Analysis of 500kV composite insulator fracture fault

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Abstract. This paper describes the fracture of composite insulator string of B phase on Tower 72 of 500kV line. A series of tests have been taken on the core rod and sheath to analyze the causation of the accident, including hydrophobicity test, dissection analysis, dye penetration, SEM and FTIR. It is found that the surface of the fault insulator is chalked, and its hydrophobicity is reduced. The interface between the epoxy resin matrix and silicone rubber sheath has completely failed. Epoxy resin matrix has been degraded, and partial discharge on the surface of core rod accelerates this process. The main chain of Si-O and side chain of Si-C in silicone rubber molecule are severely broken, and the surface of the umbrella is aging. It is concluded that the interface failure between sheath and core rod is the main cause of crisp fracture. Partial discharge at high voltage end and weak interface between glass fiber and epoxy resin matrix result in the development of degradation channels. Pollution and chalking on the surface of umbrella also explain part of the reason.

1. Introduction

The excellent anti-fouling performance is considered to be the most attractive feature of composite insulators. Compared with traditional porcelain insulators, it also has the advantages of light weight, small size, and high mechanical strength, etc. It is considered to be the most economical and effective insulation means in power system [1].

According to the existing operating experience [2-4], the failure of composite insulators is mainly electrical faults caused by flashover on the surface, and a few are mechanical failures such as core rod fracture. Although the probability of mechanical fault is much lower, the drop of insulator that may be caused by such a fault poses a serious threat to the safe and stable operation of the power system.

The types of composite insulator core rod fractures mainly include ordinary fracture, brittle fracture, and crisp fracture [5-8]. The ordinary fracture is the type of fracture that occurs after the tensile force exceeds the limit of its mechanical load; the brittle fracture refers to the abnormal fracture caused by the combination of mechanical stress and acid corrosion; the crisp fracture is attributed to a variety of factors such as damp, acid environment, partial discharge, leakage current, and mechanical tension [9-12].

This paper describes the investigation into a 500kV composite insulator fracture fault. A series of tests were carried out to analyze the defect of the fault insulator and the fracture mechanism of the core rod, including appearance inspection, hydrophobicity test, dissection analysis, dye penetration, SEM and FTIR. Based on the results, technical reference is provided for the diagnosis and treatment of the fracture fault of the core rod in the future.
2. Brief description of the fault
A fault occurred between phase A (bottom phase) and phase B (middle phase) of the 500kV line. It was found that the composite insulator of B phase (middle phase) was broken, causing the middle phase conductor grounded, and part of the conductor was in contact with the A phase (lower phase) conductor. It was heavy rain when the fault occurred, the wind was between moderate gale and fresh gale, and the temperature was 6°C.

3. Results of the insulator test

3.1. Appearance inspection
The appearance inspection of the faulty phase composite insulator found that the fracture was located between the 5th and 6th shed at the high voltage end. From the first shed to the 15th shed at the high voltage end, the sheath under the shed was perforated or cracked. Obvious chalking, stiffening, and cracking can be discovered on the sheath, as is shown in Figure 1.

![Figure 1. Appearance of the faulty insulator.](image)

3.2. Hydrophobicity test
The measurement of hydrophobicity of insulators includes hydrophobicity, hydrophobicity weakening and recovery characteristics and hydrophobicity migration characteristics. Insulator umbrellas are taken from high voltage, medium voltage, and low voltage sections of insulators respectively, and are divided into two groups: the uncleaned surface and the cleaned surface. The results are shown in Figure 2 respectively.

![Figure 2. Initial hydrophobic HC classification of uncleaned umbrella sample.](image)

It can be found from the test results that: (1) After long-term operation, the hydrophobicity of composite insulator silicone rubber umbrella decreases greatly, which can be attributed to the chalking
and pollution caused by the aging of silicone rubber surface. (2) After surface cleaning, the hydrophobicity of insulators recovers, which can be verified that surface pollution has some influence on hydrophobicity, but the hydrophobicity after cleaning is only HC3-HC4. (3) Umbrellas with either clean or unclean surfaces do not have hydrophobicity migration, which further shows that the chalking of silicone rubber surface is the main factor for the decrease of hydrophobicity.

