Electric Field Analysis on Buffer Layer of HV XLPE Power Cable by Finite Element Method

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Abstract. In recent years, white defects in power cable buffer layer has been discovered many times around the world. It would be a hazard to electricity transmission if these defects are not detected and solved in time, finally resulting in a power outage. In this paper, the selection of a physics field and the building of a three-dimensional model on cable electric field simulation are mentioned and improved. The distribution of electric field was calculated with two factors: the gap between water-blocking tape and aluminum sheath, the conductivity of water-blocking tape. The results demonstrate that the existence of the gap increases the electric field intensity in the air layer. Increasing the conductivity of water-blocking tape is beneficial to reduce the electric field intensity. It was explained that white defects is closely related to the air discharge in buffer layer.

1. Introduction
The power cable gradually replaces the overhead line and becomes a main power transmission channel in the city. In Xiamen, the cable rate has reached 23% as the length of high-voltage (HV) cable has exceeded 400 kilometers. With a large number of cables being put into operation, some similar faults of 110 kV Cross Linded Polyethylene (XLPE) cables have been found these years, that is, many white defects appeared on insulating shielding, water-blocking tape and the inner wall of the aluminum sheath. The problem has been declared in Beijing, Shanghai, Zhejiang etc. and some foreign countries like Singapore, Australia. Continued deterioration of these defects may lead to complete penetration of insulating shield and main insulation, which would cause a serious power outage. Therefore, it is never a question that could be ignored.

Yang Juan et al. found that the longitudinal water-blocking structure would cause a typical partial discharge and it is very important to control the gap between the metal sheath and core [1]. Liu Xiaodong et al. found through experiments that alternating current resistance of the buffer layer in faulty cable are much larger than those in normal cable. It is assumed that there is a large potential difference between insulating shielding and metal sheath [2]. Li Chenyinthought moisture is at the root of defects [3]. Sun Jin found the volume resistivity of water-blocking tape conforms to standard while the surface resistance is higher than what standard suggests [4]. She supposed the cable has been infiltrated by water and dried up later. Charles Q. Su [5], a researcher at Monash University in Australia, believed buffer layer is failed to withstand the charging current, and then the current caused local overheating and finally jeopardized insulating shield.
Cable manufacturers, cable operators, and scientific researchers have not determined the cause of this phenomenon. According to several fault cases of Xiamen’s power cable, this paper analyzed the influence of different factors on the electric field distribution in buffer layer by using COMSOL, a finite element simulation software. The simulation results in this paper can provide a suitable theoretical basis and important data support for next study of the cause of buffer layer discharge and its design in high-voltage cable.

2. Model and method

2.1 Model building

110 kV XLPE cable generally consists of a copper conductor, a conductor shield, a main insulation (XLPE), an insulating shield, a buffer layer (water-blocking tape and air), a corrugated aluminum sheath and an outer sheath. The structure of 110 kV XLPE cable is shown in figure 1. The parameters of 110 kV XLPE cable from a reliable manufacturer are given in table 1.

![Figure 1. The structure of 110 kV XLPE cable.](image)

| NO. | Structures                      | Outside radius / mm | Thickness / mm |
|-----|---------------------------------|---------------------|----------------|
| 1   | Copper conductor                | 13                  | -              |
| 2   | Conductor shield                | 14.7                | 1.4            |
| 3   | Main insulation (XLPE)          | 31.7                | 16.5           |
| 4   | Insulating shield               | 32.9                | 1              |
| 5   | Water-blocking tape             | 35.1                | 2              |
| 6   | Air                             | 35.6                | 0.5            |
| 7   | Corrugated aluminum sheath      | 42.6                | 2              |

The structure of aluminum sheath and buffer layer is relatively special:

- For a better bending property, aluminum sheath is usually made into a spiral structure. It is called a corrugated aluminum sheath for it is wavy with peaks and troughs in each waveform cycle when viewing from a longitudinal section. The gap between corrugated aluminum sheath and water-blocking tape is not a constant value.
- Buffer layer is located between insulating shield and corrugated aluminum sheath. It comprises of a water-blocking tape and air in order to meet a buffer requirement. When cable is running, its internal structures displaced downward due to gravity. It can be assumed that the underside of water-blocking tape is subjected to extrusion deformation because of its large flexibility, while other structures of cable are hardly deformed.
- Water-blocking tape would swell or shrink influenced by humidity and temperature. As a result, it also makes a variety of the gap between itself and corrugated aluminum sheath, as shown in figure 2.
With above factors, simply considering a radial section or a longitudinal section of the cable cannot accurately reflect the structure of corrugated aluminum sheath and buffer layer. In this paper, the cable was modeled in three dimensions. Since outer sheath has a zero potential after aluminum sheath being grounded, it can be ignored and need not to be constructed on this model.

2.2 Finite element method

For high-voltage power cables, its conductor shield, insulation shield and water-blocking tape are made of semi-conductive materials. Distribution of electric field influenced by current cannot be overlooked for the resistivity of semi-conductive materials is relatively small (i.e., conductivity is relatively large). Electric quasi-static (EQS) is selected because Both relative permittivity and conductivity would be taken into account when calculating. The differential form of EQS is [6]-[8]:

$$\begin{align*}
\nabla \times H &= J + \frac{\partial D}{\partial t} \\
\nabla \times B &= 0 \\
\nabla \times E &= 0 \\
\nabla \times D &= \rho
\end{align*}$$

The governing equation is :

$$\left(\gamma + j\omega \epsilon\right) \nabla \cdot E = 0$$

In this simulation, the outer side of copper conductor was applied to a phase voltage (64 kV), the outer surface of aluminum sheath was grounded and frequency was set to 50 Hz. The cable model was divided by free tetrahedral meshes and the meshes in small parts were refined specially. According to GB/T 11017.2-2014, material parameters of 110 kV XLPE cable are shown in table 2. The meshes of the cable model is shown in the figure 3.

| NO. | Structures                        | Relative permittivity $/\epsilon_r$ | Conductivity $/S \cdot m^{-1}$ |
|-----|-----------------------------------|-------------------------------------|--------------------------------|
| 1   | Copper conductor                  | $1e7$                               | $5.998e7$                      |
| 2   | Conductor shield                  | 100                                 | $\geq 1e-3$                    |
| 3   | Main insulation (XLPE)            | 2.3                                 | $1e-15$                        |
| 4   | Insulating shield                 | 100                                 | $\geq 2e-3$                    |
| 5   | Water-blocking tape               | 500                                 | $\geq 2e-3$                    |
| 6   | Air                               | 1                                   | $1e-16$                        |
| 7   | Corrugated aluminum sheath        | $1e7$                               | $2.746e7$                      |
3. Results and discussion

3.1 Gap variation
When cable is running, the upper side of water-blocking tape may be separated from aluminum sheath and then a continuous air layer is formed between aluminum sheath and water-blocking tape. As showed in figure 4, when the conductivity of water-blocking tape is 0.002 S·m⁻¹, the maximum electric field intensity $E_{\text{max}}$ in the air layer is substantially positively correlated with the gap between aluminum sheath and water-blocking tape.

![Electric field intensity vs. gap](image)

**Figure 4.** The relationship between $E_{\text{max}}$ and gap.

When there is only a tiny gap, electric field intensity in the air is really large. As the gap is gradually increased, electric field intensity is reduced. It should be noted that electric field intensity in the upper air layer is very small and can be ignored. $E_{\text{max}}$ is situated on the tangent surface between water-blocking tape and aluminum sheath (i.e., the junction of extrusion part and non-extrusion part). It proves that why discharge points on the inner wall of aluminum sheath contain sodium which from water-blocking tape. Electric field distribution when gap is 0.1mm is shown in figure 5.

![Electric field distribution](image)

**Figure 5.** Electric field distribution when gap is 0.1mm.

**Figure 6.** Electric field distribution when gap is -1mm.
When the upper side of water-blocking tape is in good contact with aluminum sheath (i.e., the gap is negative), the $E_{\text{max}} (0.07 \text{ kV} \cdot \text{mm}^{-1})$ is much smaller than $E_{\text{max}}$ when there is a gap present. In this situation, those points which easily discharge in the above case are no longer present and $E_{\text{max}}$ is located in both sides of water-blocking tape extrusion. Electric field distribution when gap is -1mm is shown in figure 6.

