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The Quantitative Evaluation of Aging State of Field Composite Insulators Based on Trap Characteristics and Volume Resistivity-Temperature Characteristics

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Abstract – In order to obtain a better understanding of the ageing process of the field composite insulators, it is necessary to explore a quantitative-valuation method for the aging state evaluation. And the linear relationship between volume resistivity and temperature is proposed. In this paper, the composite insulators with different lengths of operating lives from two manufacturers were tested. The relationship between trap characteristics and volume resistivity-temperature characteristics were analyzed based on Thermal Stimulated Current (TSC), volume resistivity-temperature test, Scanning Electron Microscope (SEM) and Fourier Transform Infrared Spectroscopy (FTIR). Furthermore, the application of trap characteristics in the quantitative evaluation of aging state of composite insulators was discussed. The results showed that there was a general negative correlation between the relative variation ratio of trap charges and the volume resistivity-temperature characteristics. Meanwhile, the physicochemical properties would change with the aging time, which would result in the increasing of electron traps. Combined with the TSC and volume resistivity test results, the trap characteristic thresholds which indicated the serious age of the composite insulators had been proposed.

Keywords: Composite insulators, Aging condition, Quantitative evaluation, TSC, Trap characteristics, Volume resistivity-temperature characteristics.

1. Introduction

Composite insulators are widely used in extra-high voltage engineering due to their excellent ability to prevent pollution flashover, but its aging resistance is poor, which attracts more research attention focussing on the long-term aging-resistance performance and life evaluation. At present, the aging condition for field composite insulators is mainly estimated through field real-time monitoring and off-line testing in the laboratory [1-4]. With the advantages of high reliability and feasibility, off-line tests in a laboratory have been the main approach taken in assessment of the aging state evaluation of composite insulators. Besides it is less susceptible to the complex electromagnetic environment. Various types of methods were used for the evaluation of the ageing state of composite insulators, such as flashover voltage, leakage current, hydrophobicity, hardness, tear strength, SEM, and FTIR, most of which directly indicated the surface properties of such composite insulators.

Actually, the aging process of composite insulators is affected by electric stress, mechanical stress, and environmental stress, which can change the surface properties and affect the intrinsic characteristics and spatial characteristics at the same time [5, 6]. In recent years, TSC is gradually applied to space charge characteristics research into aged polymer [7-10], and these researchers have demonstrated that aged composite insulators will engender more traps with higher energy levels. However, quantitative analysis of the ageing state of such components is rare [9]. Researchers have chased down quantitative relationships between trap character and static contact angle [10] through analysis of the changes in contact angle and TSC of silicone rubber in designated aging conditions (corona discharge). However, the relationship is not instructive for field insulators. Meanwhile, insulator surface properties, including flashover voltage, hydrophobicity, and so on, are susceptible to environmental factors and cyclic loading, while the correspondence regarding their intrinsic characteristics remains inconclusive.

Volume resistivity is important in insulating materials and is related to temperature to a certain extent [11, 12]. Composite insulator external insulation is usually a polymer based on silicone rubber, whose volume resistivity and temperature characteristics follow certain rules that can provide some references for TSC techniques when quantitatively evaluating the severe aging condition of composite insulators. Meanwhile, there is a close connection between TSC testing and volume resistivity, which are closely related to the spatial characteristics of the material.

Here, composite insulators with different operating ages from two manufactures were used; their trap characteristics

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were tested by TSC, and the volume resistivities of the test samples at different temperatures were measured using the three-electrode system. The trap characteristics and volume resistivity characteristics were thus analysed. To understand the ageing state of the composite insulators, Scanning Electron Microscope (SEM) and Fourier Transform infrared spectroscopy (FTIR) tests were undertaken.

2. Experimental Work

2.1. Sample preparation

Tests, such as TSC and FTIR, require samples of a certain thickness and homogeneity: thinner, more homogeneous samples were obtained from composite insulator sheds. Some jumbo size samples with uniform, flat, surfaces are difficult to section by regular means, because the shape of such sheds is complex and the composite insulator material is more tenacious and may suffer more severe chalking. Fig. 1 shows a set of special sliced instruments invented by our research team, from which can be directly obtained samples with a diameter of 20 mm and a thickness of 1.3 mm from the insulator shed.

