Preparation of cleaning and repairing agent and its double cleaning effect on surface contamination of silicone rubber external insulation

Yueju Zhao1,2, Xiwei Xie1,2,∗, Jinbiao Shi1,2, Huaping Shan1, Min Liu1, Jie Liu3, Jianhui Wang2, Boyan Jia3, Yongli Zheng1,2, Qiang Chen1,2, Chunfeng Zhao1,2, Jilin Teng1,2 and Wenhua Miao1,2

1 Beijing Guodian Futong Science and Development Co. Ltd., Beijing, 100070, People’s Republic of China
2 NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing, 211106, People’s Republic of China
3 DC Technical Center of State Grid Corporation of China, People’s Republic of China
4 State Grid Zhejiang Electric Power Research Institute, People’s Republic of China
5 State Grid Hebei Electric Power Research Institute, People’s Republic of China

∗ Author to whom any correspondence should be addressed.

E-mail: xiexiwei@sgepri.sgcc.com.cn

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Abstract
Due to the long-term operation of power grid and the interference of external uneven electric field environment, silicone rubber insulators are prone to aging and scaling, and their hydrophobicity and external insulation performance are easily affected. In order to solve this problem, a kind of silicone rubber insulator outer surface cleaning and repairing agent was prepared with self-made composite solvent and silicone as the main raw materials, supplemented by catalyst, surfactant and other additives. So as to achieve the dual effect of efficient cleaning and aging repair, improve its hydrophobicity and prolong its service life. Through hardness test, hydrophobicity test, SEM test, FT-IR test, EDS test, mechanical property test and aging test characterization, and comparing the cleaning effect of different cleaning methods, it is found that the cleaning effect of cleaning repair agent is the best. In addition, it is found that the hydrophobicity of insulator has been greatly improved, from HC4 to HC1, and the mechanical properties have also been improved. This is because after using the cleaning and repairing agent, the powdered layer on the insulator surface is removed, and more hydrophobic methylene (Si–(CH3)2) and methylene (Si–(CH3)3) are attached to the insulator surface, which reduces the -OH binding force between the insulator surface and water molecules. In addition, through the observation of the surface and cross-section micro morphology, it is found that the surface roughness of the insulator is greatly reduced and the micro cracks disappear after using the cleaning and repairing agent, which highlights a certain repairing effect. Finally, the aging test also shows that the cleaning repair layer has a certain durability. The results show that the cleaning and repairing agent can effectively clean and repair the aged insulator, improve its anti-pollution flashover ability and prolong the service life of silicone rubber insulator.

1. Introduction

High voltage insulators, especially silicone rubber composite insulators, play an important role in the safe operation of power lines. Because of its good electrical insulation, surface hydrophobicity and anti-pollution flashover characteristics, it has a broad application prospect in power system, especially in UHV and EHV transmission lines and projects [1, 2]. With the long-term operation of high-voltage, extra-high voltage and ultra-high voltage projects, due to the extension of operation time, ultraviolet radiation, high heat and humidity environment, high salt fog environment, corona discharge, inhomogeneous electric field distribution and the influence of rain, snow, wind and sand, the metal post on the insulator will break to a certain extent, and the obvious aging phenomena such as serious pollution accumulation and pollution flashover will appear on the
upper and lower surfaces, and the pollution range of the upper surface area will increase the degree of pollution is greater than that of the surface area below \([3–10].\) Generally, the current aging evaluation methods for insulators mainly include hydrophobicity test, salt spray aging test, UV aging test, corona aging test, solid coating test, inclined plane method etc \([11–14].\) In order to prevent the deterioration of electrical properties of silicone rubber insulators due to aging, the existing researchers add Nano fillers hybrid silica or hydrogenated silicone oil to improve the properties of the composites \([15–18].\) However, insulator flashover will lead to unexpected or inevitable power failure, so it is necessary to maintain and repair the power system.

Generally, the main cleaning methods for the polluted silicone rubber insulator are manual water cleaning, manipulator assisted cleaning, artificial solvent scrubbing, RTV anti-pollution flashover coating and so on \([2, 19].\) However, the use of manual direct water cleaning can remove part of the surface pollution, but it needs power-off operation or live operation, which will bring many difficulties to the construction, and even affect the normal power demand. If solvent is used for cleaning, the surface pollution can be removed, but the smell is strong, which will not only damage the internal structure of silicone rubber insulator, but also cause environmental pollution. Moreover, the application of RTV anti-pollution flashover coating can improve the hydrophobicity and anti-pollution flashover ability of insulators in a short time, but because of the pollution attached to the surface all the year round, it has caused its aging, seriously affected its insulation and mechanical properties. RTV coating will fall off due to aging, and cannot fundamentally solve the problem, so a new method to clean the surface pollution of aging insulators needs to be developed \([20].\)

In this study, a cleaning and repairing agent was prepared to clean the contamination on the outer surface of silicone rubber insulator and repair micro cracks, as shown in scheme 1. It can effectively restore the hydrophobicity of the insulator surface, repair the micro cracks on the surface and extend the service life of the insulator. The insulators, which have been running for 14 years, were cleaned by water and cleaning and repairing agent respectively. Then, the cleaning mechanism and effect of the cleaning and repairing agent were comprehensively analyzed by comparing its element change, functional group change, hardness, hydrophobicity, surface micro morphology and mechanical properties.

