Discussions on Fracture Mechanisms of Composite Insulator

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Abstract: During actual operation, the fiber reinforced plastic (FRP) rod of composite insulator was usually cracked with major characteristics of brittle and decay-like. The made a systematical expatiation of the failure modes of FRP rod, and the mechanisms of these two common fracture types were analyzed. At last, as far as possible to avoid the occurrence of FRP rod fracture accidents in the transmission lines, from the point of view of operation and running, advice about promoting the manufacture level and installation quality of composite insulators were given.

1. Introduction
Composite insulator is a common electrical insulation equipment, which is generally consisted of high strength fiber reinforced plastic (FRP) rod, heat curable silicone rubber shed + sheath and high voltage + low voltage end metal fittings [1-5], as shown in Fig. 1. For the advantages of such as excellent mechanical properties, good insulation and anti-pollution flashover performances, etc., composite insulator has been worldwide applied in high voltage transmission systems [6-7]. In 1990 the composite insulator is firstly introduced in China, which is mainly used in heavily polluted areas. Up to now, the use count of composite insulators operated in china transmission systems is nearly 8 million according to statistics [8].

![Figure 1. Schematic diagram of composite insulator](image)

Although composite insulator has many advantages mentioned above, however, with the increase of service life and effects by heavy pollution operating environment, interface breakdown, shed aging, mechanical property reduction and FRP rod brittle fracture may be occurred. With long-term effect of high fields, partial discharges will be induced in insulator sheath and fittings, which will deteriorate the performance and even lead to breakdown and fracture of composite insulators.

A study of in-serviced composite insulator failures was carried out in 1994 by CIGRE and IEEE.
The findings indicated the failure of composite insulator was mainly caused by aging, mechanical properties and electrical properties problems, and the fracture and falling off of FRP rod accounts for 57% [9]. So far, the FRP rod fracture accidents are becoming more and more frequently and severely, which cause a great impact on the security and stability of transmission lines.

As the key component of the composite insulator, FRP rod is mainly consisted of resin and glass fibers, which is always bearing the load from the powerline and steel tower. The composite insulator is seldom broken unless the FRP rod suffers a huge force impact. However, the in-serviced composite insulator may be fractured by enduring a small loading, which is usually named abnormal fracture and belonged to a severe failure of the power system. One of the characteristics of the brittle fracture is that the FRP rod is always cracked perpendicularly, and the fracture surface is covered with a few normal fracture sections. Besides, there are also some accidents of FRP rod belong to another fracture type. When the FRP rod is cracked by this fracture type, the cracked FRP rod appears to be a piece of decayed wood, thereby named decay-like fracture [10]. Nowadays, decay-like fracture of FRP rod is occurred more frequently, seriously threatening the security and stability of transmission systems. In this paper, typical cases containing both brittle and decay-like failures of the operated composite insulators in the past several years were summarized, which was hoped to give some suggestions and technical guidance for the operation and maintenance of composite insulators in China.

2. Brittle fracture

The brittle fracture of composite insulator FRP rod is usually accompanied by a combined action of stress and corrosion. During running, when the sealing is invalid, the acidic liquid from outside will gradually percolate through the interface of the sheath and FRP rod under the action of electric fields. Subsequently, cracks will be formed at the surface of FRP rod and constantly extended, resulting in a gradual decrease of the effective cross-sectional area of FRP rod. Once the remained cross-sectional area of FRP rod could not stand the mechanical load of wires, brittle fracture accident will be occurred [11]. It can be seen Fig. 2 that the FRP rod is normally cracked along the axis and the fracture surface is smoother and flatter.

![Figure 2. Fracture surface of the brittle fractured FRP rod](image)

Zhang et al. investigated the fracture cause of a 500 kV composite insulator by means of water diffusion detection. Investigation results show that the hydrophobicity of the high voltage shed, central shed and low voltage shed is all excellent, while the crack of FRP rod was mainly related to the unqualified bonding process of composite insulator. With unqualified manufacturing technology, defects such as air voids, paper strips etc. will be introduced in the interface between the FRP rod and sheath. After actual operation, partial discharges will occur in these defects, and the interface of FRP rod-sheath is gradually corroded and aged, furthermore causing the FRP rod brittle cracked [12].