Research has demonstrated that the operating environment of an insulator exerts certain influences on its aging properties [13, 14]. Here, the silicone rubber composite insulators from the same manufacturer operating in the similar environment were chosen as test objects. In addition, accounting for the influence of electrical field distribution on the insulator surface, whole samples were taken from the upper surface of the first shed on the high-voltage side: the upper surface was uniformly divided into four areas to obtain such samples, thus weakening the effect of surface distribution, as shown in Fig. 2 [15]. The data in this paper are the mean average of the four samples unless stated otherwise.

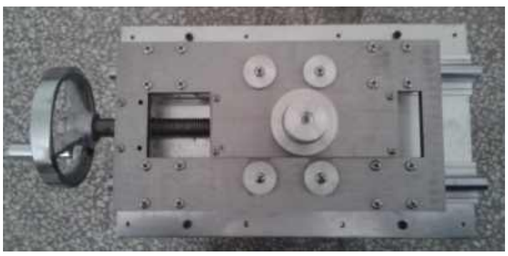


Fig. 1 Special slicing instrument for composite insulators

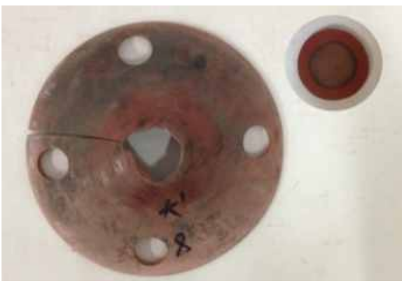


Fig. 2 Sampling regions

The samples were cleaned using absolute ethyl alcohol and deionised water to eliminate the influence of moisture and impurities on the surface of the samples. After that, the samples were placed in an oven at 30 °C for 24 h. Both surfaces of the samples were evaporation coated with gold film to a 50 nm thickness to guarantee fine contact between the samples and the electrodes. Table 1 shows the serial numbers from the different manufactures and the service life to date. The raw materials ratio of insulator and the production process were different in two manufacturers, so this paper focused on comparing the insulator characteristics of the same manufacturer.

2.2. TSC experiment

The TSC test theory is applied as shown in Fig. 3. The sample is heated to 316 K by a temperature controller which causes excitation of the carriers: a DC polarisation voltage of 10 kV is applied to the sample which is maintained at the constant test temperature for 20 min by closing switch S1. Then the sample is cooled immediately to a low temperature which makes the carriers appear to be “frozen” so that no current flows through the circuit. We then open switch S1 and remove the voltage, and, finally, the short circuit current of both sides of the sample is measured, with a linearly increasing temperature ramp rate of 2 K/min, by microammeter. Captured trap charges gain energy thus gradually becoming mobile particles as the temperature increases; meanwhile, the dipole depolarises in turn from small to large polymer chains, which generates current in the external circuit, so the TSC spectrum can be obtained. Some parameters, such as trapped charge Q, trap energy H, and so on are obtained through the TSC curves [16]. The TSC test was conducted at 4×10^{-3} Pa in

Table 1. Sample information

Manufacturer	A				B			
Sample	A1	A2	A3	A4	B1	B2	B3	B4
Service life (ys)	4	8	9	15	4	10	15	19

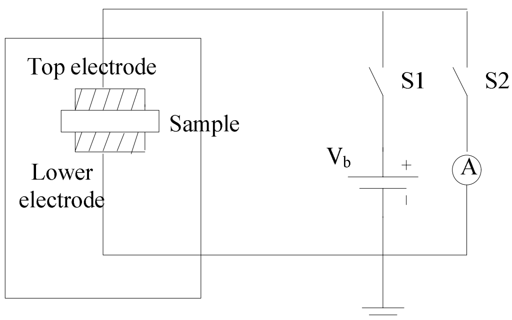


Fig. 3 TSC test principle

a vacuum to prevent surface flashover when applying a voltage. A Keithley 6517B electrometer was applied to measure the current.