2. Materials and methods

2.1. Materials and equipment
Silicone rubber insulator sheds in operation for 14 years, several; organosilicon: viscosity 20000 MPa·s, Toshiba silicone company, Japan; High density composite solvent and organosilicon surfactants (The surface tension is 20 N/m), self-made (Beijing Guodian Futong Technology Development Co., Ltd.); silicon dioxide, Weifang Hengshuo Nano materials Co., Ltd.; Dimethyl silicone oil, Aladdin; Wacker cleaning agent, Wacker chemical (China) Co., Ltd.

Vacuum kneader: NH, Shandong Longxing Chemical Machinery Group Co., Ltd.; Three roller grinder: SM-160, Shandong Longxing Chemical Machinery Group Co., Ltd.; Double planet mixer: 15 L, Shandong Longxing Chemical Machinery Group Co., Ltd.; Microcomputer controlled electronic universal testing machine: KDIII-5, Shenzhen Kaiqiangli Testing Instrument Co., Ltd.; Scanning electron microscope (SEM): S-4800, Hitachi Japan; Energy dispersive X-ray spectrometer (EDS): JED-2300; Fourier transform infrared spectrometer (FT-IR): Nicolet is50, Thermo Fisher Scientific; Video contact angle tester: OCA 20, dataphysics, Germany; Ultraviolet aging instrument: Q-SUN, Wuxi Yierda test equipment manufacturing Co., Ltd.; Salt Spray test chamber: YW/R-150, Surui electronic equipment (Beijing) Co., Ltd.
2.2. Sample preparation
The organosilicone, silicon dioxide, dimethyl silicone oil and other base materials were weighed according to a certain proportion, and mixed in the kneader. The temperature range is 110 °C ∼ 130 °C, and the vacuum degree is below 0.098 MPa. After mixing for 5–6 h, the material is discharged and grinded in a three roller mill for two to three times. Put the mixed initial mixture into the planetary mixer, add a certain amount of self-made surfactant and composite solvent, disperse at the speed of 50 R min⁻¹ for 1-2 h, filter and fill, then the cleaning and repairing agent can be prepared.

The prepared cleaning and repairing agent can be used after standing for 24–48 h under the sealed condition at room temperature, and can be directly used for cleaning and repairing the surface of aging composite insulators.

2.3. Characterization
Insulator specimens with thickness not less than 6 mm shall be prepared under the adjustment environment of GB/T 531.1-2008 [21]. The test shall be conducted with a shore hardness tester perpendicular to the surface of the specimen. At least five points shall be selected for each specimen and the average value shall be taken.

According to the measurement method of DL/T 627-2018 [22], the hydrophobicity grading HC value of the test piece surface was measured under standard experimental conditions to evaluate its hydrophobicity, hydrophobicity loss, hydrophobicity recovery and hydrophobicity migration.

A microcomputer controlled electronic universal testing machine (Mester Industrial System (China) Co., Ltd.) was used to test the tensile strength of the sample (1500 mm × 10 mm × 4 mm) made according to the test standard GB/T 528-2009 [23] in the laboratory environment for 24 h, and the tensile speed was 50 ± 5 mm min⁻¹. Each group of specimens was tested more than three times, and the test results were averaged. In the laboratory environment, the C-type right angle tear test piece with thickness of 2.0 ± 0.2 mm was made according to GB/T 529-2008 [24] test standard. After 24 h, the tear strength test was carried out. The crack separation rate was 50 ± 5 mm min⁻¹, each group of samples was tested at least three times, and the average value was taken.

Scanning electron microscopy (SEM) (bcpcas-4800, Hitachi Japan) were used to observe the surface and cross-section morphology of silicone rubber insulator before and after cleaning. All samples were coated with a thin layer of gold before scanning electron microscopy.

Attenuated total reflection Fourier transform infrared (ATR-FTIR) spectra of composites were monitored using a Nicolet iS50 FT-IR spectrometer (Thermos Fisher scientific) in a wavenumber range of 4000–550 cm⁻¹.

500 h salt spray test was carried out in YW/R-150 Salt Spray test chamber. The aging insulators with cleaning and repairing agent or not were placed in a 45° salt spray box. The temperature of the chamber was set at 35 °C and the temperature of the saturated air was set at 47 °C. After 500 h, the salt spray resistance of insulators treated with cleaning and repairing agent was evaluated by visual inspection of these samples, and the contact angle and tensile properties of these samples surface were tested.

