Calibrating Method of Aging Degree of Silicone Rubber for Composite Insulator in the Power Grid Operation

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Abstract. There are many factors that cause the aging of composite insulators, and the aging of the insulators will cause greater harm to the operation of the power grid and the quality of power consumption of users. This paper analyzes the mechanism of insulator aging caused by different factors, and uses optical microscope to study the microscopic morphology of insulators to determine the degree of insulator aging. The board-to-board partial discharge experimental device is used to further verify the accuracy of the calibration, and the partial discharge voltage is used as the characteristic quantity to judge the degree of aging. The results show that the partial discharge voltage changes with the aging degree of composite insulators, and presents a certain rule. This research provides a favorable reference for the aging calibration method of composite insulators.

Keywords: Composite insulator, aging calibration, optical microscope, partial discharge.

1. Introduction

Composite insulators have been widely used in power transmission and distribution lines because of their light weight, excellent hydrophobicity and hydrophobicity migration, high insulation strength and good pollution resistance. In UHV projects, composite insulators occupy an important position because their creepage distance is much greater than that of glass and electric porcelain insulator strings [1]. However, as the service life increases, some defects of composite insulators are also revealed. Defects such as sheds deterioration, umbrella disc penetration, dirt deposition, surface chalking and cracking will bring great harm to the normal operation of the power grid [2]. This requires researchers to develop an effective method for calibrating the aging degree of silicone rubber insulators.

As a criterion, aging reflects the irreversibility of material degradation [3]. The current methods for judging the aging degree of insulators based on electrical characteristics are mainly leakage current method and thermal stimulation current method [4]. The detection is mainly based on the leakage current, the amount of trapped charge of the material and the surface resistivity, etc. [5]. Literature [6] used orthogonal test method to make aging samples, and then TSC test, scanning electron microscopy experiment and Fourier infrared spectroscopy experiment were performed on the samples to study the influence of humidity and air pressure on the aging process of composite insulators. The results showed that thermal stimulation the current test results can effectively determine the degree of aging, and the
degree of aging is related to humidity and air pressure. Tsinghua University team used tracking resistance, electrical corrosion resistance and water repellency as the detection characteristics, using thermogravimetric analyzer and Fourier infrared spectroscopy as auxiliary basis, combined with mathematical analysis to verify the feasibility of the two detection characteristics [7]. The Z Farhadinejad team’s research shows that solar ultraviolet radiation will corrode the surface of composite insulators, changing the atomic content of surface elements, and reducing the content of element C. Research by Song Wei et al. showed that the static contact angle of insulators will decrease after long-term operation, resulting in a decrease in the hydrophobicity and hydrophobicity of silicone rubber materials, and the increasing trap density at the same time [8, 9, 10]. In view of the phenomenon of cracking and chalking of high-temperature vulcanized silicone rubber after long-term operation, literature [11, 12] proposed a method based on color difference analysis, which uses the color change of the composite insulator umbrella skirt as a feature to reflect the degree of aging. Use the RGB color space to quantitatively divide the aging degree, but only based on the color distinction can only roughly determine the insulators with large aging degrees, and cannot be widely used.

This paper proposes a method to calibrate the aging degree of silicone rubber insulators using optical microscope and board-to-board electrode partial discharge experiments. 11 insulator samples with 10kV-110kV line voltage level in a certain area of North China are selected and processed into experimental samples. Taking the surface micro-morphology and partial discharge voltage of silicone rubber as the aging characteristics, the insulation state of composite insulators is divided into 5 grades through experimental methods.

2. Another section of your paper

2.1. Aging mechanism of composite insulators

Silicone rubber is a high molecular polymer formed by ring-opening polymerization of cyclic polysiloxane. Silicone rubber composite insulators are mainly composed of O, C, Si, H and other elements. Silicone rubber has a higher molecular backbone bond energy, which is composed of silicon-oxygen bonds formed by covalent bonding of Si and O elements, and its side groups are organic groups [13,14]. The external insulation of composite insulators is usually made of high-temperature vulcanized silicone rubber, and high-temperature vulcanized silicone rubber is mainly made of raw rubber, which is formed through cross-linking reaction of vulcanizing agent. The main components of the raw rubber used in production are methyl vinyl siloxane chain links and dimethyl siloxane chain links, and its molecular structure is shown in Figure 1.

