Study on insulation performance of EPR cable terminal containing metal particles

Huang Jisheng¹, Xiang Enxin², Li Lini³

1 Senior Engineer, Lincang Power Supply Bureau, Yunnan Power Co., Ltd. Lincang, Yunnan, China.
2 Senior Engineer, Yunnan Electric Power Research Institute, Yunnan Power Co., Ltd., Kunming, Yunnan, China.
3 Master's degree, College of Electrical Engineering Southwest Jiaotong University Chengdu, Sichuan China
E-mail: 41972987@qq.com/4758275@qq.com/ huangxusheng@yn.csg.cn

Abstract. The 35kV EPR cable terminal is widely used in the distribution network. During the production process, metal particles are easily introduced due to environmental and technological reasons, resulting in frequent breakdown of the terminal breakdown accident. In order to study the influence of metal particles on the insulation performance of EPR cable terminals, a model of metal particles defect in cable terminals on the extension line of the main insulation and the control tube is built. The electric field distribution of cable terminals under power frequency voltage is calculated by COMSOL simulation software. At the same time, a sample of cable terminals containing metal particles is made, and local discharge is used. The partial discharge information of the cable terminal sample is tested by the electric test platform. The results show that the introduction of metal particles will increase the electric field distortion inside the cable terminal, strengthen the discharge activity of the cable terminal, and increase the discharge amount significantly, which seriously affects the insulation performance of the EPDM cable terminal.

1. Introduction
As an important part of the distribution network, the 35kV ethylene-propylene rubber (EPR) cable bears the key role of transmitting electrical energy. As the weakest part of its insulation, the cable terminal has its electrical insulation performance, which directly affects the transmission system and electricity. The effective operation of the equipment [1] is related to the reliability of the distribution network. According to the fault data of the cable line, in the 35kV EPR cable, the terminal operation failure accounted for about 70% of the total number of cable line operation failures [2]. When the cable terminal is installed in the field, the external semiconductor shielding layer, conductive shielding layer and sheath of the cable need to be cut off, and the interception is prone to electric field distortion during operation [3], which affects the insulation performance of the cable termination; In the process of environmental and manufacturing processes, it is easy to introduce conductive impurities, which change the electric field distribution at the end of the cable, and affect its electrical insulation performance.

At present, domestic and foreign scholars have carried out various researches on various types of cable defects, and have achieved fruitful results. The Liu Gang team of South China University of Technology studied the breakdown characteristics of the main insulation of the cable joint with impurities. The results show that the impurity-containing defects will cause partial electric field
distortion inside the cable joint, and will break down the insulation material in severe cases \cite{4}; Rittmam GW and other scholars have provided some directions for fault diagnosis of cable joints by studying the partial discharge information of cable joints containing impurities \cite{5}; North China Electric Power University scholars are currently studying the effective electric materials and structures to make the internal electric field of cable accessories effective. Optimization \cite{6}. However, after the metal particles are mixed, how the electric field of the 35kV cable terminal is distorted in the presence of defects, how the metal particles with different parameters affect the highest electric field value, how the discharge at the metal particles develops, and how the discharge performance of the terminal changes. There are fewer reports and there is an urgent need for relevant research. Based on there, this paper studies the influence of the internal electric field distribution when the metal particles in the cable terminal are located at different positions, and finds the position with the greatest impact, so as to focus on the pre-fabrication and normal operation; and through the partial discharge test, the key is extracted. Information to explore the local discharge characteristics of particles inside, providing a basis for fault diagnosis.

2. Electric field analysis

2.1. Modeling of cable terminal

According to the on-site anatomical results and the ex-factory data, the cable termination is to cut off the outer semi-conductor layer, the metal shielding layer and the sheath of the cable body \cite{7}, and the control tube and the heat-shrinkable tube which can uniformly distribute electric field are pre-formed by layer-by-layer heat shrinking. Finally, the shed is used to isolate the waterproof, so the cable end is a multi-layer structure, and its model is shown in Figure 1.

![Figure.1 Cable terminal model diagram.](image)

In this study, the electric field analysis of the 35kV cable termination is required. The required material parameters are conductivity and relative dielectric constant. By understanding the factory parameters and field test, the relevant material parameters are shown in Table 1.

| Material name             | Relative dielectric constant | Reference conductivity(S/m) |
|---------------------------|-----------------------------|-----------------------------|
| Cable core                | 1                           | 5.71e7                      |
| Semiconductor layer       | 100                         | 2                           |
| Stress control tube       | 30                          | 1e-8                        |
| Insulating layer          | 3.5                         | 1e-15                       |
| Heat shrinkable tube      | 2.3                         | 1e-12                       |
| Sheath                    | 6                           | 5e-12                       |
| Umbrella skirt            | 7.7                         | 5e-12                       |
| Glue                      | 7                           | 5e-9                        |
2.2. Theoretical analysis of electric field