The experimental device is Q-SUN ultraviolet aging instrument, using UV-B series ultraviolet lamp, the ultraviolet wavelength is 313 nm, the energy range is 314 ~ 419 KJ mol⁻¹, the average energy is 399 KJ mol⁻¹. The ultraviolet aging instrument is divided into two parts to irradiate the samples. Each part has four ultraviolet lamps. The irradiating area is 0.5 m² and the total irradiating power is 500 W. The sample is placed in the sample tray, and the length and width of the irradiated surface of a single sample is 100 × 60 cm².

3. Results
In order to prolong the service life of silicone rubber insulators, cleaning and repairing agents were prepared to clean and repair the surface dirt of aging insulators. The state of aging insulator before and after cleaning is shown in figure 1. It can be seen from figure 1 that after the aged insulator is cleaned with cleaning and repairing...
agent, the surface dirt is cleaned, and the color of the aged insulator can return to its original state. In the test, the aged insulators were cleaned with clean water and cleaning and repairing agent respectively. Through hardness test, mechanical property test, hydrophobicity test, scanning electron microscope, energy dispersive spectrometer, infrared spectrum and other test methods, the cleaning and repairing effects were compared, and the mechanism and performance changes were comprehensively analyzed. The results are as follows.

3.1. Hardness of insulator before and after cleaning
According to GB/T 531.1-2008 [21], the hardness values of silicone rubber insulators before and after cleaning are tested with shore hardness tester under laboratory conditions, and the results are shown in table S1 (available online at stacks.iop.org/ MRX/8/065101/mmedia).

It can be seen from figure 2 and table S1 that the hardness of silicone rubber insulator before and after cleaning has little change, and fluctuates between 71–75 shore a. This shows that the cleaning and repairing agent has little effect on the hardness of silicone rubber insulator, and even slightly reduces the hardness, which has a positive effect on prolonging the service life of insulator.

3.2. Hydrophobicity of insulators before and after cleaning
Hydrophobicity test is a method to characterize hydrophobicity, which is a surface property of solid materials. Water on the surface of hydrophobic solid can form separated water droplets or droplet state instead of continuous water film. According to the requirements of hydrophobicity test in DL/T 627-2018 [22], hydrophobicity classification test is carried out for silicone rubber insulator. And the hydrophobicity of RTV coating should meet the following requirements: (1) initial hydrophobicity classification: HC1-HC2; (2) hydrophobicity weakening: HC3-HC4; (3) hydrophobicity recovery: HC2-HC3; (4) hydrophobicity migration: HC2-HC3. The samples should be tested under standard laboratory conditions (temperature 23 °C ± 2 °C, relative humidity 50% ± 10%).

3.2.1. Initial hydrophobic properties
The initial hydrophobicity grading characteristic refers to the initial hydrophobicity grading value of the sample surface, which is expressed by HC value. The smaller the HC value, the better the hydrophobicity. HC7 has the worst hydrophobicity, indicating that the surface of the material is completely covered by water film, and there is no water drop on the surface, reflecting its hydrophilicity. The initial hydrophobicity classification diagram is shown in figures 3(a)–(e), and the data results are shown in table S2.

Through the initial hydrophobic test, it is found that the silicone rubber insulator umbrella skirt aging after 14 years of operation, and the hydrophobicity also decreases, and the hydrophobicity grade is only HC3-4. After the test, there is obvious water belt on the insulator surface, and the hydrophobicity is poor. After washing, the insulator surface has no obvious change in hydrophobicity and hydrophobicity. After cleaning with ethanol, although a small amount of surface pollution can be removed, some water belts are attached to the surface, and the hydrophobicity grade is HC3. After washing with water-based Wacker cleaning agent, the hydrophobicity of aging insulator is HC2-3, which is slightly improved compared with that before cleaning. After cleaning the polluted insulator with cleaning and repairing agent, it is found that the cleaning effect is the best. Through the preliminary test of its hydrophobicity, it is found that the hydrophobicity has been greatly improved. The results show that after the insulator is cleaned with the cleaning and repairing agent, the water band on the surface of the
insulator disappeared, most of the separated water droplets exist on the surface of the insulators, and the hydrophobicity grade is HC1-2, which makes the cleaning and repairing agent achieve good cleaning effect.

3.2.2. Hydrophobic loss characteristics

Firstly, the insulator shall be immersed in distilled water for 96 h. During the test, the sample shall be completely immersed in water, and the conductivity of distilled water shall be less than 10 $\mu$S cm$^{-1}$. After the sample is taken out, the water droplets on the surface of the sample are removed, and the residual water is absorbed with filter paper, and then the hydrophobicity loss test is carried out within 10 min. The hydrophobicity loss classification diagram is shown in figures 4(a)–(e), and the classification data results are shown in table S3.

