Breakdown mechanism Analysis of Silicone Oil Flocculation in XLPE Cable Terminations

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Abstract. In order to find out the fundamental cause of terminal breakdown of a porcelain-covered oil-filled cable for a 220 kV cable line, a theoretical model of particle phase flow was adopted to analyze the breakdown mechanism by means of finite element simulation. The results show that the breakdown of cable terminal was caused by the flocculation produced by the aging of the silicone oil filled material. When the critical state of the flocculation was reached, the grounding channel was formed along the stress cone, and the electric field in the cable terminal was distorted. The electric field intensity of cable insulation had reach 8.25kV/mm, which was 13.4 times that of normal operation. Under the combined action of high electric field and moisture, many water tree had appear on the outer surface of the cable insulation layer, which leads to the breakdown of the cable insulation layer on the top of the stress cone. The research results can provide an important reference for the design and maintenance of HV and UHV cable termination.

1. Introduction

Oil-filled cable terminal occupies a considerable proportion in the high-voltage cable terminal, because of its mature manufacturing process and operation experience, [1-6]. At present, silicone oil and polyisobutylene are commonly used as insulation oil, and the selection principle is based on the compatibility with the cable terminal stress cone material. Insulating oil has been affected by external factors such as oxygen, humidity, high temperature, strong electric field and impurities. With the increase of the operating time of cable terminals, the aging degree of insulation oil will gradually intensify, resulting in the insulation performance of the terminal greatly reduced, thus causing the cable terminal heating and even insulation breakdown failure [7-10]. In 2012, the CIGRE B1 working group made a fault statistics on the terminals with voltage grade of 51kV -400kV. Statistics show that 61 cable line terminal faults were collected from 1988 to 2010. Most of the fault terminals were composite sets of terminals, and 18 porcelain sets of terminals. Insulation oil was an important cause of faults, mainly including partial discharge caused by silicone oil condensation and various faults caused by insulation oil leakage [11]. Therefore, it is of great significance to study the aging and breakdown characteristics of insulation oil in cable terminals for effectively preventing cable terminal faults and evaluating the operation status of cable terminals.

In June 2011, a power supply bureau has been running for nine years for 220 kV oil-filled porcelain cable terminal failure, the cable terminal stress cone material for EPDM, filling insulation oil material
for silicone oil. The breakdown point of the cable insulation layer was about 45 mm away from the upper surface of the stress cone (see Fig. 1), and there were many water trees on the surface of cable insulation (see Fig. 2). By dissecting the non-fault phase of the same unit, it was found that the characteristics of silicone oil in the terminal have been changed. White flocculation was suspended in the silicone oil. After a certain period of time, the silicone oil was layered, as shown in Figure 3. In this paper, the settling process of flocculation and its distribution in cable terminal after silicone oil aging was analyzed, the breakdown point of cable terminal was simulated, and the mechanism of cable terminal breakdown caused by silicone oil flocculation was demonstrated.

Fig. 1 breakdown location of cable termination

Fig. 2 cable breakdown picture

Fig. 3 silicone oil in cable terminal

2. Particle phase flow theory

According to the Euler equation, there are three possible boundary conditions for particle velocity and temperature [12,13]:

1#-new oil
2#-upper layer silicone oil after stratification
3#-lower layer flocculation after stratification

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1) wall attachment conditions:
The motion of particles is completely suspended by wall friction, for example, when the particle size is small or the wall is relatively rough.
\[ u_s = v_s, \]  \hspace{1cm} (1)
The subscript \( w \) denotes the radial and axial velocities of the particles on the wall (the same as below), \( u_{s,w} \) and \( v_s \) (m/s), respectively.

2) full slip condition:
Particles can resist free slip on the wall, and there is no velocity difference between the particles. This makes sense only if the friction-free wall or its influence can be neglected, where \( v_{s,ab} \) is the axial velocity at the adjacent nodes.
\[ u_{s,w} = 0, \quad v_s = v_{s,ab} \]  \hspace{1cm} (2)
\( n \) is the normal coordinate of the wall, and the subscript \( nb \) represents the adjacent nodes.