3.3. Dissection analysis
To check the situation of the core rod, the fault insulator was dissected. It is obvious in Figure 3 that the core rod became white and the surface was chalked. The epoxy resin was decomposed, causing the glass fiber directly exposed. Obvious carbonization channel can be seen on the core rod, and the interface between the sheath and the core rod was loose. The sheath became brittle and stiffened.

![Image](image-url)

(a) The chalked and carbonized core rod

(b) The brittle and hardened sheath

Figure 3. Inner appearance of the faulty insulator.

The insulator was dissected along the high-voltage end to the low-voltage end, and the length of the degradation channel was found to be about 2.3 m. The core rod was cut off to do the light transmittance ratio test from the axial direction. The result was that the core rod of B-phase was impregnated unevenly, and no abnormalities were found in the A-phase and the C-phase.

3.4. Dye penetration
A total of 12 three-phase test samples were cut, and the length of the sample was in the range of 10 mm ± 0.5 mm. The cut surface of the sample was smoothed with a fine abrasive cloth. A layer of glass balls with the same diameter were placed in a container tray, and the dyeing solution was poured into the container. The dyeing solution was ethanol solution containing 1% violet methylene dye. It would rise through the core under capillary action, and the result was observed after 15 minutes.

After dyeing for 15 minutes, the A phase and C phase dyes did not penetrate the sample and met the standard requirements. In the B2 test sample, the dye penetrated the entire sample along the interface of the core rod and the sheath, and the phase B test did not meet the standard requirements. Through the dye test, it was found that there were defects in the interface of the faulty core rod and the sheath.
3.5. Scanning electron microscope (SEM)
The core rod and the shed were observed by scanning electron microscopy (SEM). The model of SEM was ZEISS EVO-18. After the sample was sprayed, the SEM observation was carried out, and the elemental composition of the micro-area of the sample was analyzed using the energy spectrum analysis (EDS) attached to the SEM.

3.5.1. Microscopic appearance of the fracture surface. Figure 4 shows the microscopic appearance of the fracture surface in low and high magnifications. It can be seen from Figure 4(a) that the glass fiber has been separated from the epoxy resin matrix, the glass fiber is completely exposed; the glass fiber is severely damaged and broken, and a large amount of fragments are attached to the surface of the broken glass fiber.

Figure 4(b) is a further enlargement of the concentrated area of the broken glass fiber and the fragments, and it can be seen from the figure that the surface of the broken fiber is densely covered with protrusions and particles.

![Figure 4](image-url)

**Figure 4.** Microscopic appearance of the fracture initiation position ((b) is detailed view of the area in (a)).
The results of micro-element EDS analysis of glass fiber and surface debris show that the main elements of fragments and glass fiber are composed of O, Si, Ca, Al, and a small amount of Na and Mg, but C element is not observed.

It is indicated that the epoxy resin matrix has been completely decomposed in the core rod cracking and decaying zone, and the fragments are mainly scattered glass fibers.

The SEM micromorphology and EDS elemental analysis of the core rod's sturdy position indicate that: (1) The cracking of the core rod leads to the decomposition of the epoxy resin matrix, and the loss of the wrapping and protection of the glass fiber; (2) The glass fiber suffered severely aging and damage, resulting in fracture and uneven surface.

3.5.2. Microscopic appearance of the umbrella. Figure 5 shows the microscopic appearance of the shed surface after cleaning with absolute ethanol and deionized water in low and high magnifications. It can be seen from Figure 5(a) that there are obvious cracks on the surface of the shed sample, indicating that the surface of the silicone rubber is aged significantly. Figure 5(b) is a further enlargement of Figure 5(a), and it can be seen that there is a large number of fine particles on the surface of the silicone rubber. EDS analysis showed that the main elements of the shed surface were Si, Al and O and a small amount of C, corresponding to polydimethylsiloxane (PDMS) and fillers such as silica and Al(OH)₃.