The loss of hydrophobicity test shows that the hydrophobicity of insulators become worse after soaking in distilled water, and the hydrophobicity grade is HC5-6. The hydrophobic loss of insulators after washing is HC4-5, but the cleaning effect is still not obvious. The hydrophobic loss grade of the insulator after cleaning with ethanol is HC7, and its surface is completely wetted by water and has lost its hydrophobicity. The hydrophobic grade of insulator washed with water-based waker cleaning agent is HC6-7, and it still shows poor hydrophobicity. The hydrophobic loss of insulator after cleaning with cleaning and repairing agent reached

![Initial hydrophobic grading value of insulators without cleaning](image)

![Initial hydrophobic grading value of insulators after water cleaning](image)

![Initial hydrophobic grading value of insulators after ethanol cleaning](image)

![Initial hydrophobic grading value of insulators after cleaning with Wacker cleaning agent](image)

![Initial hydrophobic grading value of insulators after cleaning with cleaning and repairing agent](image)

Figure 3. Initial hydrophobicity of insulators with different cleaning methods.
HC2-3, which is better than any other cleaning methods. It further shows the high efficiency cleaning ability of cleaning agent. In addition, silicone rubber insulation can maintain good hydrophobicity and prolong its service life under a certain degree of external influence.

3.2.3. Hydrophobic recovery characteristics

The water droplets on the surface of insulator were wiped and dried, and placed for 24 h under laboratory conditions to test its hydrophobicity recovery. The hydrophobic recovery characteristic diagram of insulator is shown in figures 5(a)–(e), and hydrophobic classification data is shown in table S4.

The results show that the hydrophobicity recovery grade of un-cleaned insulator is HC3-4, that of water cleaned insulator is HC3-4, that of ethanol cleaned insulator is HC4-5, and that of Wacker cleaning agent is HC2-3. The hydrophobicity recovery grade of insulator is HC1-2, which meets the requirements of normal insulator hydrophobicity. The results show that the cleaning and repairing agent can clean and repair the aging insulator surface after a certain period of operation, and achieve good hydrophobicity recovery.

Figure 4. Hydrophobic loss characteristics of insulators with different cleaning methods.
3.2.4. Hydrophobic migration characteristics

According to the hydrophobic migration test in DL/T 627-2018 [22], the prepared sewage solution (salt density is 0.1 mg cm\(^{-2}\), ash density is 0.5 mg cm\(^{-2}\)) is used to contaminate the insulator. Then the contaminated samples were placed in the laboratory for 96 h, and the hydrophobicity classification test was carried out. The hydrophobic migration characteristics of insulators before and after cleaning are shown in figures 6(a)–(e), and the hydrophobic migration classification data are shown in table S5.

It is found that the hydrophobicity migration of aging insulator is poor, and its hydrophobicity grade is only HC6. After cleaning with the cleaning and repairing agent, its hydrophobic mobility reaches HC4, which is slightly improved.

To sum up, through the hydrophobicity test of aging insulator after 14 years of operation, it can be seen that after a long time of operation, the surface of insulator is aging and shows poor hydrophobicity, which can not achieve long-term hydrophobic effect. Cleaning and repairing agent was prepared to remove the polluted layer on the surface of aging insulator and improve its hydrophobicity. And through comparing different cleaning methods, it can be seen that after cleaning the aging insulator with cleaning and repairing agent, the initial hydrophobicity and hydrophobicity recovery of the aged insulator is improved from HC3-4 to HC1-2.

Figure 5. Hydrophobic recovery of insulators with different cleaning methods.
3.3. Surface morphology of insulators before and after cleaning

In order to analyze and compare the cleaning effect of different cleaning methods on the surface of aging silicone rubber insulator, the surface roughness, crack width, particle and hole distribution of different parts of aging silicone rubber insulator were observed by scanning electron microscope (SEM). Figures 7(a)–(e) shows the micro morphology of cracks on the aged silicone insulator, which are not cleaned, washed with water, washed with ethanol, washed with Wacker and cleaned with cleaning repair agent. Figures 8(a), (b) shows the micro morphology of the internal structure in the section before and after the aging insulator surface is cleaned with cleaning repair agent.

Figures 7(a)–(e) shows the micro morphology and particle distribution of surface cracks on silicone rubber insulators before cleaning. The results show that there are many protrusions and holes on the surface of the insulator, which will lead to the decrease of hydrophobicity [25, 26]. By comparing figures 7(a)–(e), under the irradiation of 2000× magnifying scanning electron microscope, it can be seen that the surface of aging insulator is still rough after being cleaned by water and ethanol. After being cleaned by Wacker cleaning agent, the insulator surface becomes more flat, which indicates that Wacker cleaning agent has a certain cleaning effect on the polluted insulator surface. After using the cleaning and repairing agent, the surface cracks of insulators are obviously repaired, the cracks become narrower, the surrounding cracks are smoother, the holes and particles are reduced, the surface roughness is reduced, and the surface is relatively flat. From the micro surface, the cleaning and repairing agent can effectively repair the surface cracks of insulators.