3) partial slip condition:
This is the boundary condition between the two above. The particles are partly stagnant on the wall and move at the speed of "slip". In this case, the particle pulsation always exists. For example, the component of the pulsation parallel to the wall may not be equal to zero. The collision between the particle and the wall will cause the wall shear stress to the particle, and dissipate part of the pulsation energy. But the macroscopic velocity gradient at the wall will cause its irregular motion and produce pulsating energy.

3. failure analysis
According to the analysis of the non-fault phase of the same unit, it was found that the silicone oil in the fault cable terminal had produced white flocculation due to aging, which indicates that the breakdown of the cable terminal was not accidental.

The material composition of white flocculation is analyzed, and the main component of flocculation is potassium phosphate. It was found that dimethyl silicone oil was the main component of the terminal silicone oil. In the synthesis of dimethyl silicone oil, KOH was used as catalyst and organosilicon phosphate was used as neutralizer. Both can neutralize to form potassium dihydrogen phosphate, potassium dihydrogen phosphate and potassium phosphate [14], which are white flocculation in silicone oil. Because there are a lot of conductive particles in the white flocculate, these conductive particles, affected by the electric field and temperature field, carry out Brownian motion and sedimentation movement in silicone oil in the cable terminal. In the collision and contact caused by the micro-force, the particles are bonded and flocculated, and then the white flocculate was formed.

The motion of white flocculation in silicone oil in cable terminal can be described by Euler equation under ideal conditions. According to Euler equation, the interaction between flocculation was very intense in liquid-solid two-phase motion. This is not only manifested in the complex and changeable force on the flocculate, but also in the interaction between the flocculate and the solid wall on the influence of concentration distribution. The flocculation motion at the insulation wall of cable termination is not completely static or slippery, but affected by other factors such as wall motion and near wall motion. Therefore, the flocculation movement on the wall can be divided into three types: (1) wall attachment: the flocculation movement is completely suspended due to wall friction. (2) full slip: flocculation can have no resistance to slip on the wall. (3) partial slip: flocculation are partly stagnant on the wall and move at the speed of "slip".

According to the cable terminal structure, the state of flocculation in the cable terminal can be divided into three processes: (1) flocculation attachment: the flocculation distributed in silicone oil deposits in the upper part of the stress cone under the action of electric field, temperature field and gravity field in the cable terminal, as shown in Figure 4 (a). (2) Partial slip of flocculation: When the flocculation was deposited to a certain extent in the upper part of the stress cone, it will slip along the side of the stress cone, so that the flocculation settles to the bottom flange of the terminal, see Figure 4 (b). (3) Critical state of flocculation: When deposited to a certain extent, the silicone oil at the bottom of stress cone is replaced by flocculation, and the flocculation at the top, side and bottom of stress
cone are connected together to form a channel, as shown in Figure 4 (c). At this point, because the bottom of the cable terminal was a metal flange directly grounded, and the flocculation contain conductive ions, the channels formed by the flocculation was grounded, and the electric field distribution near the stress cone is changed, and the electric field at a certain distance above the stress cone (i.e. at the apex of the triangle) is distorted, causing cable insulation breakdown.

![Flocculation Status](image)

(a) attached wall (b) partial slip (c) critical state.  
**Fig. 4** Flocculation status of cable insulation wall

4. Simulation analysis

In order to further verify the failure mechanism of stress cone, the electric field intensity distribution of flocculation in different states is analyzed by finite element simulation.