The cable terminal runs at 35kV power frequency. The power frequency changes slowly in time. It can be solved by electrostatic field. The electrostatic field belongs to the scattered and non-rotating field. It needs to meet several basic equations [8]:

\[ \nabla \times E = 0 \]  
\[ \nabla \times D = \rho \]  

Among them, \( E \) in equation (1) is the electric field strength, which indicates that the loop characteristic of the electrostatic field is an irrotational field; \( D \) in equation (2) is the electric current density and \( \rho \) is the charge density, this formula is a differential equation of Gauss law, which shows that the electrostatic field is a divergent field, and the divergence of the electric flux density at any point in the electrostatic field is equal to the free charge volume density at that point.

The cable terminal is a multi-layer structure, and the layers are inconsistent with the materials of the layers. They belong to different media. The interfaces on different media need to meet the connection relationship, as shown in equation (3), where \( D_1 \) and \( D_2 \) are shown in Figure 2. \( D_1 \) is the normal component of the electric flux density of the first layer of material, \( D_2 \) is the normal component of the electric flux density of the second layer of material, and \( \sigma \) is the free charge surface density, equation (3) indicates that the normal component of the electric flux density on both sides of the interface is not continuously, the amount of discontinuity is equal to the free charge areal density at the interface. At the same time, this study uses finite element simulation analysis, for each layer of material, meshing is required. For the grids in the same layer of material, the electrical flux density needs to be changed without meshing.

\[ D_2 - D_1 = \sigma \]  

Figure 2 Dielectric interface diagram

2.3. Analysis of simulation results

2.3.1. Electric field simulation without metal particles.

According to the actual operating conditions, the cable terminal runs at a power frequency of 35kV, and the metal shield layer is grounded. The electric field distribution is shown in Figure 3.

As can be seen from Figure 3, when no metal particles appear at the cable terminal, the maximum electric field intensity appears at the truncation point of the external semiconductor layer, and the
maximum value is 6.83MV/m. It can be seen from the enlarged picture that the larger electric field intensity is distributed in the insulating layer area, and the distortion of the electric field distribution is obvious near the maximum value.

2.3.2. Electric field simulation of metal particles.

The cable terminal is a multi-layer structure. During the installation process, due to the environment and manufacturing process, metal particles are easily introduced during the heat shrinking process. In order to better analyze the influence of the introduction of metal particles on the insulation performance of the cable terminal, this paper builds A cable termination model of metal particles at different positions, respectively, a triangular metal particle with a bottom edge of 1 mm and a height of 1 mm placed at a position 0 mm, 65 mm, 130 mm, 193 mm, 194 mm, 258 mm from the outer semiconductor layer cut-off. The electric field distribution of the cable terminal at 35 kV power frequency is obtained, wherein the junction of the outer semiconductor layer is 194 mm, which is the connection between the control tube and the tail glue. Figure 4(a)-(g) correspond to the electric field distribution of the metal particles introduced at seven different positions.

![Electric field distribution map of cable terminal containing conductive impurities](image)

Figure. 4 Electric field distribution map of cable terminal containing conductive impurities

It can be seen from Figure. 4 that when the metal particles are introduced into the cable terminal, the electric field distribution distortion is intensified; as shown in Figure 4(a), the metal particles are located at the cutoff of the outer conductor layer, and the electric field strength is 7.6 MV/m at the
maximum. The maximum electric field strength of the particles increases by 11.7%. This position is also the position where the maximum electric field strength is minimized when the metal particles are introduced. As shown in Figure 4(b) and 4(c), the metal particles are located in the control tube and the insulating layer. When the time is between, the electric field strength increases, but by comparing the two positions, the introduction position of the metal particles has a small influence on the distribution of the electric field strength within a certain range of the two positions; Figure 4(d)-4(f) is the introduction of metal particles near the junction of the control tube and the tail glue. It can be seen from the Figure that the introduction of metal particles near the position has a great influence on the electric field distribution, especially the positional distance at which the metal particles are introduced. The outer semiconductor layer is 194mm, which is the position where the electric field distribution is the most affected at all positions where the metal particles are introduced. The maximum electric field strength is 18.7 MV/m, which is three times the maximum electric field strength when no metal particles are introduced. The position is the (356, 20) position corresponding to the cable termination model, and the breakdown field strength of the ethylene-propylene rubber is 20 to 45 MV/m [9]. The maximum electric field strength is close to the breakdown field strength. In this case, the insulation loss will be accelerated continuously, and the insulation breakdown accident is likely to occur; Figure 4(g) shows that the metal particles are introduced to the junction of the tail rubber and the insulation layer, and the electric field distortion is very serious near the junction of the metal particles and the insulation layer. The maximum electric field strength is 15.2 MV/m, which is 123.5% higher than the maximum electric field strength when no metal particles are introduced. Therefore, the introduction of metal particles in the tail rubber portion has a great influence on the insulation performance of the cable termination, and needs to be emphasized in the installation prefabrication.