Figure 6. Hydrophobic transfer characteristics of insulators with different cleaning methods.
When the magnification is 200×, the micro morphology of the cross section before and after cleaning the aging insulator with the cleaning and repairing agent is shown in figures 8(a), (b). It is found that there are two layers on the cross section of aging insulator, the upper layer is aging layer, the lower layer is silicone rubber layer, and the dividing line is obvious, it can be seen that the aging degree is serious. Compared with figure 8(b), after cleaning with cleaning repair agent, three layers appear on insulator section, and the upper layer is cleaning repair layer. The repair layer can completely cover the aging layer, even penetrate into the cracks in the aging layer, which plays the role of repairing the surface cracks of the aging insulator. Overall, the distribution of its internal structure is more uniform, clear and complete. The composite layer contains silicone rubber molecules, which can be combined with the internal structure of the aging layer on the insulator surface, which is conducive to improving the mechanical properties of the material. The results show that the cleaning and repairing agent can effectively repair the surface cracks of insulators and prolong the service life of insulators.

3.4. Infrared spectrum analysis of insulators before and after cleaning

Figure 9 shows the infrared spectrum of aging insulator before and after cleaning, and table 1 shows the wave number and peak area of characteristic functional groups of aging insulator before and after cleaning. The degradation mechanism of aging silicone rubber insulator is that the main chain of silicone rubber is crosslinked, and hydrolysis and surface oxidation will occur under different external influences [27]. The infrared data show that, the absorption peak corresponding to wave number 734 cm⁻¹ represents Si–(CH₃)₃, the absorption peak corresponding to wave number 794 cm⁻¹ represents Si–(CH₂)₂, and the absorption peak corresponding to wave number 1013 cm⁻¹ represents Si–O–Si group.

By comparing the changes of peak areas of characteristic functional groups on insulator surface before and after cleaning, it can be found that the peak areas of hydrophobic methylene and methine groups on Si increase after cleaning with cleaning and repairing agent, which indicates that cleaning and repairing agent can improve the hydrophobicity of insulator surface to a certain extent.
The decrease of Si–O–Si bond peak area further indicates the substitution of methylene and methine groups, which makes more methylene groups adhere to the insulator surface, and the broken silica bond is better combined by methyl grafting, which plays a role in repairing the surface structural cracks of insulator.

3.5. Electronic energy spectrum analysis of insulators before and after cleaning

The chemical composition and mass fraction distribution of the surface and cross section of aging silicone rubber insulator before and after cleaning were tested by edx. The element composition distribution is shown in figures 10(a), (b), figures 11(a), (b), figure 12 and the mass fraction is shown in table 2. It can be seen from figures 10(a), (b) and 11(a), (b) that the main elements existing in the surface cracks of insulators before and after cleaning with cleaning and repairing agent are C, O, Si, Al, Fe (a small amount), among which Al and Fe are the important elements of inorganic fillers added in the processing of silicone rubber insulators. It can be seen from table 2 that after cleaning, the weight percentages of C, O and Fe on the insulator surface increase from 17.14%, 47.15% and 2.6% to 20.13%, 49.53% and 3.07% respectively, and the weight percentages of Si and Al decrease from 17.72% and 15.39% to 15.04% and 12.23% respectively. In general, through EDS test, it can be found that the content of Si and Al on insulator surface is reduced by cleaning and repairing agent. This is because the cleaning and repairing agent can change the surface structure of the aged insulator by removing the powdered layer, which greatly improves the hydrophobicity of the surface. The contents of C and O were also increased due to the migration of methylene.

Table 1. Wave number and peak area of characteristic functional groups on aging insulator surface before and after cleaning.

| Characteristic functional groups | Wave number (cm⁻¹) | No cleaning | After cleaning |
|---------------------------------|-------------------|-------------|---------------|
| Si–(CH₃)₃                  | 734               | 105.72      | 120.89        |
| Si–(CH₃)₂                  | 794               | 233.33      | 358.65        |
| Si–O–Si                       | 1013              | 2570.55     | 2313.34       |

3.6. Mechanical properties of insulators before and after cleaning

3.6.1. Tensile property

According to the conditions in GB/T 528–2009 [23], the silicone rubber insulator is made into standard spline with a tool. The insulator surface is cleaned with water, ethanol, Wacker cleaner and cleaning repair agent respectively, as shown in figure 13 and 14. The results show that the cleaning and repairing agent can effectively...
remove the dirt on the insulator surface. Then the universal testing machine is used to set the corresponding tensile parameters for tensile test, and the results are shown in figure 13 and table 3.

The test results show that the mechanical properties of silicone rubber insulator decrease after 14 years of operation, the tensile strength is 2.85 MPa, and the elongation at break is only 76.03%, which indicates that the aging degree is high and the pollution accumulation is serious. It can be seen from figure 13 and table 3 that, in terms of tensile strength, different cleaning methods have little effect on it; while in terms of elongation at break, the use of cleaning and repairing agent has the greatest effect on it, which is 7.74% higher than that of the uncleaned insulator. Compared with the effect of Wacker cleaning agent, the elongation at break decreased slightly.
3.6.2. Tear resistance

According to the conditions of GB/T 529-2008 [24], the silicone rubber insulator is made into standard tear resistant spline with cutter, and the insulator surface is cleaned with water, ethanol, Wacker cleaning agent and cleaning and repairing agent respectively, as shown in figure 15 and 16. The results show that the cleaning effect of the cleaning and repairing agent is obvious, and it can effectively remove the dirt on the insulator surface. Then, the universal testing machine is used to set the relevant tear resistance parameters for tear resistance test, and the results are shown in table 4.