2.3 Volume resistivity at different temperatures

The diameter of each sample is 20 mm, however, the recommended diameter in existing test standards is 80 mm: these prepared samples cannot be directly tested by the standard method. Therefore, a volume resistivity testing system for sub-size samples of field insulator material was invented based on three-electrode testing theory and its precision and stability were calibrated. Volume resistivities at different temperatures were measured, and some key data can be found in the literature [17, 18].

The test temperature range is 293K-343K. The temperature of the sample was increased 10 K for 10 min when the ambient temperature of the chamber was raised to the set temperature. Then, 1 kV was applied. The current after 10 min was used as the follow-up analysis data. The absorption current was attenuated to zero after 10 min of pressure. And then remove the voltage to continue to heat up to the next set value to repeat the process. The final use of the measured results according to the following formula to calculate the volume resistivity at each temperature:

$$\rho_v = R_v \frac{S}{h} \quad (1)$$

Where, $R_v = U/I$, $S = \pi d^2/4$, d is the diameter of measuring electrode, U is the DC voltage amplitude, I is the leakage current flow through the electrometer, h is thickness of the sample. Each specimen was tested three times to examine the reproducibility of the test.

2.4. SEM and FTIR tests

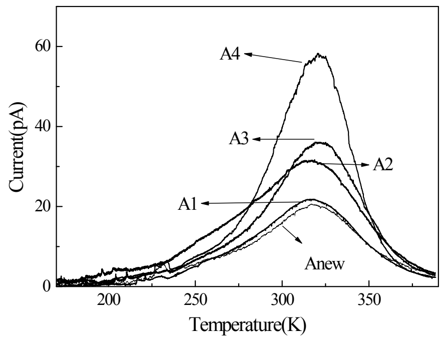
The Scanning Electron Microscope (SEM) test uses a KYKY-2800B digital scanning electron microscope with a resolution of 4.5 nm and a magnification of 15 to 25,000 times. The surface topography of samples was assessed by SEM. Silicone rubber samples may generate charge accumulation under the effect of an electron beam, which will affect the incident electron beam spot and trajectory of secondary electrons emitted by the samples thus causing a decrease in image quality. Therefore, the samples were coated with gold film acting as a conductive layer to minimise charging effects. The film thickness was approximately 20 nm.

Nicolet Is5 Fourier transform infrared spectrometer (FTIR) from Thermo Fisher, USA was selected in this experiment. Using iD3 all-reflective attachment of its total reflection prism by the ZnSe crystal composition, measuring the spectral range of 600~4000cm^{-1}, a resolution of 4cm^{-1}, set the number of times each test scan 32 times. FTIR was used to analyse the change of the molecular structure and functional groups on the surface and in the inner parts of typical silicone rubber insulators. A background spectrum was obtained before each measurement to compensate for the humidity effect and carbon dioxide in the air by spectra subtraction.

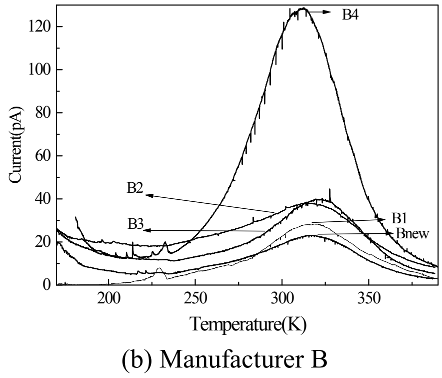
3. Experimental Results and Discussion

3.1. TSC results

TSC curves of samples from two manufacturers are shown in Fig. 4. New samples from two manufacturers were tested for comparison. The new samples were taken from the middle part of the insulator shed, which was less susceptible to environmental factors [15]. Fig. 4 shows that: (1) The TSC curves of two new samples from two manufacturers showed a main peak around 318K, indicating that the insulator substrates (silicone rubber) of different manufacturers were almost the same. The TSC curve shapes of A, B two manufacturers have certain difference, but TSC curve shapes of the same manufacturer sample are similar. There may be some differences in formulations and production process, such as different accessory ratios, different temperatures and different pressures [19]. (2) Generally, TSC peaks of composite insulators presented a tendency to increase with increasing service time especially for samples serving for more than 10 years. Relatively speaking, changes in B4 were the most



(a) Manufacturer A



(b) Manufacturer B

Fig. 4 TSC spectrogram of samples A and B distinct and its current peak reached 128 pA.