### 3.2 Conductivity variation

Water-blocking tapes from different manufacturers have different conductivities. For a certain water-blocking tape, its conductivity can vary between several orders of magnitude as it becomes wet or dry. If there is a gap, $E_{\text{max}}$ would increase sharply when conductivity drops below the order of $10^{-3} \text{ S} \cdot \text{m}^{-1}$. $E_{\text{max}}$ is less than 3 kV·mm$^{-1}$ as conductivity returns to the minimum recommended by the standard. When conductivity continues being improved, $E_{\text{max}}$ is infinitely close to zero. However, when there is not any gap, $E_{\text{max}}$ is almost zero regardless of how large conductivity is. The relationship between $E_{\text{max}}$ and conductivity is shown in figure 7.

![Figure 7. The relationship between $E_{\text{max}}$ and conductivity.](image)

There are several points which the value is a lot more than 3kV·mm$^{-1}$ when there is a low conductivity. When constructing this three-dimensional model, water-blocking tape was subtracted by the convex portion of the aluminum sheath to form a shape of extruded concave. The air sandwiched between aluminum sheath and water-blocking tape is extremely thin so that some large electric field intensity points can be caused by a very low potential difference. Although the points with a large electric field intensity cannot be avoided, they do not affect the conclusion that discharge would definitely occur here once the conductivity.

In fact, when objects come into contact, they are bridged by a certain film rather than in contact with a geometric face. For cable, when conductivity is low as water-blocking tape is getting wet, the tangent plane always adheres to water film so that extremely thin air there cannot be existed. The points with a large electric field are eliminated. Furthermore, the presence of water film makes water-blocking tape indirectly connected to aluminum sheath, it could be considered that current is flowing. Therefore, these points do not affect the judgment of final conclusion.

### 4. Conclusions

The cable should be built as a 3D model when studying the buffer layer discharge problem. Electric quasi-static should be selected for several layers are made of semi-conductivity materials. Ensure water-blocking tape is in full contact with aluminum sheath. In this case, even if the conductivity of water-blocking tape is extremely low, any discharge point is not existed in air layer. Improving the conductivity of water-blocking tape can reduce electric field intensity. When the conductivity is large, the air layer does not discharge even if there is a large gap between water-blocking tape and aluminum sheath.

Large electric field intensity in tangent plane is unavoidable but would not abrupt the judgment of final discharge conclusion.
5. Reference

[1] Yang J 2010 Study and Analysis of the Water-Blocking Construction in HV Power Cables Electric Wire & Cable

[2] Liu X D, Liu P Z and Wang X G et al 2017 Study of Measurement of AC & DC Resistance of High Voltage Cable Related to Insulation Screen Burn 4 pp15-8

[3] Li C Y, Li H Z, and Chen et al J 2018 Analysis of Buffer Discharge Problem of High Voltage XLPE Power Cable Power Engineering Technology

[4] Sun J, Li D C, and Hu X L et al 2016 Analysis and Mechanism Study on Internal Discharge Failure of 110 kV Cable Contemporary Chemical Industry 45 2014-6

[5] Su C Q 2011 Failure analysis of three 230 kV XLPE cables. In: Transmission and Distribution Conference and Exposition: Latin America, pp 22-5

[6] Liu Y, Su Y and Li W P et al 2016 Study on Electric Field Simulation Method of 10 kV XLPE Cable Joint High Voltage Electrical Appliance 30-5

[7] Xu Z N, Lv F C and Li H M et al 2011 Effect of Drying Belt on Electric Field Distribution of Stained Post Insulator High Voltage Technology 37 276-83

[8] Zhang L, Zhang W, and Li R P et al 2014 Defect Simulation and Electric Field Analysis of 10 kV XLPE Cable Terminal Insulating Materials 83-8

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