It can be seen from figure 15 and table 4 that the silicone rubber insulator without cleaning still has good tear resistance after 14 years of operation, and its average tear strength is 8.47 MPa. The results show that the tear resistance

![Figure 12. Histogram of content change of main elements on insulator surface and section before and after cleaning.](image12)

![Figure 13. Change chart of tensile properties of insulators before and after cleaning.](image13)

![Figure 14. Weight percent (%)](image14)

### Table 2. Element mass fraction distribution of surface and cross section of aged insulator before and after cleaning.

| Element type | Before insulator surface cleaning | After insulator surface cleaning | Before cleaning insulator section | After cleaning insulator section |
|--------------|-----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| C            | 17.14                             | 20.13                            | 20.06                            | 20.14                            |
| O            | 47.15                             | 49.53                            | 42.49                            | 41.87                            |
| Si           | 17.72                             | 15.04                            | 21.23                            | 21.83                            |
| Al           | 15.39                             | 12.23                            | 13.19                            | 13.12                            |
| Fe           | 2.60                              | 3.07                             | 3.03                             | 3.04                             |
strength of the insulator after cleaning is 8.71 MPa, which is 2.83% higher than that before cleaning, while the tear strength of the insulator after cleaning is 8.64 MPa, which is 2.01% higher than that before cleaning. However, water and ethanol have little effect on the tear strength of insulators, even slightly reduced.

In conclusion, in terms of mechanical properties, the cleaning and repairing agent has a positive and favorable effect on the aging insulator, and can achieve good cleaning effect; while other cleaning methods have little effect on its mechanical properties.

3.7. Durability of insulators after cleaning with cleaning and repairing agent

3.7.1. Effect of cleaning and repairing agent on UV aging resistance

In order to better simulate the environment of day and night alternation in the actual use of insulators, a cycle time of the experiment is set as 4 h of UV exposure and 4 h of condensation. The UV radiation intensity is 500 W, the exposure temperature is 60 °C, and the condensation temperature is 50 °C. After about 500 h of UV irradiation, the samples were taken out to test their mechanical properties and contact angle.

3.7.1.1. Tensile property

After 14 years of operation, the insulator surface is cleaned with water and cleaning and repairing agent respectively, and then placed in the ultraviolet aging test chamber for 500 h test. The tensile data results are shown in the table 5.

The test results show that after 14 years of operation, the tensile strength of the silicone rubber insulator is slightly increased by 16.5% compared with that of the UN cleaned insulator after being cleaned by the cleaning and repairing agent and placed in the ultraviolet aging box for 500 h. The change rate of elongation at break was increased by 27.8%, which indicated that the cleaning and repairing agent had good UV aging resistance and extended its service life.

3.7.1.2. Contact angle

After 14 years of operation, the insulator surface was cleaned with cleaning and repairing agent, and then the aged insulators before and after cleaning were put into the ultraviolet aging test chamber for 500 h test. Take samples every 100 h to test the static contact angle. The data results are shown in the figure 17.

The contact angle test results show that the contact angle of the aged silicone rubber insulator decreases from 124.9° to 110.7° after 500 h of ultraviolet radiation after cleaning with the cleaning and repairing agent, and the decrease is relatively slow, and it can maintain good hydrophobicity. However, the contact angle of the UN cleaned insulator decreases from 107.1° to 81.9° and the decrease range is large, which indicates that the insulator is seriously aged and has poor hydrophobicity. It can be seen that the cleaning and repairing agent can protect the insulator surface to a certain extent and improve its UV aging resistance. Through the cleaning of aging insulator, its hydrophobicity is also improved, which plays a repairing role and effectively prolongs the service life of aging insulator.

3.7.2. Effect of cleaning and repairing agent on salt spray resistance

3.7.2.1. Tensile property

The samples before and after cleaning the aging insulator with cleaning and repairing agent were placed in the salt spray box, and the 500 h salt spray aging test was carried out on the surface of the samples. The results of stretching data are shown in the table 6.
Table 3. Tensile test data of insulators before and after cleaning.