The quantity of trap charges on each sample was calculated based on the TSC curve. The trap level of the silicone rubber sample is calculated using the half-width method.

$$H = \frac{2.47 T_m^2 k}{\Delta T} \quad (2)$$

Where, H is the trap level. T is the thermodynamic temperature, K. T_m is the temperature of peak current, K. ΔT is the temperature difference of TSC curve half-peak, K. k is the boltzman constant.

$$Q_T = \int_{t0}^{t1} I(t)\,dt = \frac{1}{\beta}\int_{T0}^{T1} I(T)\,dT \quad (3)$$

Where, Q_T is the released charge, nC. I is the thermal stimulated current value, pA. ($t0$, $t1$) is the start time and end time of the thermal stimulated current curve, s. ($T0$, $T1$) is the minimum temperature and maximum temperature of the thermal stimulated current curve, K. β is the heating rate, ℃/s. The results are shown in Table 2. It shows that the trap charge quantities of test samples from manufacturers A and B were different, illustrating that the micro-structures differed. Meanwhile, the relative change ratio increases with duration of service life and the changes in B4 is the largest, demonstrating that trap charges will change only if the structure of the insulator is significantly changed.

Table 2 Trap parameters for samples of different ages from manufacturers A and B

Sample	TSC peak (pA)	Temperature peak (K)	Trap charges (nC)	Ratio
Anew	18.02	320	50.07	1.00
A1	21.86	319	52.50	1.05
A2	31.70	319	86.34	1.72
A3	36.12	322	81.79	1.63
A4	58.32	322	110.18	2.20
Bnew	23.05	319	55.25	1.00
B1	28.33	319	55.23	1.00
B2	38.08	320	129.92	2.35
B3	44.66	325	94.52	1.72
B4	128.36	320	245.39	4.41

Table 3 Volume resistivity results with different temperatures

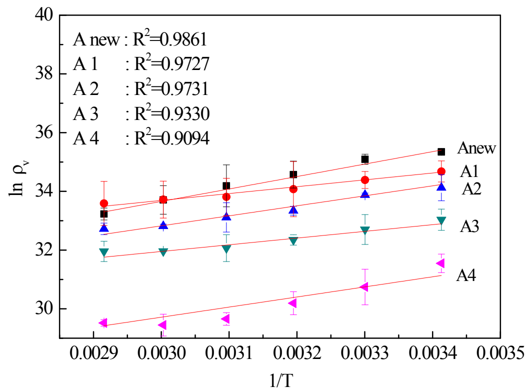
Volume resistivity ($10^{15}\Omega\cdot$cm)	293	303	313	323	333	343
A new	2.24	1.74	1.03	0.71	0.44	0.27
A1	1.15	0.85	0.63	0.48	0.44	0.39
A2	0.66	0.52	0.3	0.24	0.18	0.16
A3	0.22	0.16	0.11	0.084	0.076	0.076
A4	0.05	0.022	0.013	0.0076	0.0061	0.0066
B new	2.94	2.54	1.92	1.49	1.28	1.26
B1	1.51	1.55	1.3	1.05	0.91	0.74
B2	0.39	0.31	0.49	0.28	0.34	0.37
B3	0.24	0.18	0.17	0.21	0.58	0.61
B4	0.051	0.058	0.058	0.058	0.07	0.1

