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Analysis on the Influence of Different Filth Grades on the Hydrophopathy of Composite Insulators

Ming Hao[1,a,*], Xuchen Zhang[2,b], Hong Wu[1,c], Yanheng Wu[1,d], Bo Wu[1,e]

[1]High Voltage Technology Research Institute, Power Research Institute of State Grid Ningxia Electric Power Co., Ltd, Yinchuan, Ningxia Hui Autonomous Region, China
[2]Transformer Substation Construction Branch, State Grid Ningxia Power Transmission and Transformation Engineering Co., Ltd, Yinchuan, Ningxia Hui Autonomous Region, China
[a]839735629@qq.com, [b]2205781582@qq.com, [c]623265551@qq.com, [d]wuyanheng@163.com, [e]wubo8484@163.com
[*]Corresponding author

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Abstract: Composite insulator is an important insulation equipment of overhead transmission lines. Different pollution levels will cause different degrees of influence on the hydrophopathy of composite insulator. The decrease of hydrophobicity level and the increase of pollution level will reduce the pollution flashover voltage of composite insulator and affect the reliable operation of composite insulator. In order to accurately study the influence of different pollution grades on the hydrophobicity of composite insulators, the hydrophobicity test, equivalent salt density test and non souble deposit density test were conducted on the composite insulators of voltage grade of 5-18 years, 35kV and above in Ningxia power grid. The results show that under the same operating years, composite insulators with higher pollution levels have lower hydrophobicity and are more prone to flashover. The evaluation results can provide important reference value for the subsequent operation and maintenance of composite insulators.

1. Introduction

Early transmission lines employed porcelain and glass insulators. Due to pollution, salt deposits, and other factors, continuous deposition occurs on the surfaces of these insulators. Under conditions of high atmospheric humidity—especially during fog, dew, drizzle, and other adverse weather—the leakage current along the insulator surface and the surface conductivity increase rapidly. This leads to a reduction in the insulator's flashover voltage, resulting in flashover events and causing self-destruction of glass insulators, which poses significant threats to the safe operation of power systems [1-3].

Extensive research has demonstrated that, compared to porcelain and glass insulators, composite insulators possess excellent hydrophobicity and hydrophobicity transfer properties. They also feature light weight, high mechanical strength, superior anti-pollution flashover performance, and ease of maintenance [4-5].

To effectively assess the significance of hydrophobicity, researchers worldwide have investigated the effects of various factors on the hydrophobicity of composite insulators [6-8]. By using composite insulator sheds as test samples and setting kaolin and diatomaceous earth as pollution materials for salt density and dust density, they analyzed the impact on hydrophobicity after the formation of pollution layers on the insulator surface. Under conditions of corona discharge, structural damage to composite insulators affects hydrophobicity. Moreover, many scholars have studied the influence on the hydrophobicity of composite insulators by simulating natural operating environments, such as temperature, humidity, and corona discharge simulations. However, differences still exist compared to actual operating environments, lacking field test support [9-11].

In recent years, the rapid socio-economic development in Ningxia, along with the construction of numerous chemical plants and other highly polluting industrial facilities, has accelerated environmental degradation, leading to increasing pollution of transmission line equipment. To accurately assess the impact of different pollution levels on the hydrophobicity of composite insulators, tests and analyses were conducted on composite insulators operating for 5 to 18 years at voltage levels of 35 kV and above in the Ningxia power grid, providing important reference value for the subsequent operation and maintenance of composite insulators.

2. Pollution Level Determination Basis and Hydrophobicity Test Methods

2.1. Sample Information

A total of 205 composite insulators were tested in this study, all of which were in-service units collected from different regions and lines. Among them, there were 43 units at 35 kV, 68 units at 110 kV, 54 units at 220 kV, 8 units at 330 kV, 6 units at ±660 kV, and 26 units at 750 kV. Samples at 35 kV to 220 kV accounted for 80.48% of the total, with operating years concentrated between 8 to 13 years, closely reflecting the structure of the Ningxia power grid. This sampling proportion effectively represents the operating conditions of composite insulators in the region.

2.2. Basis for Determining Pollution Levels

Pollution environments in power systems are generally divided into four types: desert, coastal, industrial, and agricultural. The on-site pollution level of naturally polluted insulators is usually expressed by equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD). ESDD is the equivalent salt amount per unit area of the insulator surface, while NSDD is the total amount of non-soluble residues cleaned from the unit area of the insulator surface divided by the surface area. For standardization, the on-site pollution level is divided into five grades from very light to very heavy: Grade a (very light), Grade b (light), Grade c (medium), Grade d (heavy), and Grade e (very heavy).

2.2.1. Calculation of ESDD

ESDD is determined by measuring the conductivity and temperature of the water containing the pollutants. The correction of conductivity is as follows:

$$\sigma_{20} = \sigma_{\theta}\left[1 - b(\theta - 20)\right] \tag{1}$$

where: θ is the solution temperature (℃); σ_{θ} is the volume conductivity at temperature θ℃(S/m); σ_{20} is the volume conductivity at 20 ℃ (S/m); b is a temperature-dependent factor.

