Study on Abnormal Heating Mechanism of FRP Rod of Composite Insulator

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Abstract. In recent years, abnormal heating phenomenon has occurred in composite insulators in China, which have brought potential trouble to the safe operation of power grid. The abnormal heating of fiber reinforced plastic (FRP) rod is an important reason for the temperature rise of composite insulators. In order to study the mechanism of abnormal heating of the FRP rod of composite insulator, three analysis methods of material including scanning electron microscopy (SEM), fourier transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS) are combined to make a microscopic analysis of abnormal heating phenomenon and sample of mandrel, which find that the abnormal heating mandrel of epoxy resin matrix and glass fiber were all deteriorated and accompanied by the invasion of moisture and the produce of HNO3. The experimental results show that polarization loss, partial discharge and resistance loss caused by deterioration of mandrel are the main reasons for abnormal heating of FRP core of composite insulator.

1. Introduction
Composite insulators are widely used in power systems because of their excellent flashover resistance, high specific strength and low cost. In recent years, the amount of composite insulators in newly built AC/DC UHV transmission lines has exceeded 70% [2]. By the end of 2014, the number of composite insulators running on 110 kV and above transmission lines in China has exceeded 7 million [3]. Because of the long-term electric field, mechanical force and complex and changeable environmental stress during operation, many abnormal heating faults have occurred in composite insulators since they were put into operation [4-5]. Many scholars have studied these faults and made a lot of achievements. Cheng Yangchun applied voltage to composite insulators with simulated defects and real defects and took infrared thermal images. The results showed that the resistance loss caused by sheath aging was the main cause of composite insulators heating [6]. Edson G studied the effects of surface contamination, equalizing ring and aging of silicone rubber on abnormal temperature rise and corona discharge of composite insulators. It was pointed out that surface contamination and improper configuration of equalizing ring would cause abnormal heating of composite insulators [7]. Wang
Liming Through studying the abnormal temperature rise accident of a 500 kV AC composite insulator in high humidity area of South China, proposed that the aging of silicone rubber umbrella sleeve generates polar groups, and the dielectric loss caused by repeated polarization in alternating electric field leads to abnormal temperature rise of composite insulators in this area [8]. Tu Youping studied the influence of ambient humidity on the abnormal heating of composite insulators. It was pointed out that the main causes of abnormal heating of composite insulators at high voltage end were high humidity and aging of the sheath surface at high voltage end [9-10].

Above research is mainly aimed at the phenomenon of end temperature rise caused by umbrella sleeve deterioration in abnormal heating of composite insulators, and there is also a fault of non-end temperature rise caused by abnormal heating of FRP rod during operation. At present, there is no literature report on its heating mechanism. However, the abnormal heating of core will accelerate its deterioration, and even cause abnormal fracture of composite insulators [11-13]. Therefore, it is of great significance to study the mechanism of abnormal heating of FRP rod of composite insulator.

Microscopic analysis methods such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Photoelectron Spectroscopy (XPS) have been widely used in the detection of micro-morphology and composition of composites [14-16]. In this paper, the mechanism of abnormal heating of FRP rod of composite insulator is discussed through experimental analysis of a composite insulator with abnormal temperature rise in operation and comparison with the sample of stock core rod.

2. Experimental Analysis

2.1. Introduction of Experimental Samples

The experimental sample in this paper is from a composite insulator with abnormal heating in humid and hot areas of southern China. The insulator is an AC 500 kV composite insulator which was put into operation in 2005. Its operation time is about 10 years. It was found that the heating area was located in the middle of composite insulator by infrared thermometry during inspection, and the maximum temperature rise was 33.5K. In order to prevent serious accidents such as breakdown and fracture of composite insulator, the insulator was replaced and analyzed experimentally. After examining the sheath, it was found that the FRP core in the heating area was decay-like aging, as shown in Fig.1.