![Figure 5. Microscopic appearance of the clean umbrella surface.](image-url)
Figure 6 shows the micro appearance of the sheath near the fracture, more specifically, the sheath interface (Figure 6(a)) and the fracture surface (Figure 6(b)). It can be seen from Figure 6(a) that the structure of the sheath interface is complicated, and there are glass fibers and epoxy-based fragments. The EDS elemental composition analysis showed that only a small amount of C element was present in the particles scattered on the sheath, indicating that the interface between the epoxy resin and the silicone rubber sheath had completely failed.

![Figure 6. Microscopic appearance of the sheath interface and fracture surface.](image)

It can be seen from Figure 6(b) that the microscopic morphology of the sheath fracture is composed of loose granular structure. The compositional analysis of EDS elements shows that there are significant differences in the composition of the particles at the fracture of the sheath, including regular particles with high Na content (spectrum 2), agglomerated fine particles with high Ca content (spectrum 1) and scattered fine particles with a small amount of Fe and K elements (spectrum 3 and spectrum 4), which indicates that the failure of the sheath interface may be related to the infiltration of inorganic salts.
3.6. Fourier transform infrared spectroscopy (FTIR)
The core rod and the shed sample were respectively subjected to Fourier transform infrared spectroscopy (FTIR) analysis, and the test equipment was a Nicolet IS10 type Fourier infrared spectrometer. Among them, the cracked zone test sample and the intact core rod were tested by KBr tableting method; the umbrella surface and the aging layer were tested by infrared spectroscopy using the attenuated total reflection (ATR) accessory.

3.6.1. Fourier transform infrared spectroscopy analysis of core rod. Figure 7 shows the infrared spectrum results for spectra of different positions at the fracture and unaged core rod. The characteristic peak positions corresponding to typical functional groups are shown in the figure.

![Figure 7. Infrared spectra of different positions at the fracture and unaged core rod.](image)

It can be seen from the infrared spectrum of the core before and after aging: (1) The functional groups of the epoxy resin matrix such as methyl (–CH3), aromatic structure (benzene ring structure) and aliphatic structure are hardly observed in the aged samples, indicating that the epoxy resin matrix has been decomposed. (2) The –OH content in the aged core rod is greatly increased, indicating that the aging is accompanied by a significant hydrolysis process. (3) The content of Si–O bond in the aged core rod also decreased, indicating that the glass fiber also undergoes ion exchange and hydrolysis. (4) Compared with the infrared spectrum of the intact core rod, the C=O functional group in the amino compound appears in the aged core rod, indicating that the surface discharge of the core rod may cause the epoxy resin matrix to react with O2 and N2 to form an amino compound.

![Figure 8. Infrared spectrum of shed.](image)
3.6.2. **Fourier transform infrared spectroscopy analysis of shed.** The surface of the inner layer (the aging layer of the fracture surface) and the outer layer (the dirt layer is removed, and the chalked layer reserved) of the shed were inspected by infrared spectroscopy using ATR-enhanced infrared spectroscopy. The test results are shown in Figure 8.

From the infrared analysis of the inner and outer layers of the shed, it can be seen that: (1) The content of Si-O and CH groups which compose the silicone rubber is significantly reduced, indicating that the Si-O main chain and the Si-C side chain of the silicone rubber molecule are largely broken, and the surface of umbrella is aging. (2) The O-H group corresponding to the main filler of silicone rubber, namely flame-retardant Al(OH)3, also decreased, probably because the main chain breaks and the degree of cross-linking is reduced, so that the filler loses support.

3.7. **Simulation of electric field**

The electric field calculation model of the insulator is established according to the drawings. The dielectric constant of silicone rubber is 3.5, and the core rod 5. The ball head applies the peak value of the operating voltage, and the ball socket sets the ground potential. The solution domain is infinite.

![Figure 9. Distribution of the fault insulator electric field.](image)

The results shown in Figure 9 indicate that the field strength at the high voltage end of the composite insulator is 3.8kV/cm, the low voltage end 1.8kV/cm, and the middle of the insulator 0.7kV/cm. There is no obvious abnormality in the overall potential and field strength distribution of the insulator.