A 220 kV composite insulator (FXBW-220/100) operated for 10 years was found to be fractured with brittleness characteristic in 2009. It can be found after inspection that the fracture site was located in
the middle of second and third sheds (high voltage end), and the surface of the nearby sheath is seemed to be serious contaminant and chalked. After analysis, it was thought that the composite insulator high voltage sheath was long time eroded by salt spray. Over time, void would be formed in the interface of sheath and FRP rod, and the moisture will subsequently permeate into it when the sheath was cracked. Then electrical discharge was continuously acted on the surface of FRP rod due to electric field distortion. This process would induce the formation of acid liquids, therefore further accelerating the erosion of FRP rod. Once the remained cross-sectional area of FRP rod could not bear the loading from powerline and steel tower, brittle fracture accident would be triggered [13]. Similarly accident happened in 2010, one 500 kV composite insulator serviced in B phase of 31# tower was observed to be broken up [14]. The investigation results indicated that this failure was also resulted from electric field distortion, which destroyed the mechanical properties of FRP rod by acid corrosion. In addition, surface of sheds were found to be covered with a lot of pollutants, which further accelerated the electrical stress corrosions of high voltage sheath. Eventually, with the action of long-term electrical discharges, the sheath was cracked and the FRP rod would be constantly eroded until could not withstand stress fracture occurred.

3. Decay-like fracture

So far, decay-like aging of the operated composite insulator has become one of the most primary failures, which is principally resulted from the manufacture technologies. Decay-like fracture is usually related to the long-term partial discharges inside the FRP rod [15-16]. If a void is induced in the sheath-rod interface as a result of unqualified production process, electrical discharges will occur in subsequent operation of the composite insulator. Long-term electrical discharges lead to the epoxy resins being oxidized and discomposed, and the glass fibers will be then broken one by one, finally resulting in the decay-like fracture of composite insulator. Decay-like fracture is always induced near the high voltage end of the composite insulator, and the fracture surface is usually displaying apparent features of carbonized, ragged as well as chalked.

Lutz et al investigated the fracture cause of a 500 kV composite insulator operated for five years [17]. The visual observations revealed that the surface of fracture was crude with no apparently brittle fracture features. In addition, a few pits were found after peeling the sheath from the cracked FRP rod, which revealed that there was nearly no adhesive force remained in the sheath-rod interface before the composite insulator broken (Fig. 3).

![Eroded pit formed in the cracked composite insulator sheath](image)

The Fourier transform infrared (FTIR) test results showed that the concentration of -OH, -CO and nitrate ion \((\text{NO}_3^-)\) inside the aged FRP rod was very high. As known, \(\text{NO}_3^-\), -OH, and -CO were normally formed in the hydrolysis process of epoxy resins, which is most probably resulted from partial discharge activities in combination with absorbed moisture and ozone generation. The results also revealed that the fundamental fracture cause of composite insulator was due to the poor adhesion force, which resulted in several voids forming in the sheath-rod interface. And the aging process may...
be shown as following: voids formation→water vapor permeation→hot spot formation→sheath splitting→sheath pitting→FRP rod eroded→decay-like fracture.

Lu et al have investigated the phenomenon of abnormal heating for two 500 kV composite insulators operated in 30# and 168# towers. The far infrared measurement results indicated that the local temperature of the composite insulator was exceeded to 14.2 °C [18]. Investigation results revealed that the abnormal heating of the composite insulator principally resulted from the decay-like aging of FRP rod, as can be seen in Fig. 4. If the abnormal phenomenon was not found in time, the FRP rod would be cracked in the near future, causing serious consequences. Unlike brittle fracture of FRP rod mentioned above, decay-like fracture is usually a slow development process. So it is hard to find by macroscopic observation.

![Figure 4. Decay-like aging of FRP rod](image)

In conclusion, it can be seen that the FRP rod crack failure has become to be a very serious accident in transmission system. As mentioned above, the crack cause of FRP rod is mainly related to the adhesive bonding quality of interface (sheath-rod, rod-end fitting, etc.) as well as the quality of rod. Therefore, it is very necessary to carry out normal inspections such as rod penetration, water diffusion, line frequency withstand voltage test and wave impulse voltage test to detect the original defect in composited insulator before operating. In addition, extra care should be taken to the compression joining process of end metal fitting and FRP rod. Only in this way, the FRP rod quality and the sealing quality will be better guaranteed. Furthermore, measurements such as structural optimization, high voltage sheath thickness increasing and climbing distances increasing etc. should also be meaningful. It should also be noted that Dai et al found micro-cracks were induced at the grinding areas of FRP rods under stress corrosion experiments, which may finally cause the brittle fracture accident [19]. Consequently, more attentions should be paid on the surface roughness of the grinded FRP rod.

4. Inclusion

It is widely recognized (generally accepted) that the FRP rod fracture accidents have a great impact on the safety and stability of transmission lines, seriously affecting our daily life and economy activities. So far, the FRP rod fracture accidents are all occurred over the high voltage transmission lines. Being a common electrical component, composite insulators have a significant role in anti-flashover for transmission equipment. For the purpose of guaranteeing the safety and stability of transmission systems, carrying out study and research of the fracture accidents of composite insulator is very meaningful. By summering of the common FRP rod fracture accidents, we can learn experiences and lessons, thereby avoiding the occurrence of similar accidents and ensuring the safety and stability of transmission systems.

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