![Figure 1. The appearance of abnormal heating core rod](image)

In order to locate the heating source, the operating voltage is applied to the FRP rod of the peeled sheath in the laboratory. The abnormal heating area is consistent with the result of the patrol temperature detection, and the maximum temperature rise reaches 52.0K. This indicates that the abnormal heating source is on the FRP rod, which is different from the abnormal heating phenomenon at the end of composite insulator caused by the aging of the sheath of the umbrella skirt proposed in the literature [6-11].
In addition to the abnormal heating sample, this paper uses a stock core sample of the same model and production batch as a reference, and carries out SEM, FTIR and XPS analysis on the heating sample and the stock sample respectively. The heating sample is taken from the most serious part of the temperature rise.

2.2. SEM
In order to study the microstructures of abnormal heating FRP rod, S-3700N scanning electron microscopy was used to observe it. The results were compared with stock sample. Two samples were magnified 1000 times and 4000 times respectively. The results of scanning electron microscopy were shown in Fig.2.

From Fig.2, it can be seen that the glass fibers in the stock sample are wrapped with epoxy resin, the interface between glass fibers and resins is well bonded and the interface structure is intact, while the epoxy resin in the heated samples has been seriously decomposed, the glass fibers are loose, and the interface between resin and fibers is invalid. This is because the high temperature caused by the abnormal heat of insulators accelerates the aging and decomposition of epoxy resin, and the thermal expansion coefficient of resin and fiber is not consistent, resulting in internal stress at the interface of fiber/resin matrix, which leads to resin decomposition and destruction of the interface structure. It can also be found in Fig.2 that the glass fiber surface of the heated sample is covered with particles suspected of corrosion marks, which may be caused by the corrosion of acidic substances, compared with the glass fiber surface of the stock sample, which is very smooth.

2.3. FTIR
Fourier transform infrared spectroscopy is an effective method to analyze the chemical composition of materials, which can be used to analyze the chemical reactions of FRP rod during operation: if the content of functional groups changes, the corresponding characteristic absorption peaks will change; if new materials are formed, new characteristic peaks will appear in infrared spectroscopy.

The main components of FRP rod are glass fiber, bisphenol A glycidyl ether epoxy resin, a small amount of curing agent and coupling agent. The main characteristic functional groups and their corresponding absorption peaks are shown in Table 1[17-19].

![Figure 2. The images of SEM](image-url)
Table 1. Typical characteristics of infrared absorption peak and the corresponding wave number for FRP rod

| Absorbing Group | Wave Number /cm⁻¹ |
|-----------------|-------------------|
| O-H             | 3700-3200         |
| CH₃             | 2970-2920         |
| C=O             | 1736              |
| Benzene         | 1608              |
| Benzene         | 1510              |
| C-C             | 1182              |
| C-O-C           | 1040              |
| Benzene         | 831               |
| Si-O            | 480               |

In this paper, IR Affinity-1S Fourier Transform Infrared Spectrometer is used to measure the FTIR characteristics of stock and abnormal heating samples respectively. According to Attenuated Total Reflection (ATR) mode, the scanning times are 20, the resolution is 2 cm⁻¹, and the scanning range is 400-4000 cm⁻¹. The results are shown in Fig.3.

Figure 3. FTIR spectrums of abnormal heating sample and stock sample

By comparing the infrared spectra of the abnormal heating sample and the stock sample, it is found that there are obvious differences between them. The analysis is as follows.

1) Compared with the stock sample, a new absorption peak with wave number of 1384 cm⁻¹ appeared in the FTIR diagram of the heated sample, indicating that nitrate ion appeared in the core rod of the heated sample. Because the FRP rod itself does not contain nitrogen element, nitrogen oxides will not be produced during aging and nitric acid (HNO₃). Therefore, it can be considered that nitric acid in the mandrel is produced by the interaction of moisture and partial strong field discharge [20]. The reaction mechanism is that N₂ and O₂ in the air produce NO₂ under the action of high field discharge, as shown in formula (1); NO₂ and O₂ dissolve in water to produce nitric acid, as shown in formula (2).

\[
\text{N}_2 + 2\text{O}_2 \xrightarrow{\text{discharge}} 2\text{NO}_2 \quad (1)
\]

\[
4\text{NO}_2 + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 4\text{HNO}_3 \quad (2)
\]
The nitric acid further corroded the core rod of composite insulator, accelerated the aging and decomposition of epoxy resin matrix, and caused the corrosion marks on the surface of glass fiber as shown in the scanning electron microscope pictures.