4. **Analysis of fracture causes of composite insulators**

4.1. **The interface failure between sheath and cod rod is the main cause of crisp fracture**

It can be seen from the appearance of the faulty code rod that the degradation degree near the interface between the core rod and the sheath is greater than that inside; The outer region of the core rod (i.e. zone close to the interface between the core rod and the sheath) is the most degraded area; Dyeing tests showed defects in the interface between the core rod and the sheath. It can be concluded that during the fracture process, the initial degradation point is at the interface between the core rod and the sheath.
4.2. Partial discharge at the high voltage end is an important factor for the crisp fracture
The fracture occurred at the high voltage end, where the electric field strength is 5.4 times that of the middle insulator and 2.1 times that of the low voltage end. Therefore, for the entire insulator, the high voltage end is a field strength concentration zone. The partial discharge in the high field strength zone is more intense, and the degradation of epoxy resin matrix accelerates under the influence of partial discharge.

4.3. The weak interface between the glass fiber core rod and the epoxy resin matrix is an important reason for the development of degraded channels
Through the dissection test, it was found that the interface between the glass fiber and the epoxy resin in the carbonization channel, the glass fiber was separated from the epoxy resin matrix, and the glass fiber was loosely arranged. The degradation of the epoxy resin does not depend entirely on the interface of the sheath with the core rod. Even in the area where the interface is well bonded, it can be found by SEM and FTIR analysis that the epoxy resin matrix of the faulty core rod is severely degraded, and the glass fiber is directly exposed to the air. The degradation and decomposition of the epoxy resin matrix lead to the glass fiber to lose protection and break.

When the carbonization channel develops to a certain length, the internal and external potentials of the composite insulator sheath are different, causing the sheath to break down and form a hole, so that the internal and external potentials of the sheath are forcedly consistent. Thereafter, the partial discharge at the interface continues, and when the carbonization channel develops to a certain length, the sheath again breaks down and forms a hole. Repeatedly, as the discharge progresses, a plurality of perforations is formed on the composite insulator sheath. Under the combined effects of moisture, partial discharge, leakage current, acidic medium and mechanical stress, it eventually leads to abnormal fracture of the composite insulator.

4.4. The obvious aging of silicone rubber accelerates the development of crisp defects
The visual inspection and SEM analysis of the umbrella showed that the surface of the silicone rubber after 12 years of operation was severely chalked and cracked. The shed was seriously polluted with poor hydrophobicity. The overall performance of silicone rubber was degraded, which accelerated the development of defects.

5. Conclusions
The fault is attributed to the interface failure between sheath and core rod at the end of the insulator. Due to intense electric field at the high voltage end, partial discharge occurred and caused electric corrosion at the damaged part of the sheath; The core rod lost protection from sheath after long-term electric corrosion; Moisture and rain water entered the interface between the sheath and the core rod, which caused the epoxy resin matrix in the core rod to hydrolyze and pulverize, as a result, the glass fiber directly exposed to air; The glass fiber aged and degraded under the action of leakage current and hydrolysis; The overall mechanical strength of the fracture surface decreased, eventually led to the whole core rod to break.

After investigation to find out the cause of the failure, we advise to keep a close watch on the same batch of composite insulators and replace them during the next regular maintenance. In the installation and maintenance of composite insulators, damage to the shed, sheath and end seals should be avoided. In addition, the composite insulator should not be stepped on, and the pressure equalization ring should not be reversed. During maintenance, special attention should be paid to the connection parts of sheath and end fitting. The composite insulator with damaged end seal and serious damage of the sheath should be replaced in time. On the other hand, new diagnostic methods, for example, infrared temperature measurement technology to detect the abnormal temperature rising of the composite insulator, and optical measurement using UAV, have a broad application prospect in maintenance of power system. In the meantime, more research should be carried out to find out the mechanism of the crisp fracture of composite insulators.
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