The calculation of equivalent salt deposit density is:

$$ESDD = S_a \bullet V / A \quad (2)$$

where: S_a is the salinity (kg/m^3); V is the volume of distilled water (cm^3); A is the area of the insulator surface from which the pollution was collected (cm^2).

2.2.2. Calculation of NSDD

For NSDD, the polluted water containing the equivalent salt deposit is filtered through filter paper and then dried. The dried filter paper containing the pollutants (residue) is weighed. The calculation is:

$$NSDD = 1000(W_t - W_i) / A \quad (3)$$

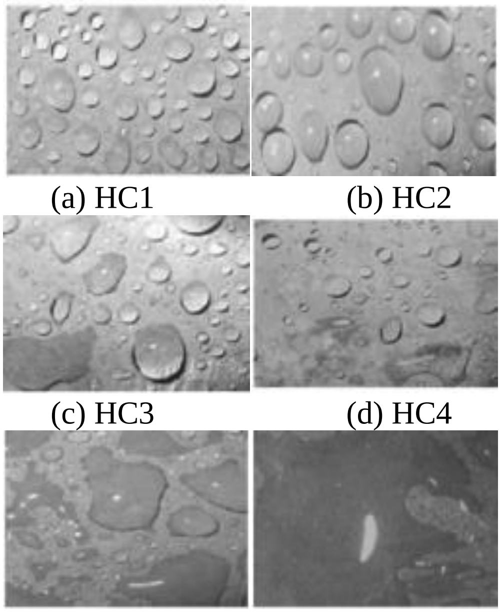
where: W_t is the weight of the filter paper containing pollutants under dry conditions (g); W_i is the initial weight of the filter paper under dry conditions (g); A is the area of the insulator surface from which the pollution was collected (cm^2).

2.3. Hydrophobicity Test Methods

In this experiment, the spray classification method is adopted, with the measurement method and requirements for the spraying device as follows:

The spray nozzle should be 25 cm away from the test sample, spraying once per second, totaling 25 times. After spraying, water should flow down the surface. The spraying direction should be as perpendicular to the sample surface as possible. The hydrophobicity classification (HC) value should be read within 30 seconds after spraying. The sample should be placed at an angle of about 20°–30° with the horizontal plane.

This method classifies the hydrophobic state of the material surface into six levels, denoted as HC1–HC6. HC1 corresponds to a highly hydrophobic surface, and HC6 corresponds to a completely hydrophilic surface. Typical states are shown in Figure 1.



(a) HC1 (b) HC2

(c) HC3 (d) HC4

(e) HC5 (f) HC6

Figure 1: Typical States of Spray Classification Method

3. Analysis of Experimental Results

3.1. Distribution of Sample Pollution Levels

In this experiment, 205 composite insulators were tested for ESDD and NSDD. Through calculation and analysis, 21 composite insulators were at pollution level **b**, 47 at level **c**, 28 at level **d**, and 106 at level **e**. According to pollution source investigations, the pollution sources in the Ningxia power grid are mostly from transportation, industrial activities, agriculture, domestic activities, the service industry, and combinations of two or more types. Verification showed that areas with severe industrial pollution are mostly classified as pollution level **e**. The pollution crystals formed by trace elements in the air such as Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-} cause significant corrosion to composite insulators.

For this test, 20 typical data sets were selected from the 205 composite insulators for display, and the results are shown in Table 1.

Table 1: On-site Pollution Level Determination Results of Operating Composite Insulators

Batch No.	Voltage Level (kV)	ESDD (mg/cm²)	NSDD (mg/cm²)	Pollution Level	Operating Years (years)
1	220	0.0439	0.2548	b	13
5	110	0.1126	0.2071	c	11
13	110	0.3277	0.4693	d	14
14	110	0.0899	0.2749	c	14
18	110	0.1093	0.2984	c	11
24	110	0.1486	0.2639	c	14
32	110	0.0366	0.1954	B	12
41	330	0.6127	0.7433	e	11
44	330	0.0747	0.2890	c	11
45	35	0.5337	0.7124	e	11
48	110	0.6180	0.8355	e	14
53	110	0.2946	0.3483	d	13
96	110	0.0585	0.1947	b	13
112	220	0.0548	0.2038	b	12
146	330	0.6430	0.8744	e	14
147	220	0.4628	0.5044	d	11
160	330	0.0379	0.1285	b	6
200	750	0.3427	0.4929	d	8
203	220	0.7475	0.6294	e	15
204	220	0.8530	1.0226	e	15

3.2. Hydrophobicity Test

Hydrophobicity tests were conducted on 205 composite insulators. According to regulations, when the hydrophobicity level of insulator samples is within the range of HC1–HC5, they can continue to operate. The hydrophobicity measurement results showed:

HC6 (Unqualified): 3 samples, which should be immediately withdrawn from service.

HC5 (Annual Inspection Required): 16 samples; HC3–HC4 (Inspection Every 3 Years): 114 samples; HC1–HC2 (Inspection Every 6 Years): 19 samples.

In this test, the hydrophobicity of the samples was relatively good. The specific distribution is shown in Figure 2.