2) The peak strength of hydroxyl absorption of heating sample is obviously higher than that of stock sample, which indicates that the hydroxyl content of heating core rod increases, which may be caused by oxidation of epoxy resin to hydroxyl and water intrusion into core rod during operation.

3) The absorption peaks at 2970-2920, 1736, 1457, 1182, 1040 and 480 cm\(^{-1}\) show that the absorption peaks strength of heating sample are significantly lower than stock sample, indicating that the contents of methyl, ester, aliphatic C-H, C-C, C-O-C and Si-O bonds in heating sample decrease. The structure of methyl and aliphatic group is the functional group of epoxy resin matrix. The Si-O bond is the functional group of glass fiber in the mandrel. The ester group comes from the anhydride curing agent and the silane coupling agent in the core rod. It indicates that the silicon-oxygen bonds of the main chain, side chain and glass fibre of the resin matrix have been broken in the core rod of the abnormal heating sample, and the ester groups of the curing agent and coupling agent have been hydrolyzed. It is corroborated by SEM analysis that the epoxy resin is caked off and the glass fibers are exposed and corroded. In addition, for the absorption peaks of benzene ring structure with wave numbers at 1608, 1510 and 831 cm\(^{-1}\), the heating sample and the stock sample showed fluctuation, and did not show obvious increase or decrease, because the benzene ring structure was relatively stable.

2.4. XPS

XPS is a material microscopic analysis technology, which can accurately analyze the composition and relative content of elements in compounds. In this paper, Kratos Axis Ultra DLD XPS and Vario EL cube element analyzer are used to analyze abnormal heating sample and stock sample respectively. The results are shown in Table 2.

| Element Species | Element Content of Stock Sample (%) | Element Content of Heating Sample (%) | The Ratio of the Two Contents |
|-----------------|------------------------------------|---------------------------------------|-----------------------------|
| C               | 12.16                              | 6.23                                  | 0.512                       |
| H               | 0.631                              | 0.327                                 | 0.518                       |
| N               | 0                                  | 0.27                                  | ∞                           |
| O               | 40.79                              | 43.99                                 | 1.079                       |
| Si              | 25.564                             | 27.16                                 | 1.063                       |
| Ca              | 13.361                             | 13.79                                 | 1.032                       |
| Al              | 5.40                               | 5.83                                  | 1.08                        |
| Mg              | 1.26                               | 1.436                                 | 1.14                        |
| Na              | 0.435                              | 0.519                                 | 1.193                       |
| Fe              | 0.243                              | 0.273                                 | 1.123                       |
| K               | 0.11                               | 0.122                                 | 1.109                       |
| Sr              | 0.046                              | 0.053                                 | 1.152                       |

It can be seen that the element contents of FRP rod of abnormal heating sample are significantly different from stock sample, mainly in the following aspects:

1) The content of C element in the heating sample is 0.512 times of that in the stock sample, and the content of H element in the heating sample is 0.518 times of that in the stock sample. It can be seen that the content of C and H elements in the heating sample decreases in a similar proportion. This is consistent with the aging decomposition of epoxy resin in abnormal heating core rod by SEM analysis. The reason why the content of C and H decreases in an almost equal proportion mode is that the atomic number ratio of C and H in the chain segment of epoxy resin macromolecule forming cross-linking structure is 12:13, which is close to 1:1. Moreover, since the content of C and H in the heating sample is reduced to about half of the stock sample, it can be considered that the content of...
epoxy resin decomposed by aging in the heating sample is about half of the content of epoxy resin in the original core rod.