In order to better analyze the influence of the introduction of metal particles on the electric field distribution at the end of the cable, the distribution of the electric field strength along the extension of the radial length of the extension line at the interface between the insulating layer and the outer semiconducting layer is introduced when the metal particles are not introduced and the metal particles are drew at 7 positions, as shown in Figure 5.

As can be seen from Figure 5, when metal particles are not introduced, electric field distortion occurs at the intersection of the outer semiconductor layer; when metal particles are introduced, two electric field distortions appear on the extension line of the boundary between the semiconductor layer and the insulating layer. The position is located at the interception of the outer semiconducting layer, and the other position is at the position where the metal particles are introduced, in the vicinity of the position, the electric field distortion is very serious, and the electric field intensity change can be
rapidly increased from 0.5 MV/m to 18.7 MV/m, then rapidly drops, the rapidly distorted electric field is more likely to accelerate the insulation aging near the location and reduce the insulation performance.

3. Experimental verification
In order to more intuitively explore the influence of the introduction of metal particles on the insulation performance of cable terminations, two metal particles were introduced in this study, which are the most easily introduced particles into the outer semiconductor layer and the location where the electric field distribution distortion is the most serious, which is at the cut-off point of 194 mm, the defects produced are as shown in Figure 6. The triangular metal particle having a width of 1 mm and a height of 1 mm is placed in the designated position, and the control tube, the insulating tube, and the shed are sequentially mounted in the specified order.

![Figure 6](image)

(a) Metal particle distance 0 mm from truncation  (b) Metal particle distance 194 mm from truncation

Due to its structural characteristics and micro-defects introduced during the prefabrication process, the cable terminal is severely deformed in some special parts during normal operation, some areas will have a slight discharge, accelerate the insulation aging for long-term operation, and further increase the partial discharge. The effect will cause insulation breakdown accident [10,11], so the detection of partial discharge signal is of great significance for diagnosing cable terminal defect failure.

Referring to the relevant standard [12,13], a partial discharge test circuit as shown in Figure 7 was constructed. The test circuit was shown in Figure 8. The cable terminal sample with no metal particles introduced was sample No. 1. The cable termination sample where the metal particle is introduced at the junction of the semiconductor layer is sample No. 2, and the metal particle introduction position is a cable termination sample at a distance of 194 mm from the outer semiconductor layer cut-off. No. 3 sample, and three cable termination samples are subjected to partial discharge test.

![Figure 7](image)

**Figure 7** Partial discharge test circuit

![Figure 8](image)

**Figure 8** Partial discharge circuit diagram

Three kinds of cable termination samples were tested by this partial discharge test platform. The step of each pressurization was 0.5kV [14]. After each pressurization, it was stabilized for 1 min, and the discharge was observed. When partial discharge occurred, the step length is gradually reduced by 0.1kV, and the stabilization time is 1min, so that the voltage is gradually reduced until the discharge phenomenon disappears, and then gradually increases in steps of 0.1kV, and stabilizes for 1 minute until the discharge phenomenon occurs again, and the current voltage value is recorded. It is recorded as the initial discharge voltage. The initial discharge voltage of the cable samples No.1 to No.3 is 18.3kV, 13.5kV, and 3.7kV, respectively. The results show that Low initial discharge voltage of
cable terminal with slight electric field distortion. Then, by gradually increasing the voltage to 35 kV, the discharge spectra of three cable samples in five cycles are tested, as shown in Figure 9.

![Figure 9](image)

(a) Spectrum of No.1 Cable Terminal Sample  (b) Spectrum of No.2 Cable Terminal Sample

(c) Spectrum of No.3 Cable Terminal Sample

*Figure 9* $\varphi - q - n$ of Spectrum of cable terminal samples

It can be seen from Figure 9 that when the metal terminal is not introduced into the cable terminal, the discharge is concentrated in three regions, respectively, 45° to 100°, 200° to 220°, and the discharge amount of 270° to 300° is generally distributed at about 10pC, the maximum, and the number of discharges is 4 times; when the cable terminal introduces metal particles at the cut of the outer semi-metal layer, the discharge activity is active, mainly concentrated between 80° -100° and 245° -300°, and the discharge amount reaches 150pC at the maximum; It can be seen from Figure 9(c) than, when the position of the metal particles introduced into the cable terminal is 194 mm away from the outer semiconductor layer, the discharge activity is very active, the maximum discharge capacity can reach 350 pC, and the discharge activity is not limited to the peak value of the operating voltage. There is obvious discharge phenomenon in the whole cycle. That can be seen that when the metal particles are introduced, the electric field distortion inside the cable terminal is severe, which will increase the internal discharge activity. The more active the discharge activity is, the larger the discharge is, and the cable interior is easily accelerated. The insulation aging, long-term operation will eventually lead to breakdown of the cable terminal, causing serious economic losses.