![Figure 1. Schematic diagram of the molecular structure of methyl vinyl silicone rubber.](image)

The aging performance of silicone rubber is closely related to its spiral molecular structure, related groups and environmental factors. Silicone rubber is weak in polarity and has good hydrophobicity and hydrophobicity migration. From a macro perspective, due to long-time grid operation, composite insulators are affected by aging factors such as ultraviolet rays, pollution, corona arcs, and high-voltage electric fields, which increase the mechanical strength of the umbrella skirt, even chalking, cracking, and the color gradually becomes lighter. The water repellency continues to decrease, and there is a crack between the umbrella skirt sheath and the core rod, causing electrical corrosion damage. From a microscopic point of view, the aging of composite insulators can be understood as the rupture of silicone
rubber molecular chains. Taking high temperature conditions as an example, high temperature environments will cause thermal cracking of silicone rubber materials. Usually, silicone rubber will undergo main chain degradation and side group oxidation reactions at high temperatures. The crosslinking density of the material will also increase with the increase of temperature. These factors can lead to a decrease in mechanical properties.

The acidity and alkalinity will also affect the breaking of molecular bonds. Acid rain environment, coastal areas, saline-alkali land and near chemical plants are all acid-base environments, which are corrosive to the surface of the material, causing the Si-O bond of the silicone rubber main chain to break and producing polar Si-OH bonds, reducing the hydrophobicity of the material [15]. The influence of acidic environment on silicone rubber molecules is shown in Figure 2.

![Figure 2. Silicone rubber molecules react in an acidic environment.](image)

Since composite insulators are usually used in outdoor environments, the effects of ultraviolet rays are particularly important. As shown in Figures 3 and 4, the ultraviolet energy of solar radiation will cause the C-Si bond, C-C bond or C-H bond on the side chain of the silicone rubber molecule to break to generate free radicals. C, H, Si plasma is easy to chemically react with oxygen to generate hydrophilic groups and methane gas, which will have a certain impact on the surface of the insulator and the hydrophobicity of the material.

![Figure 3. C-H bond breakage of silicone rubber molecules under UV irradiation.](image)

![Figure 4. C-Si bond breakage of silicone rubber molecules under UV irradiation.](image)

The previous paper briefly analyzed the aging mechanism of silicone rubber under three common factors. In addition, high-voltage electric field, ozone and other conditions will also affect the aging process of silicone rubber, but the essence of aging is basically caused by the breakage of the main chain of the silicone rubber molecule or the oxidation of the side chain.
2.2. Aging experiment analysis of composite insulators

2.2.1. Sample production. Eleven suspended composite insulators were taken from a 10KV-110KV line voltage level in a certain area of North China as experimental samples, including two unused brand-new insulators, and the remaining nine were connected to the grid for more than ten years. As shown in Figure 5, there are brand-new insulators, insulators with a certain degree of aging, and insulators with severe aging. It can be seen from the figure that the surface of the new insulator is smooth and the texture is soft; a certain degree of aging insulators have relatively large mechanical strength and have undergone a certain degree of deformation; severely aging samples have serious surface powder and deep corrosion.

![Figure 5. Non-aging, aging and severe aging test samples.](image)

To facilitate the measurement of the aging degree of each insulator, 11 insulators were labeled separately, and three different parts were cut on each insulator to make samples. The sampling positions were: high voltage side, near high voltage side, and far away from high voltage side. Use a cutting machine to cut the sample into slices with a length of 30 mm, a width of 20 mm, and a thickness of 4 mm. Each insulator takes 10 samples, a total of 11 sets of samples, as shown in Figure 6, which are partially cut experimental samples.

![Figure 6. Some insulator samples.](image)

After soaking the cut sample with absolute ethanol, the surface of the sample is wiped by deionized water, then dry the processed sample in a vacuum dryer, and finally put all the samples in the labeled sample bag and seal for storage.

2.2.2. Optical microscope experiment. During the experiment, the packaged insulator samples were taken out, and the surface of 11 groups of samples was microscopically observed using an optical microscope. The experimental equipment and experimental environment are shown in Figure 7.
First, adjusting the eyepiece to the magnification of 10×, the objective lens magnification of 63×, the total magnification is 630×, and then fixing the sample on the stage to observe the surface micro-topography. The observation results of some typical samples are shown in Figure 8.

