the aluminum sleeve is the ground potential phase with a potential of 0. The brighter the color in the main part of the figure, the higher the electric field strength value. From Figure 2, it can be seen that the electric field strength inside the copper core of the cable is close to 0, and the electric field strength gradually decreases in the XLPE layer. The numerical value of electric field strength is shown in Figure 3. The electric field strength of XLPE layer is high, and the value of electric field strength is the highest at the interface between the wire core and XLPE layer. From Figure 3, it can be seen that the electric field strength is highest at the interface between the wire core and XLPE layer. There is a sudden increase in electric field strength at the interface, reaching a maximum value of 0.88kV/mm. This is also the area where insulation is most prone to degradation, which can easily cause insulation breakdown[5-8].

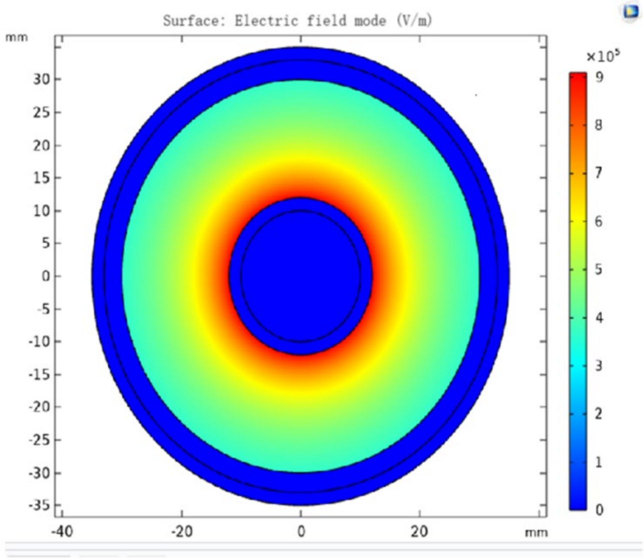

Figure 2: Distribution of electric field strength inside XLPE cable

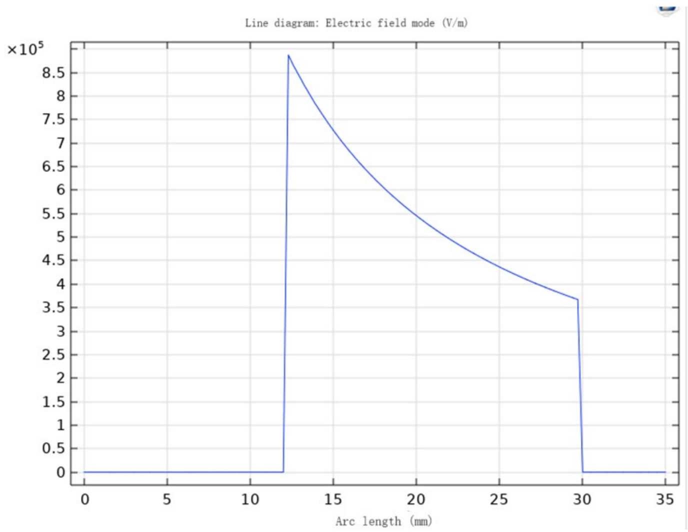

Figure 3: Electric field strength curve inside one-dimensional truncated XLPE cable

ISSN 2706-655X Vol.6, Issue 5: 25-31, DOI: 10.25236/IJFET.2024.060504

3.2 Simulation results of temperature and electric field coupling

3.2.1 Temperature field distribution characteristics

Simulate the temperature field inside the cable in COMSOL. Apply a temperature of 293.15K to the copper core of the cable during the temperature field simulation process, and simulate the temperature and electric field. The temperature changes the electric field distribution of XLPE by affecting the relative dielectric constant, coupling the temperature field and electric field. The temperature distribution characteristics inside XLPE cables are shown in Figure 4, where the core heats up due to the conduction of current, resulting in the highest temperature. Gradually decay from the inner layer to the outer layer, and the temperature of the outer semi conductive layer is close to the ambient temperature. The temperature distribution values inside the XLPE cable are shown in Figure 5, and the maximum temperature at the core reaches 293K.

According to the one-dimensional cross-section obtained from the temperature field simulation in Figure 5, the electric field distribution map shows that the temperature is highest from the coordinate origin to 12mm, reaching about 293K. When it exceeds 12mm, the temperature begins to decrease until 273K.