2) Nitrogen is not found in the stock samples, while nitrogen is detected in the heating sample. This corroborates the conclusion of FTIR analysis that nitric acid is produced by core rod under the combined action of moisture and discharge.

3) Since the content of each element is expressed as a percentage in the scanning result of XPS, when the epoxy resin in the heating mandrel decomposes, the content of C and H elements decreases, it would inevitably cause the content of other elements: Si, Ca, Al, Mg, Na, Fe, K, Sr elements to increase relatively, and the increase of the above elements content was maintained within 1.2 times.

4) The content of O element in heating sample is also higher than that in stock sample, because there are two main parts of O element in core rod: epoxy resin matrix and glass fiber with SiO\textsubscript{2} as the main component. Although the decomposition and exfoliation of epoxy resin results in the decrease of total O element, the decrease of resin matrix has little effect on O element because the content of resin matrix in mandrel is much lower than that of glass fiber. In addition, oxidation during operation, water invasion and nitric acid production mentioned above will cause the increase of O element content in the core rod.

3. Discussion

Based on the above experimental results, the heating mechanism of mandrel is analyzed and discussed in this paper.

SEM analysis shows that the epoxy resin matrix of abnormal heating core rod aging and decomposition, glass fiber exposed, corrosion marks on the surface, which means that the FRP rod has been seriously deteriorated, and the deterioration of mandrel will lead to the decline of its insulation resistance, resistance loss, resulting in more serious heating. FTIR analysis showed that nitrate ions appeared in the abnormal heating core rod, which indicated that the moisture intruded and produced strong field at the mandrel deterioration site, partial discharge occurred and nitric acid was produced. The formation of nitric acid would corrode the mandrel and aggravate its deterioration, and the polarization effect of partial discharge and invaded water in the alternating electric field would be produced heat. The results of XPS analysis show that the relative content of C and H decreases, and the N element grows from scratch, which are mutually corroborated by the serious deterioration of the heating core rod and the formation of nitric acid in the above conclusions.

Based on the above comprehensive analysis, this paper puts forward the abnormal heating mechanism of FRP rod of composite insulator: with the increase of operation life, under the combined action of strong electric field, mechanical load and complex and changeable environmental stress, the sheds and core rod of composite insulator gradually aging. Among them, the aging of sheds aggravates the process of external moisture intrusion and produces polarization loss; and the deterioration of core rod would lead to the decline of insulation resistance and lead to resistance loss. In addition, the deterioration of FRP rod would produce distortion strong field and partial discharge. Besides, the intrusive moisture generates nitric acid under the action of partial discharge, and further corrodes the mandrel. Generally speaking, polarization loss caused by moisture invasion, partial discharge and resistance loss caused by mandrel deterioration are the main reasons for abnormal heating of FRP rod of composite insulator.

4. Conclusion

In this paper, abnormal temperature rise composite insulator is stripped of sheath and applied voltage to measure temperature. It is determined that the temperature rise of the insulator is caused by abnormal heating of the FRP rod. SEM, FTIR and XPS analysis experiments were carried out on the heating part of the FRP rod, and the results were compared with stock sample. The results showed that the main reasons for the abnormal heating of the FRP rod of composite insulator were the polarization loss aggravated by water intrusion, partial discharge and resistance loss caused by core rod deterioration. Moreover, the abnormal heating and nitric acid produced by partial discharge would
accelerate the deterioration of the core rod, which would lead to more serious core rod heating. If not replaced in time, it may lead to abnormal fracture accident of composite insulator.