| Number cleaning method | Thickness (mm) | Maximum force (N) | Maximum deformation (mm) | Average tensile strength (MPa) | Average elongation at break (%) |
|------------------------|----------------|-------------------|--------------------------|-------------------------------|-------------------------------|
| No.86                  | No cleaning    | 2.08              | 2.86                     | 2.85                          | 15.678                        | 78.39                         | 76.03                         |
| No.87                  | 1.91           | 31.06             | 2.71                     | 14.519                        | 72.59                         |
| No.88                  | 2.07           | 37.14             | 2.99                     | 15.422                        | 77.11                         |
| No.89                  | **After water cleaning** | 2.09      | 36.87                    | 2.94                          | 13.785                        | 69.25                         | 67.59                         |
| No.90                  | 1.98           | 34.10             | 2.87                     | 12.592                        | 62.92                         |
| No.91                  | 2.06           | 35.97             | 2.91                     | 14.122                        | 70.61                         |
| No.92                  | **After ethanol cleaning** | 1.96      | 33.87                    | 2.88                          | 14.759                        | 73.80                         | 70.22                         |
| No.93                  | 1.88           | 33.05             | 2.93                     | 14.244                        | 71.22                         |
| No.94                  | 1.93           | 32.54             | 2.81                     | 13.127                        | 65.64                         |
| No.95                  | **After cleaning with Wacker cleaning agent** | 2.02      | 35.75                    | 2.95                          | 14.879                        | 74.40                         | 75.97                         |
| No.96                  | 2.11           | 35.07             | 2.77                     | 15.025                        | 75.13                         |
| No.97                  | 1.99           | 33.67             | 2.82                     | 15.674                        | 78.37                         |
| No.98                  | **After cleaning with cleaning and repairing agent** | 2.11      | 36.97                    | 2.92                          | 14.306                        | 71.53                         | 81.92                         |
| No.99                  | 1.96           | 35.16             | 2.99                     | 18.412                        | 92.06                         |
| No.100                 | 1.94           | 32.71             | 2.81                     | 16.431                        | 82.16                         |
The test results show that the mechanical strength of the aged silicone rubber insulator is not decreased after being cleaned by the cleaning and repairing agent and then placed in the salt spray aging box for 500 h, and the tensile strength and elongation at break of the insulator after salt spray aging are increased by 4% and 21.52% respectively. The results show that the cleaning and repairing agent has good salt spray resistance to silicone rubber insulation surface.

Figure 15. Bar chart of insulator durability before and after cleaning.

Figure 16. Tear resistant sample of insulator before and after cleaning.

Table 4. Tear resistance test data of insulators before and after cleaning.

| Number | Cleaning method                  | Thickness (mm) | Maximum tearing force (N) | Tear strength (MPa) | Mean tear strength (MPa) | Rate of change (%) |
|--------|----------------------------------|----------------|---------------------------|---------------------|-------------------------|-------------------|
| No.101 | No cleaning                      | 2.1            | 17.77                     | 8.46                | 8.47                    | —                 |
| No.102 |                                  | 2.0            | 16.78                     | 8.39                |                         |                   |
| No.103 |                                  | 2.0            | 17.12                     | 8.56                |                         |                   |
| No.104 | After water cleaning             | 2.0            | 16.82                     | 8.41                | 8.39                    | 0.94              |
| No.105 |                                  | 2.0            | 16.78                     | 8.39                |                         |                   |
| No.106 |                                  | 2.1            | 17.58                     | 8.37                |                         |                   |
| No.107 | After ethanol cleaning           | 2.1            | 17.24                     | 8.21                | 8.24                    | 2.72              |
| No.108 |                                  | 2.2            | 18.00                     | 8.18                |                         |                   |
| No.109 |                                  | 2.1            | 17.47                     | 8.32                |                         |                   |
| No.110 | After cleaning with Wacker      | 2.2            | 19.14                     | 8.70                | 8.64                    | 2.01              |
|        | cleaning agent                   |                |                           |                     |                         |                   |
| No.111 |                                  | 2.1            | 18.23                     | 8.68                |                         |                   |
| No.112 |                                  | 2.2            | 18.81                     | 8.55                |                         |                   |
| No.113 | After cleaning with cleaning     | 2.0            | 17.44                     | 8.72                | 8.71                    | 2.83              |
|        | and repairing agent              |                |                           |                     |                         |                   |
| No.114 |                                  | 2.0            | 17.56                     | 8.78                |                         |                   |
| No.115 |                                  | 2.0            | 17.22                     | 8.61                |                         |                   |
Table 5. Change data of mechanical properties of insulators cleaned with cleaning and repairing agent.

| No.   | Cleaning method                  | Thickness (mm) | Maximum force (N) | Tensile strength (MPa) | Average value (MPa) | Maximum deformation (mm) | Elongation at break(%) | Average elongation at break(%) |
|-------|----------------------------------|----------------|-------------------|------------------------|---------------------|---------------------------|------------------------|---------------------------------|
| No.116| No cleaning                      | 2.14           | 30.174            | 2.35                   | 2.41                | 9.566                     | 47.83                  | 52.11                           |
| No.117|                                  | 2.16           | 31.234            | 2.41                   | 11.175              | 10.527                    | 55.875                 |                                 |
| No.118|                                  | 2.34           | 34.819            | 2.48                   | 10.275              | 12.797                    | 52.635                 |                                 |
| No.119| After cleaning with cleaning and | 2.25           | 37.665            | 2.79                   | 2.80                | 13.944                    | 69.72                  | 66.59                           |
|       | repairing agent                  |                |                   |                        |                     |                           |                        |                                 |
| No.120|                                  | 2.19           | 36.398            | 2.77                   |                    | 13.215                    |                        |                                 |
| No.121|                                  | 2.21           | 37.638            | 2.84                   |                    | 13.215                    |                        |                                 |
3.7.2.2. Contact angle

The surface of aging insulator is cleaned with cleaning and repairing agent, and then the insulator before and after cleaning is put into salt spray aging test chamber for 500 h aging test. Samples were taken every 100 h to test the change of static contact angle. The data results are shown in the figure 18.