Figure 7. Optical microscope experiment.

According to the results of microscope observation, sample 1# is a brand-new sample with no holes and cracks on the surface, smooth and flat, and good texture. There are only a few white spots in the image. Such white spots are internal particles of silicone rubber, usually aluminum hydroxide and silica, etc., which are incorporated to improve the performance of silicone rubber. There are small holes in the
sample 2#, indicating that the molecular chain of the silicone rubber molecule on the surface of the sample has been broken, the side chain is oxidized, and the methane gas produced escapes from the surface. On the whole, the smoothness of the insulator surface decreases and the flatness decreases. From the observation in Figure 2-4, it is not difficult to find that the surface of 4#, 7#, 8# is similar to that of 2# sample, with a small amount of white spots on the surface, indicating that the internal additives are gradually exposed. So, they can be classified into one category. 3# sample and 6# sample have larger surface poles than 2# sample, the aging depth also deepens, the number of white spots increases sharply, and many obvious gullies are formed on the surface. The surface of the 5# and 11# samples is quite different from the previous samples. The surface holes are more serious due to corrosion, the aging has extended to the inside of the material, and the white spots are all over the surface of the sample. In summary, the microscopic morphology results of the insulator samples observed by the optical microscope can be classified, as shown in Figure 9.

![Image](image_url)

**Figure 9.** Observation of the surface micro-morphology of the sample’s aging degree calibration.

The observation results are calibrated on the sample bag. From this, the qualitative classification of the aging degree of the silicone rubber samples can be preliminarily classified into five categories. The specific determination results are as follows:

- **Category I:** Samples 1# and 9#, no aging or very low aging;
- **Category II:** Samples 2#, 4#, 7# and 8#, the insulators have detectable aging, the surface hydrophobicity gradually decreases, and holes appear;
- **Category III:** Samples 3# and 6#, the hole area is enlarged, and the aging is gradually serious;
- **Category IV:** Samples 5# and 10#, increased surface defects of the material, and the aging is further deepened;
- **Category V:** Sample 11#, the surface of the material is severely chalked, and the aging extends to the inside of the material.

2.2.3. **Plate-to-plate electrode partial discharge experiment** the optical microscope experiment can intuitively reflect the information of the aging state of the insulator surface. To verify the accuracy of the above calibration results, this paper continues to do partial placement experiments on 11 sets of samples. The experimental device and schematic diagram are shown in Figure 10.
The HFCT high-frequency current sensor is used to detect the pulse current of the partial discharge experiment. The HFCT sensor converts the high-frequency current signal into the corresponding voltage through electromagnetic coupling for measurement, because this voltage amplitude is proportional to the high-frequency pulse current amplitude [16]. The partial discharge signal in electrical equipment is very weak, while the high-frequency current sensor has wide bandwidth and smooth amplitude-frequency response curve. It can track the partial discharge situation in time, and its transfer function is expressed as

\[
H(S) = \frac{U(S)}{I(S)} = \frac{MS}{L_0 C_0 S^2 + \left(\frac{L_0}{R_0} + R C_0\right) S + \frac{R_0}{R} + 1}
\]  

Wherein the upper cut-off frequency is

\[
f_1 = \frac{L_0 + RR_0 C_0}{2\pi L_0 R C_0} = \frac{1}{2\pi R C_0}
\]  

The lower cut-off frequency is

\[
f_2 = \frac{R + R_0}{2\pi (L_0 + RR_0 C_0)} \approx \frac{R + R_0}{2\pi L_0}
\]
Among them, $R_0$ is the equivalent resistance of the coil, $L_0$ is the equivalent inductance of the coil, $C_0$ is the equivalent stray capacitance of the coil, and $R$ is the external integral resistance. Therefore, in this experiment, the high-frequency current sensor is the first choice to detect the partial discharge voltage.

Connect the experimental equipment according to the schematic diagram. After the test is normal, experimenter take out the encapsulated 11 sets of samples, and place them in the center of the lower plate of the device according to the microscope observation sequence mentioned above, then adjust the distance between the upper and lower plates to 50mm and place them on the insulated tabletop. After confirming the safety, experimenter turn on the power supply, adjust the voltage regulator for discharge experiment. In order to avoid large errors in the experimental results, three partial discharge data were recorded for each group of experimental insulator slices each time. When the high frequency signal is sensed in the HFCT sensor for the first time, the waveform amplitude and phase of the voltage and pulse current applied between the partial discharges devices are collected for the first time. After continuous pressure, when the discharge sound happens between the plates, the second acquisition is performed Partial discharge data. When the discharge sound reaches the maximum, we collect data for the third time.