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References
[1] Zhang Guanjun, Zhao Lin and Zhou Rundong, “Review on aging characterization and evaluation of silicon rubber composite insulator,” High Voltage Apparatus, Vol. 52, No. 4, pp. 1-15, 2016.
[2] Sun Wenjian, Li Yawei, and Liu Xuandong, “Influence mechanism of UV on surface hydrophobicity of composite insulators in high altitude areas,” Power System Technology, Vol. 42, No. 3, pp. 996-1002, 2018.
[3] Liang Xidong, Gao Yanfeng, and Wang Jiafu, “Rapid development of silicone rubber composite insulator in China,” High Voltage Engineering, Vol. 42, No. 9, pp. 2888-2896, 2016.
[4] Xie Congzhen, Zeng Leilei, and Gan Yongye, “Study on pyrolysis characteristics of FRP rod of composite insulators based on TG-FTIR analysis,” Transactions of China Electro-technical Society, Vol. 33, No. S1, pp. 227-233, 2018.
[5] Cheng Yangchun, Li Chengrong, and Chen Mian, “Research on heating mechanism of composite insulator of high voltage transmission line,” Power system Technology, Vol. 29, No. 5, pp. 57-60, 2005.
[6] Chen Hao, Chen Yuan, and Zhao Xuesong, “Application of infrared temperature measurement technology in detection of composite insulator,” Electric Equipment, Vol. 7, No. 9, pp. 42-43, 2006.
[7] Costa E G D, Ferreira T V, and Neri M G G, “Characterization of polymeric insulators using thermal and UV imaging under laboratory conditions,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, No. 4, pp. 985-992, 2009.
[8] Wang Liming, Zhang Zhonghao and Cheng Li, “Cleaning effect of rainfall on surface contamination of insulators,” Power system Technology, Vol. 39, No. 6, pp. 1703-1708, 2015.
[9] Tu Y, Gong B and Wang C, “Effect of moisture on temperature rise of composite insulators operating in power system,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, No. 4, pp. 2207-2213, 2015.
[10] Tu Y., Gong B., and Yuan Z., “Moisture induced local heating of overhead line composite insulators,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, No. 4, pp. 483-489, 2017.
[11] Wang Zulin, Huang Tao and Liu Yan, “On-line inspection of defective composite insulators by infrared temperature measurements,” Power System Technology, Vol. 27, No. 2, pp. 17-20, 2015.
[12] Wang C, Li T, and Tu Y, “Heating phenomenon in unclean composite insulators,” Engineering Failure Analysis, Vol. 65, pp. 48-56, 2016.
[13] Lutz B, Cheng L and Guan Z, “Analysis of a fractured 500 kV composite insulator-identification of aging mechanisms and their causes,” IEEE Transactions on Dielectrics & Electrical Insulation, Vol. 19, No. 5, pp. 1723-1731, 2012.
[14] Song Wei, Shen Wenwei and Wang Guoli, “Influence of corona discharge aging on trap characteristics of high temperature vulcanized silicon rubber material,” High Voltage Engineering, Vol. 39, No. 4, pp. 979-986, 2013.
[15] Wang Fochi, Lü Fangcheng and Yang Shengjie, “The aging characteristic of silicon rubber sheds of 110kV composite insulators based on FTIR test,” Transactions of China Electrotechnical Society, Vol. 30, No. 8, pp. 297-302, 2015.
[16] Qin Yongxiong, Yu Lan and Fu Jia, “Research on microscopic properties and hydrophobicity of
high temperature vulcanization silicone rubber under long-ware ultraviolet radiation,”
Transactions of Electrotechnical Society, Vol. 29, No. 12, pp. 242-249, 2004.

[17] Lu Ming, Zhang Zhonghao and LI Li, “Reason analysis of decay-like aging for composite
insulator,” Power System Technology, Vol. 42, No. 4, pp. 1335-1341, 2018.

[18] Andersson J, Gubanski S M and Hillborg H, “Properties of interfaces between silicone rubber
and epoxy,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, No. 5, pp.
1360-1367, 2008.

[19] Lin Y C, Chen X and Zhang H J, “Effects of hydrothermal aging on epoxy-based anisotropic
conductive film,” Materials Letters, Vol. 60, No. 24, pp. 2958-2963, 2006.

[20] Liang Xidong and Gao Yanfeng, “Study on decay-like fracture of composite insulator: part I:
the principal character, definition and criterion of decay-like fracture,” Proceedings of the
CSEE, Vol. 36, No. 17, pp. 4778-4786, 2016.