4. Conclusion

In this paper, by using the finite element simulation software to simulate the electric field distribution of the cable terminal when introducing metal particles at different positions, and testing the partial discharge information of the cable terminal through the partial discharge test platform, the following conclusions are obtained:

(1) When the cable terminal introduces metal particles at a distance of 194 mm from the cutoff of the semiconductor layer, that is, the connection between the control tube and the tail glue, the electric field distortion is the most serious, and the electric field strength is 18.7 MV/m at the maximum;
(2) The results of partial discharge detection show that the introduction of metal particle makes the internal discharge activity of the cable terminal more active. When the metal particle is introduced at 194 mm from the cutoff of the semiconductor layer, the maximum discharge can reach 350 pC.

(3) The electric field distribution and partial discharge activity of the cable terminal with metal particles introduced at different positions have different characteristics, which provides a good foundation for the fault diagnosis work to be carried out next.

5. References

[1] Wan Hang, Zhou Kai, Zeng Qin, Zhang Chunshuo, Gong Jun, Huang Yonglu. Research on the location method of medium voltage cable terminal operating voltage based on phase location device [J]. Electrical Measurement & Instrumentation, 2019, 56(7): 30-34.

[2] CHENG Zihua. Faults and Prevention Measures of 35kV Power Cable in Tianjin CX Power Supply Company [D]. Tianjin: Tianjin University, 2015.

[3] Wu Ke, Ma Chunliang, Zhou Kai, et al. Partial discharge and surface ablation characteristics of air gap defects in 10 kV cable termination [J]. Insulating Material, 2015(7): 38–43.

[4] LIU Gang, CHEN, et al. Analysis on breakdown attribute of 110kV XLPE cable joint main insulation with impurities [J]. High Voltage Engineering, 2010, 36(10):2450-2453.

[5] Rittmam G W, Heyer S V. Water contamination in a crosslinked polyethylene cable joint [J]. IEEE Transactions on Power Apparatus and Systems, 1976, 95(1):302-306.

[6] SHANG Kangliang, CAO Junzheng, ZHAO Zhibin, et al. Simulation Analysis and Design Optimization of 320 kV HVDC Cable Joint [J]. Proceedings of the CSEE, 2016: 2019-2024.

[7] Zhao Qingjie, Zhou Kai, et al. The analysis of high frequency harmonic and the research of the problem for cable termination during passing natural section of traction locomotive [J]. Electrical Measurement & Instrumentation, 2017, 54(6): 17-22.

[8] Feng Cizhang, Ma Xikui. Introduction to Engineering Electromagnetic Field [M]. Beijing: Higher Education Press, 2000, 20.

[9] Lin Kongyong, Jin Chenjuan, Liang Xingyu. Rubber Industry Manual, Volume 6 [M]. Beijing: Chemical Industry Press, 1993:1-13.

[10] Zhang Ji Pei. The Study on Extraction and Processing Technology of High Frequency Signal of Partial Discharge in Cable[D]. Si Chuang: Southwest Jiaotong University, 2018.

[11] Tian Y, Lewin P L, Davies A E, et al. Partial discharge detection in cables using VHF capacitive couplers [J]. Dielectrics & Electrical Insulation IEEE Transactions on, 2003, 10(2): 343-353.

[12] National Electrical Appliance Industry Association. GB 18889-2002. Test method for power cable accessories with rated voltage of 6 kV (Um=7.2 kV) to 35 kV (Um=40.5 kV). Shanghai: Shanghai Cable Research Institute, 2002.

[13] National Electrical Industry Association. GB-T 7354-2003. Partial discharge measurement. Xi'an: Xi'an Institute of High Voltage Electrical Appliances, Wuhan: Wuhan Institute of High Voltage, 2003.

[14] Zhu Lin. Electric field simulation and structural optimization of cable termination and line side cubicle for locomotive in alpine region [D]. Si Chuang: Southwest Jiaotong University, 2018.

Acknowledgments
Thank you for the support of the project YNKJXM20180719 of China Southern Power Grid Corporation.