2.2.4. Analysis of results. In the data recorded in the partial discharge experiment in Section 2.2.3, the time-domain waveforms obtained from the three measurements of sample 1# are shown in Figure 11.

![Figure 11. Time-domain waveform diagram of sample 1# in three experiments.](image-url)

It can be seen from Figure 11 that the main pulse of the discharge waveform is mainly in the range of 0-100μs. When the voltage is applied between the plates, the amplitude of the main pulse waveform is about 0.1V. With the increase in voltage, the amplitude of main pulse rises slightly. Figure 12 shows the phase spectrum corresponding to the three discharges in the above figure. Each point in the figure represents a discharge pulse. It can be observed from the figure that as the voltage between the plates increases during the whole process, the discharge volume gradually increases, and the interval between
two adjacent partial discharge pulses is gradually shortened. The number of discharge pulses in a period from 102 to 229, and finally to 5000, there is an upward trend. The discharge phase was mainly concentrated in the first half of the period at the beginning of the experiment and when the sound just appeared, and when it was about to break down, it had spread to the second half of the period, and the amplitude was changed from 0.1-0.2V to 0.1-0.5V.

Figure 12. a), b), c) Phase spectrum.
After averaging the experimental data with MATLAB, the partial discharge voltage of each group of samples is obtained, as shown in Table 1.

Table 1. Partial discharge voltage of insulator slice.

|     | Start to discharge/kV | Appear sound/kV | Will be breakdown/kV | Overall average discharge voltage/kV |
|-----|-----------------------|-----------------|----------------------|-------------------------------------|
| 1#  | 4.750                 | 5.000           | 9.000                | 6.250                               |
| 2#  | 4.625                 | 4.875           | 8.750                | 6.083                               |
| 3#  | 4.500                 | 4.750           | 8.375                | 5.875                               |
| 4#  | 4.625                 | 4.875           | 8.000                | 6.000                               |
| 5#  | 4.500                 | 4.875           | 8.125                | 5.833                               |
| 6#  | 4.750                 | 5.000           | 8.000                | 5.917                               |
| 7#  | 4.750                 | 4.875           | 8.500                | 6.042                               |
| 8#  | 4.625                 | 5.000           | 8.750                | 6.125                               |
| 9#  | 4.750                 | 4.875           | 9.000                | 6.208                               |
| 10# | 4.375                 | 4.500           | 8.000                | 5.625                               |
| 11# | 4.125                 | 4.625           | 7.750                | 5.500                               |

From the overall average discharge voltage in the above table, it can be seen that the discharge voltage of samples 1# and 9# is the highest, and the voltages of samples 2#, 4#, 7#, and 8# are slightly lower than those of 1# and 9#, and the overall gap is not large. Compared with the former, sample 3#, 5#, and 6# have lower discharge voltage, and the gap is also smaller. The partial discharge voltages of 10# and 11# are the lowest, and compared with the discharge voltage of the new sample, it is found that the drop is about 0.1kV, indicating that the degree of aging has been very serious. The change rule of the discharge voltage when the initial discharge, sound appears, and about to breakdown is basically the same as the change rule of the overall average discharge voltage. It can be seen that it is feasible to quantitatively determine the degree of aging of insulators by using partial discharge experiments.

Combined with the microscopic analysis results of section 2.2, the aging degree calibration of the final 11 groups of composite insulator samples can be obtained. The results in Table 3-1 are basically the same as the calibration results in Figure 2-5. The only difference is that the 5# sample is calibrated as Category III. The partial discharge voltage decreases as the insulator ages. The final sample aging degree calibration is shown in Figure 13.

Figure 13. Composite insulator aging grade.
3. Conclusions

(1) In this paper, 11 sets of composite insulators with line voltage levels of 11kV-110kV are selected to make samples, and the aging degree of each group of insulator samples is calibrated and graded by two methods: optical microscope microscopic analysis and partial discharge experiment.