3.2. Volume resistivity testing

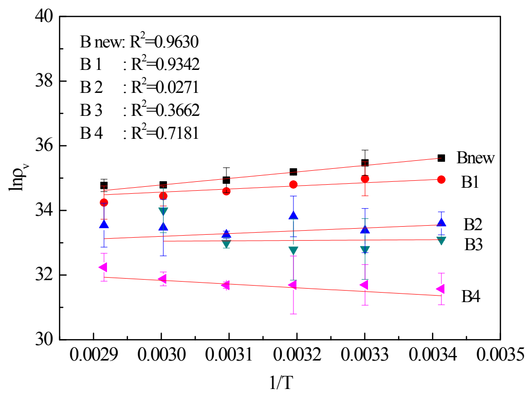
Volume resistivity results (in triplicate) for all samples from the two manufacturers are shown in Table 3. The standard deviation of the measured current values at all temperature points is almost 10-12. Generally, the relationship between volume resistivity of a polymer material and temperature follows:

$$\rho_v = A e^{E/RT} \quad (4)$$

Where, T is the thermodynamic temperature, K. A is a constant, and E is the conductance activation energy, eV. Clearly, lnρ_v-1/T is linear and the tested data were well fitted as shown in Fig. 5. The average of the tested results was linearly fitted and linear correlation coefficient R^2 was calculated. It can be seen that ln ρ_v of sample A linearly decreased with temperature. The linear correlation of A4 (after serving for 15 years) was lower than other samples from manufacturer A. As for B, the relationship in lnρ_v-1/T of B1 (after serving for five years) was linear and the other three samples did not show any trend.

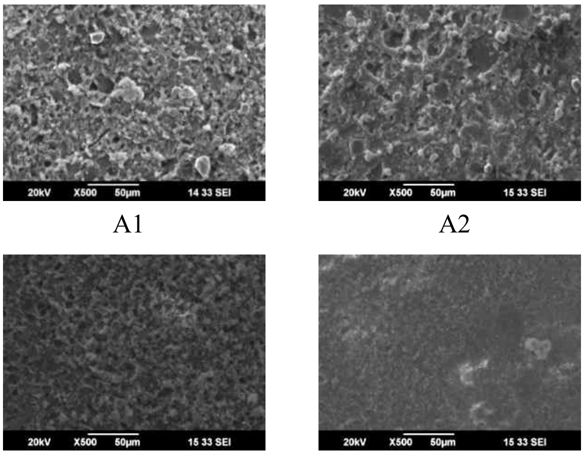


(a) Manufacturer A

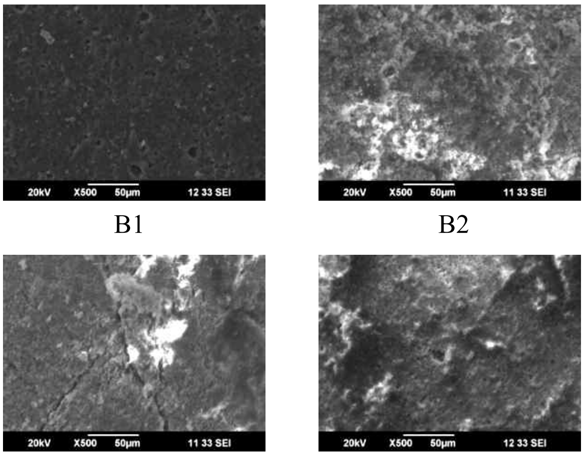


(b) Manufacturre B

Fig. 5 $\ln\rho_v - 1/T$ for samples of different ages from manufacturers A and B