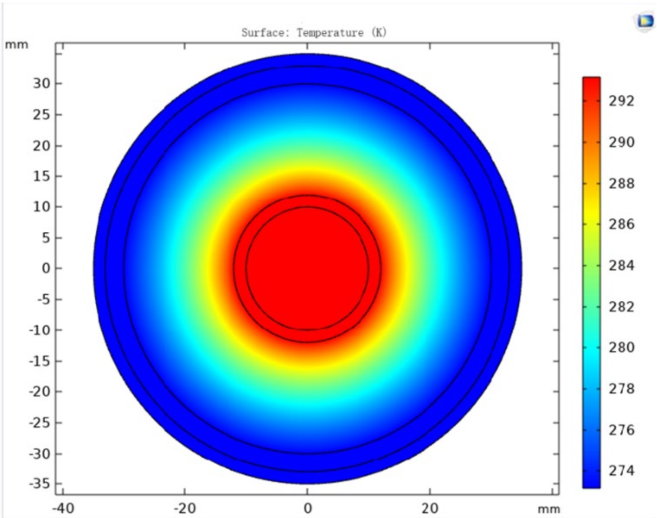

Figure 4: Temperature field intensity distribution inside XLPE cable

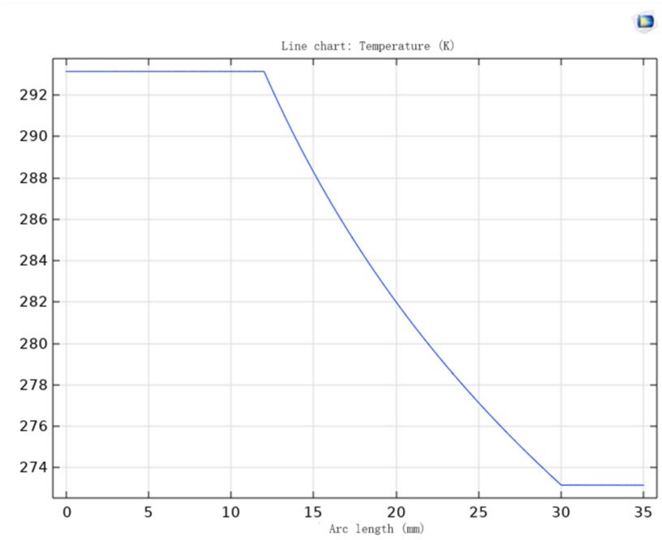

Figure 5: Temperature field intensity curve inside one-dimensional truncated XLPE cable

3.2.2 Electric field distribution characteristics

The electric field distribution characteristics inside XLPE cables are shown in Figure 6. Similarly, the brighter the color of the main body in the figure, the greater the electric field strength value. The numerical value of electric field strength is shown in Figure 7. The electric field strength of XLPE layer is high, and the value of electric field strength is the highest at the interface between the wire core and XLPE layer. From Figure 7, it can be seen that the electric field strength is highest at the interface between the online core and XLPE layer. Compared with the case where only the electric field is considered, the maximum electric field strength at the interface after considering the temperature field reaches 0.92kV/mm.

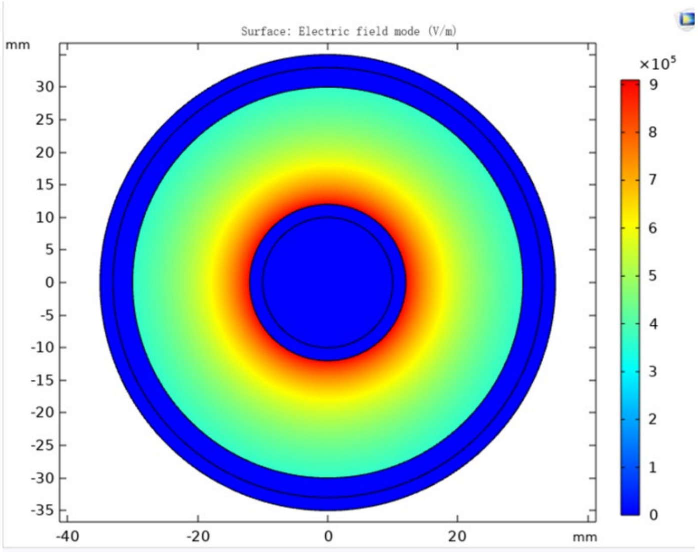

Figure 6: Distribution of electric field strength inside XLPE cable

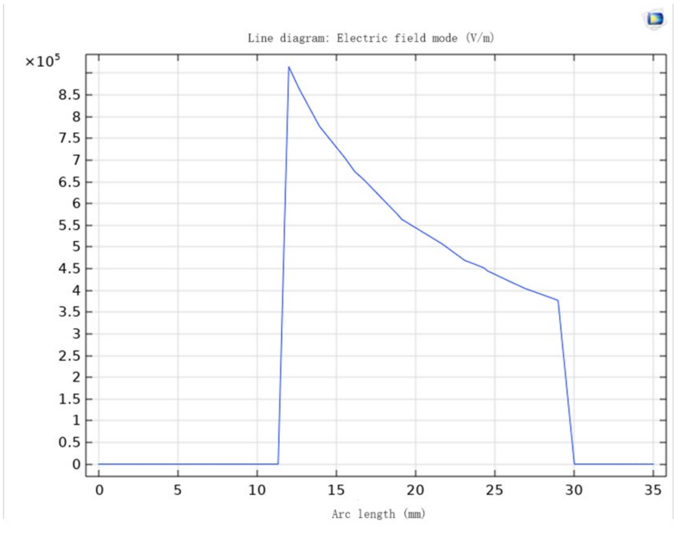

Figure 7: Electric field strength curve inside one-dimensional truncated XLPE cable

4. Result analysis

This article takes 10 kV XLPE cable as the research object, establishes a 2D model of XLPE cable using COMSOL finite element software, and conducts finite element simulation on XLPE cable under temperature electric field coupling. The following results are obtained:

(1) When only simulating the electric field without considering the temperature field, the electric field strength inside XLPE cables decreases as the distance from the conductor shielding layer increases.