The contact angle test results show that the contact angle of the cleaned aged silicone rubber insulator is reduced from 124.9° to 93.9° after 500 h salt spray aging, which still reaches the normal use level and shows good hydrophobicity. However, the contact angle of the UN cleaned insulator is reduced from 107.1° to 81.9° and the hydrophobicity is lost, resulting in serious aging. It can be seen that the cleaning and repairing agent has good salt spray resistance on the surface of aging insulator, and can effectively improve its hydrophobicity.

4. Discussion

In order to solve the serious scaling problem of aging silicone rubber insulator, a cleaning and repairing agent for silicone rubber insulator was developed. After cleaning the surface of silicone rubber insulator with water, ethanol, Wacker cleaning agent and cleaning and repairing agent for 14 years, the cleaning and repairing effect was characterized by hardness test, hydrophobicity test, mechanical property test, micro morphology test, electron spectroscopy test, Fourier transform infrared spectroscopy test and aging test.

To sum up, after 14 years of operation, the surface of silicone rubber insulator is polluted by various external factors. After using the cleaning and repairing agent, it can not only effectively remove the surface pollution of aging insulator, but also repair the surface microcracks. Compared with other cleaning methods, it reflects the effect of efficient cleaning and repairing. From the hardness point of view, cleaning agent has little effect on it. In terms of mechanical properties, Wacker cleaning agent and cleaning and repairing agent have a good effect on it, and the effect of cleaning and repairing agent is more obvious. Through the infrared test results of the surface of the insulator which is not cleaned and cleaned by the cleaning repair agent, it is found that the peak area of a large number of hydrophobic methylene (Si–(CH₃)₂), methylene (Si–(CH₃)₃) bond and other hydrophobic groups on the surface of the insulator after cleaning increases. It is analyzed that the cleaning and repairing agent can repair the insulator surface through the migration of methylene bond. Through the hydrophobicity test, it is found that the hydrophobicity of insulator is obviously improved after cleaning with cleaning and repairing agent, which confirms the conjecture of infrared test. By comparing the cross-section micrographs of the insulator surface cleaned by different cleaning methods and that of the aging insulator cleaned by cleaning and repairing agent, it is found that the other cleaning methods can only clean the contamination of the insulator surface, and the cleaning effect has no cleaning and repairing agent. On the other hand, the cleaning and repairing agent can not only clean but also repair the surface microcracks of aging insulators. The results show that the gap of the structure is smaller, the holes are reduced, the surface looks smoother and the roughness is relatively reduced, which achieves the expected effect and realizes the dual functions of cleaning and repairing the aging insulator. Finally, by comparing the UV aging resistance and salt spray resistance of the insulator after using the cleaning and repairing agent, it is found that the cleaning and repairing layer still has good mechanical properties and hydrophobicity under strong light and high salt spray environment, indicating its excellent aging resistance.
Table 6. Change data of mechanical properties of insulators cleaned with cleaning and repairing agent.

| Number | Cleaning method                        | Thickness (mm) | Maximum force (N) | Tensile strength (MPa) | Average tensile strength (MPa) | Maximum deformation (mm) | Elongation at break (%) | Average elongation at break (%) |
|--------|----------------------------------------|----------------|-------------------|-----------------------|-------------------------------|--------------------------|-------------------------|-----------------------------|
| No.122 | No cleaning                            | 2.13           | 28.76             | 2.25                  | 2.23                          | 12.274                   | 61.37                   | 62.64                       |
| No.123 |                                        | 2.07           | 28.32             | 2.28                  |                               | 11.995                   | 59.98                   |                             |
| No.124 |                                        | 2.46           | 31.88             | 2.16                  |                               | 13.312                   | 66.56                   |                             |
| No.125 | After cleaning with cleaning and repairing agent | 1.95           | 27.96             | 2.39                  | 2.34                          | 14.672                   | 73.36                   | 76.12                       |
| No.126 |                                        | 2.11           | 28.99             | 2.29                  |                               | 15.104                   | 75.52                   |                             |
| No.127 |                                        | 2.04           | 28.32             | 2.33                  |                               | 15.895                   | 79.48                   |                             |
development of cleaning and repairing agent provides a good scheme for studying the aging mechanism and repairing measures of insulators.

ORCID iDs

Xiwei Xie https://orcid.org/0000-0001-6965-6970

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Figure 18. Static contact angle variation of insulators before and after cleaning with different UV aging time.
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