(a) Manufacturer A



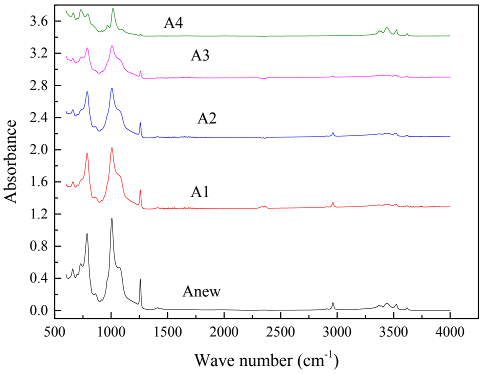
(b) Manufacturer B

Fig. 6 SEM test results

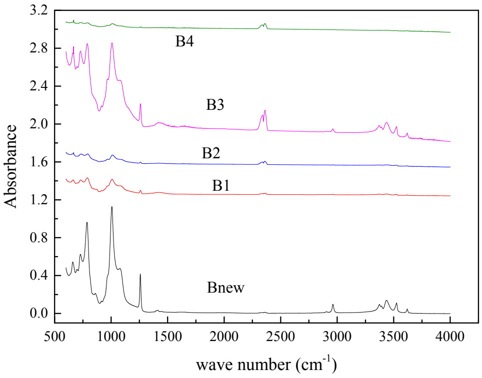
3.3 SEM and FTIR testing

SEM inspection was undertaken to observe the changes in the surface topography of the insulators during operation. The surfaces of the insulators were cleaned before inspection to eliminate the effects of pollution. Typical SEM results (magnified 500 ×) are shown in Fig. 6: in contrast to all other micrographs, it can be seen that the surface of insulator A was full of void defects, where flocculent pits could be more compact in form with increased service life. In comparison with samples from manufacturer A, sample B1 showed no distinct differences, and it appeared to be heavily pitted. However, defects in the other three samples were mainly cracks and fractures, with some reaching the size of blockbusters cracks.

Meanwhile, FTIR was conducted to observe the surface chemical structure. Fig. 7 shows the results of FTIR analysis of samples from manufacturer A and B. It can be seen that, the absorption peak of sample B insulators operating for 10 years decreased at around a wave number of 1000 cm^{-1}, demonstrating that the main chain had been destroyed, thus resulting in a decrease in its Si-O-Si content. There was a new absorption peak at a wave number of 3233 cm^{-1} which represented the presence of an -OH group. According to the FTIR spectrum, the main chain structure Si-O-Si and the side chain structure $Si\text{-}CH_3$ of samples from manufacturers A and B were quantified by their absorption peak areas, as shown in Fig. 8. Evidently, the Si-O-Si and $Si\text{-}CH_3$ contents decreased to different extents depending upon manufacturer. Relatively speaking, the change in $Si\text{-}CH_3$ content was more significant, and the



(a) Manufacturer A



(b) Manufacturer B

Fig. 7. FTIR: samples from manufacturer A and B

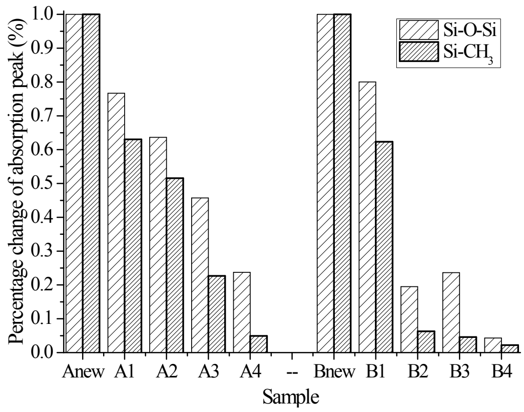


Fig. 8 Comparison of FTIR absorption peak areas

extent of the reduction in samples A4, B2, B3, and B4 was larger than that in the other samples.

3.4. Analysis of results

As shown in Fig. 4 and Table 2, the amount of trap charges increased with service life, especially for the insulators aged more than 10 years. According to the SEM results shown in Fig. 6, the surfaces of samples presented a series of new interface states. The surface of insulator A was full of void defects, where flocculent pits could be seen to be more compact with increasing years. The surface of sample B had defects such as cracks, fractures, and so on. FTIR test results showed that the main chain structure of this insulator was gradually interrupted and many removable short chain structures appeared. In addition, some chemical reactions occurred and generated silanol groups containing -OH. The inner structure of the composite insulator changed with prolonged electrical and environmental stresses, thus emerging with more physical defects and chemical traps. These defects are bound to capture more charges when applying a voltage during TSC, resulting in the current peak being increased in amplitude in the TSC curves.

On the other hand, the $\ln\rho_v$-$1/T$ relationship for silicone rubber is linear. The $\ln\rho_v$-$1/T$ curves of samples from manufacturer A, after operating for a certain number of years, presented a linear change, illustrating that sample A retained the intrinsic quality of the original polymer after many years' service. While the fitted linear curve for sample A4 (aged 15 years) was lower. Samples from manufacturer B which had been in operation for 10 years did not show any regularities in their $\ln\rho_v$-$1/T$ curves, which showed that most of the high molecular weight polymer structure had been destroyed. As SEM and FTIR results showed, structural defects in sample A4 were different from those in other samples from manufacturer A. As for samples from manufacturer B, the surface gradually showed long, deep cracks in sample B2, whose Si-CH_3 structure presented more changes with years. Micro-topographical and chemical structure changes in B2 were larger than those in B3, which explained why the trap charge relative ratio of sample B2 was larger than that of B3 and why its linear correlation coefficient was lower.