(2) When considering only the temperature field without considering the electric field: the

temperature inside the wire core is the highest, and the further away the offline core is, the faster the temperature drops until it drops to 273K (0 ℃).

(3) When both electric field and temperature field are considered, the relative dielectric constant of XLPE cable gradually decreases with the increase of temperature. The maximum electric field strength inside XLPE cable reaches 0.92kV/mm, which is slightly higher than when only electric field is considered (0.88kV/mm)[9-12].

5. Conclusion and Future Prospects

5.1 Conclusion

In order to explore the multi physical field coupling finite element simulation in the XLPE layer of cross-linked polyethylene (XLPE) high-voltage cables, this paper uses COMSOL finite element software to simulate the electric field and temperature in XLPE cables, coupling the electric field and temperature field, and obtaining the following results:

When simulating a physical field: the electric field strength (temperature) inside XLPE cables decreases (decreases) as the distance from the conductor shielding layer increases. When two physical fields are coupled, the relative dielectric constant of XLPE cables gradually decreases as the temperature increases. The electric field strength inside XLPE cables (0.92kV/mm) will be greater than when only considering the electric field (0.88kV/mm).

5.2 Future Outlook

This article innovatively couples electric field and temperature field, and uses finite element method to analyze the distribution of electric field and temperature field inside XLPE cable, in order to simulate the operation of XLPE cable under various working conditions and environments. The simulation of XLPE cable distribution lines in a multi physical field environment is of great significance for the safe and stable operation of cables and the improvement of distribution network power supply capacity, and can provide some reference for related engineering.

References

[1] David E, FourMigue J M, Parpal J L, et al. Correlation between FTIR spectra and birefringence measures in XLPE cable insulation [C]. Annual Report: Conference on Electrical Insulation and Dielectric Phenomena, Victoria, BC, Canada, 2000, 17 (2): 324-327

[2] EL KADY M A, ANDERS G A, MOTLIS J, et al. Modified values for geometric factor of external thermal resistance of cables in duct banks [J]. IEEE Transactions on Power Delivery, 1988, 3 (4): 1303-1309

[3] Xu Jun, Wang Xiaodong, Ouyang Benhong, etc. The effect of thermal aging on the physicochemical structure of cross-linked polyethylene cable insulation [J]. Insulation materials, 2013, 46 (2): 33-37

[4] Jin Tianxiong, Liu Fei, Jiang Pingkai, etc. A study on the dielectric breakdown behavior of thermal aged XLPE cable insulation [J]. Wire and cable, 2008, 6, 28-31

[5] Lu Guojun, Xiong Jun, Ruan Banyi, Liu Gang, Chen Zhijuan. Experimental study on the detection of defects in 10kV cross-linked polyethylene cable joints using oscillation wave voltage method [J]. Guangdong Electric Power, 2011, 24 (06): 18-22

[6] Shen Chen. Development of a Partial Discharge Data Analysis System for XLPE Cables Based on Graph Feature Recognition [D]. Shanghai Jiao Tong University, 2018

[7] Hu Kai, Lu Zhifei, Yang Fengyuan, Zhang Lei, Zhang Yinxian. Simulation of Typical Defects and Partial Discharge Research on High Voltage DC XLPE Cables [C]. Excellent Paper Collection of Zhejiang Electric Power Society in 2018, 2018:324-331

[8] Zhao Peng. Design of High Voltage DC Crosslinked Polyethylene (XLPE) Cable Accessories Based on COMSOL Simulation [D]. China Electric Power Research Institute, 2018

[9] Du Hao, Guan Honglu, Chen Xiangrong, Hou Shuai, Yang Min, Wang Xin. Partial discharge characteristics of typical defects in cross-linked polyethylene cables under DC voltage [J]. High Voltage Technology, 2021,47 (02): 555-563

[10] Liu Lingyu. Research on modeling and intelligent identification methods for defects in urban underground transmission cable joints [D]. Shijiazhuang Railway University, 2023

[11] Hua Liangwei, Feng Yong, Mao Yan, Wang Ying, Cao Xiaolong. Discussion on the properties and

ISSN 2706-655X Vol.6, Issue 5: 25-31, DOI: 10.25236/IJFET.2024.060504

extrusion process of cross-linked polyethylene insulation materials [J]. Wire and Cable. 1999, (06): 42-45

[12] Yang Shuo, Geng Pulong, Qu Bingni, Song Jiancheng, Liu Jucai, Tian Min. Analysis of electric field distribution and influencing factors at air gap defects in insulation of high-voltage cables for mining [J]. Industrial and Mining Automation, 2018, 44 (04): 44-51