4.1. Model parameters

According to the actual size of 220 kV cable terminal, the electric field simulation model of two-dimensional symmetrical structure was established[15]. The parameters of the material in the model are shown in Table 1. According to the actual operating voltage setting, 126kV potential was applied to the cable conductor and voltage equalizing ring, and 0 potential was applied to the metal sheath, stress cone, metal flange and air field boundary of the cable.

| Material         | Relative permittivity |
|------------------|-----------------------|
| Insulation layer | 2.3                   |
| Stress cone      | 3.2                   |
| Silicone oil     | 2.7                   |
| Flocculation     | 10                    |
| Porcelain bushing| 6.5                   |
| Air              | 1.0                   |

4.2. Calculation results

Based on the simulation results of the electric field at the cable terminal, the electric field strength and the cable insulation radius at the top of the stress cone flocculation "triangle zone" and the surface of the stress cone at the point of contact with cable insulation and silicone oil were plotted in Fig. 5 and Fig. 6.

It can be found that the electric field distribution inside the insulating layer of the cable under the condition of flocculation wall attachment and partial slip is similar to that of the normal cable terminal. The cable insulation near the cable conductor bears higher electric field and the cable insulation near the outer shield bears lower electric field. This distribution trend is cable insulation. The typical trend of electric field distribution in the layer is [16]. When the flocculation reaches the critical state, the electric field intensity distribution tends to change obviously. The electric field intensity near the cable conductor was up to 6.34 kV/mm, which was 4.5 times higher than that under normal operation. The
electric field intensity near the outer shield was 8.25 kV/mm, which was 13.4 times higher than that under normal operation.

![Electric Field Intensity Graph](image)

**Fig. 5** the electric field intensity inside the cable insulation layer at the top of the "triangle area" of the upper part of the conical part of the stress cone.

The variation trend of the electric field in the insulating layer of the cable at the top surface of the stress cone, the insulation of the cable and the contact point of silicone oil is similar to that at the apex of the "triangle zone" of the flocculation at the top of the stress cone. The electric field intensity near the cable conductor is as high as 7.05kV/mm, which is 4.6 times that of normal operation, while that near the outer shield is 5.77 kV/mm, which is 8.5 times that of normal operation.

Comparing the evolution law of electric field of cable insulating layer under three kinds of conditions of flocculation in cable terminal, it shows that the flocculation produced by silicone oil aging in cable terminal has little effect on the electric field distribution of cable insulating layer in cable terminal when it is in wall-attached state or partial slip state, and the electric field intensity is comparable to the terminal variation of cable in normal operation. In the critical state of the flocculation, the conductive ions in the flocculation form the grounding channel, which makes the electric field intensity near the outer shield increase sharply. The high electric field and the moisture in the silicone oil together cause the water branch discharge on the surface of the insulating layer of the cable and locate in the "triangle area" of the flocculation above the stress cone. The electric field at the top of the stress cone is higher than that at the top of the stress cone, which leads to the breakdown of the cable insulation at the top of the stress cone.

![Electric Field Intensity Graph](image)

**Fig. 6** the electric field intensity of cable insulation layer on the surface of stress cone and cable insulation and silicone oil contact point.

5. **Conclusion**

Through theoretical analysis and Simulation Study on breakdown caused by silicone oil aging in cable terminals, the following conclusions are obtained:

1) The white flocculation produced by aging silicone oil in cable terminals contains a large number of conductive ions, mainly phosphoric acid and potassium ions.
2) The evolution process of flocculation in cable terminal consists of flocculation wall attachment, flocculation partial slip and flocculation critical state. When the critical state of the flocculation was reached, the grounding channel is formed along the stress cone, which distorts the electric field in the cable terminal and causes the cable insulation breakdown.

3) In the critical state of the flocculation, the electric field at the top of the stress cone is as high as 8.25 kV/mm at the triangle point of the flocculation, while the electric field at the top of the stress cone is 5.78 kV/mm at the cable insulation and silicone oil contact point. Therefore, the breakdown point of the cable in the terminal caused by silicone oil aging is located at the top of the stress cone at the triangle point of the flocculation.

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