3.5. Discussion

The material properties will be significantly affected by the micro-structures and the chemical structures of polymer. As a kind of intrinsic defects, free volume is formed from the irregular holes among the chain segments in the polymer material. It provides essential space for the movement of chain segments, and it is closely related to the mechanical and electrical properties [20, 21].

From the SEM results, the main defects of the silicone rubber surface are void defects, cracks and even large gully cracks after being operated on site for different years. The sample is exposed to the air. And there is a selective adsorption of gas components in the air, which can also result in surface-specific localized trap levels. During the corona discharge process, a large amount of black or white material is precipitated on the surface of the silicone rubber sample to make the sample surface rough, and carriers are easily trapped on the surface of the precipitate to generate charges on the surface. After operating for many years bearing light, temperature and other natural factors and the inevitable impact of corona aging, the surfaces of the silicone rubber material have more serious defects, and the internal chemical bonds will also be broken, causing some changes in the overall lattice structure. In the macroscopic view, the development trend of the $\ln\rho_v - 1/T$ characteristic changes.

The base material of the composite insulator is HTV silicone rubber. Affected by ultraviolet rays, pollution, moisture or discharges, the structure of silicone rubber may be destroyed, resulting in the increase of free volume. The Si-O-Si bond is a polar bond which will be easily attacked by other polar chemical substances or high-energy particle, which will cause the fractures of the bonds. More short chains and chemical traps may appear, which provides space for chain segment movement [22-25]. In addition, some chemical bonds may also become fractured, forming free radicals. The introduction of new structures and new groups is the main reason for the increase of traps in the aged silicone rubber material. When the free volume is approximately equal to the volume of some structural units, as the temperature increases, these units have the ability to move freely and the ion mobility also increases, thus reducing the volume resistivity [16]. Within a certain temperature range, removable particles are more active with the increase of free volume, thus altering the $\ln\rho_v$-$1/T$ relationship.

Therefore, the trap characteristics and volume resistivity-temperature characteristics of silicone rubber can reflect changes of the material's physical or chemical structure. Based on this, the aging state of field composite insulators can be evaluated by a trap charges test combined with conductivity test. The $\ln\rho_v$-$1/T$ plot for A4, aged 15 years, has a poor linear correlation, which indicated that A4 was seriously aged. So, its trap charge relative variation ratio(2.20) can be defined as the threshold of severe aging. As for sample B2, aged 10 years, its linear correlation decreases to a significant extent and the threshold is 2.35 in this case. The result is unanimous with the changes of micro-structure. It is clear that the trap charges have great influence on the aging state evaluation.

4. Conclusion

(1) Trap characteristics of composite insulators may change during operation. As for the samples from two

different manufacturers, the relative variation ratio of trap charges has a negative relationship with the lnρ_v-1/T characteristics.

(2) The trap charge is an important factor on aging state evaluation.

(3) The trap characteristics of composite insulators are related to the chages of micro-structures. The changing of material structure and generating of new chemical groups, caused by insulation aging, are the main reasons for the incensement of trap charges.

(4) Based on the trap characteristics and the volume resistivity-temperature characteristics, the aging state of composite insulators can be evaluated. The trap charge variation ratio of A4 was 2.20 which was set as the threshold for samples from manufacturer A. Similarly, the threshold for samples from manufacturer B was 2.35.

It should be noted that establishing thresholds for different manufacturers should be discriminatory, considering the differences between the insulators. In addition, how to define the threshold of traps among different insulators during the aging process warrants further research.

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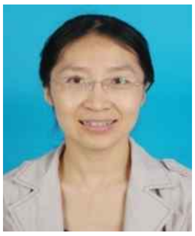

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