(2) Through optical microscope experiments, it can be seen that the higher the degree of aging of the insulator, the worse the flatness of the surface microstructure and the more holes.

(3) The partial discharge experiment shows that the aging degree of composite insulators is closely related to the partial discharge voltage. As the aging degree deepens, the partial discharge voltage gradually decreases. This index can be used as a criterion for distinguishing the aging degree of composite insulators.

(4) The qualitative analysis of the aging degree of insulators using optical microscope and the quantitative analysis of the aging degree of insulators using board-to-board partial discharge experiments are basically consistent. It can be seen that it is feasible to combine the two methods to calibrate the aging degree of composite insulators.

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References

[1] Yang Huabiao, Yang Siguang, Zhang Liping, et al. Application Status and Research Progress of Silicone Rubber in Electrical Industry[J]. Silicone Material, 2016, 30(1)28-31.

[2] Nandi Sounak, Subba Reddy B. Understanding field failures of composite insulators[J]. Engineering Failure Analysis, 2020,116(5).

[3] Wenbo Li, Dun Mao, Yue Jiang, et al. Research on Defect Detection Technology of Composite Insulator Sheath[J]. E3S Web of Conferences, 2021,252.

[4] Hui Zhang, Youping Tu, Yuliang Tong, et al. Study on Aging Characteristics of Silicone Rubber Sheds of Composite Insulators Based on TSC Test[J]. Proceedings of the CSEE, 2012, 32(19)169-174.

[5] Ruixue Wang, Bin Hai, Sili Tian, et al. Optimization of Dielectric Material Surface Charge Measurement and Impact of Plasma Treatment on Their Surface Electrical Characteristics[J]. High Voltage Engineering,2017(6)1808-1815

[6] Ying Liang, Pingping Dong, Lijuan Gao. Corona Aging Characteristics of Composite Insulators Based on Orthogonal Experiment [J]. High Voltage Engineering, 2018, 44(12)4083-4089.

[7] Yunfeng Xia, Xinning Song, Jianzong He, et al. Evaluation Method of Aging for Silicone Rubber of Composite Insulator[J]. Transactions of China Electrotechnical Society, 2019, 34(S1)440-448.

[8] Yaa Nianping, Wan Hua, Cheng Zheng, et al. Research Progress in Ageing Condition and Characterization Technology of High Temperature Vulcanized Silicone Rubber [J]. Insulating Materials, 2017, 50(12)1-9.

[9] Yong Zhu. Influence of corona discharge on hydrophobicity of silicone rubber used for outdoor insulators[J]. Polymer Testing, 2019, pp.14-20.

[10] Farhadinejad Z, Ehsani M, Ahmadi-Joneidi I, et al. Effects of UVC Radiation on Thermal, Electrical and Morphological Behavior of Silicone Rubber Insulators[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2012, 19(5)1740-1749.

[11] Hao Fu, Lifu Wang, Yaozhong Li. Degradation Condition Assessment of Composite Insulators Based on Chromatic Aberration Analysis[J]. Environmental Technology, 2015, pp.5-9.

[12] Lutz B, Cheng L, Guan Z, et al. Analysis of a fractured 500kV composite insulator-identification of aging mechanisms and their causes[J]. Dielectrics and Electrical Insulation, IEEE Transactions on, 2012, 19(5)1723-1731.

[13] Sima Kashi, Russell Varley, Mandy De Souza, et al. Mechanical, Thermal, and Morphological
Behavior of Silicone Rubber during Accelerated Aging[J]. Polymer-Plastics Technology and Engineering, 2018, 57(16)1687-1696.

[14] Guangya Wu, Wei Cai, Zhenhai Luo, et al. Analysis of the Operation Characteristics of the Composite Insulators[J]. High Voltage Engineering, 2000, 26(2)59-61+64.

[15] Shifang Yang, Zhidong Jia, Xiaogang Ouyang, et al. Hydrophobicity characteristics of algae-fouled HVDC insulators in subtropical climates[J]. Electric Power System Research, 2017.

[16] Rodrigo-Mor Armando, Muñoz Fabio A, Castro-Heredia Luis Carlos. Principles of Charge Estimation Methods Using High-Frequency Current Transformer Sensors in Partial Discharge Measurements[J]. Sensors, 2020, 20(9).