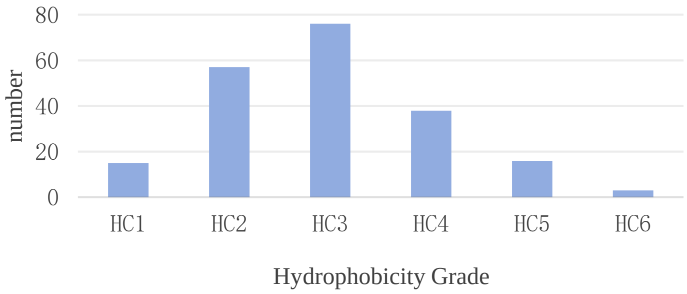


Figure 2: Distribution of Hydrophobicity

Combined with Table 1, the specific results of hydrophobicity inspection of 20 typical samples are shown in Table 2, and test images are presented in Figure 3.

Table 2: Hydrophobicity Results of Operating Composite Insulators

Batch No.	**Voltage Level (kV)**	**Pollution Level**	**Hydrophobicity Grade (HC)**
1	220	b	HC1
5	110	c	HC3
13	110	d	HC4
14	110	c	HC4
18	110	c	HC3
24	110	c	HC4
32	110	b	HC3
41	330	e	HC5
44	330	c	HC3
45	35	e	HC5
48	110	e	HC5
53	110	d	HC4
96	110	b	HC2
112	220	b	HC2
146	330	e	HC5
147	220	d	HC4
160	330	b	HC1
200	750	d	HC4
203	220	e	HC6
204	220	e	HC6

(a) No.1 (HC1) (b) No.112(HC2) (c) No.32(HC3)

(d) No.53(HC4) (e) No.48(CH5) (f) No.204(HC6)

Figure 3: Hydrophobicity of Selected Samples

Based on the comprehensive hydrophobicity experimental results, composite insulators with a pollution level of grade e and an operational lifespan of 11 years or more generally exhibited hydrophilic surfaces on their sheds, with water droplets fully adhering to the shed surfaces and appearing in sheet-like formations, corresponding to hydrophobicity levels HC5 and HC6. For composite insulators operating between 5 to 10 years with a pollution level of grade e, hydrophobicity was concentrated at HC4, allowing continued operation. Composite insulators with pollution levels of grade c and d maintained relatively good hydrophobicity, where large water droplets appeared as separate particles and were individually dispersed, while small water droplets appeared as sheets, corresponding to hydrophobicity levels HC4 and HC3, reflecting hydrophobic and intermediate transitional states. In this inspection, no samples were found at pollution level a. Under pollution level b, the surfaces of composite insulator sheds uniformly exhibited hydrophobicity, with water droplets appearing as small, separated particles, corresponding to hydrophobicity levels HC1 and HC2.

3.3. Fourier Transform Infrared Spectroscopy Analysis

Using Fourier Transform Infrared (FTIR) spectroscopy analysis, the types and contents of functional groups can be determined. Composite insulators generally use silicone rubber materials. The C–H and Si–CH_3 groups in silicone rubber are non-polar and are tightly arranged on the outside of the main chain, which is the main reason for the hydrophobicity of silicone rubber. Under the action of external water and air, silicone rubber gradually oxidizes and introduces hydrophilic –OH groups; therefore, the content of –OH can also reflect the hydrophobicity of silicone rubber. The main hydrophobic functional groups and their characteristic absorption peak wavenumber ranges are shown in Table 3.

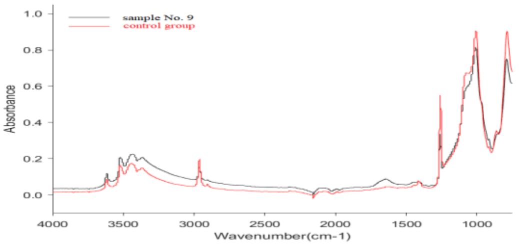
Table 3: Main Hydrophobic Functional Groups and Their Characteristic Absorption Peak Wavenumber Ranges

Functional Group	***Wavenumber Range (cm^{-1})***	***Absorption Peak Characteristics***	***Representation***
-OH	*3700~3200*	*Condensed –OH stretching vibration*	*Hydrophobicity strength*
C-H	*2960*	*Stretching vibration absorption*	*Hydrophobicity strength*
Si-CH3	*1280~1240*	*Symmetric deformation vibration*	*Hydrophobicity strength*
Si-$(CH_3)_2$	*840~790*	*Vibration absorption*	*Side-chain integrity*

To analyze the hydrophobicity of composite insulator sheds, composite insulators of hydrophobicity levels HC5, HC3, and HC2 were selected for comparison. Additionally, both the outer and inner layers of the insulator sheds were sampled, considering the inner layer as an unpolluted control for comparison.

(1) FTIR Analysis of HC5 Samples

Sample No. 9 has an operating voltage level of 110 kV and has been in operation for 10 years. Its hydrophobicity level is HC5, and the pollution level is e. The infrared spectra of Sample No. 9 and the control group are shown in Figure 4. The infrared spectra corresponding to the wavenumber range of Si–CH_3 are shown in Figure 5.



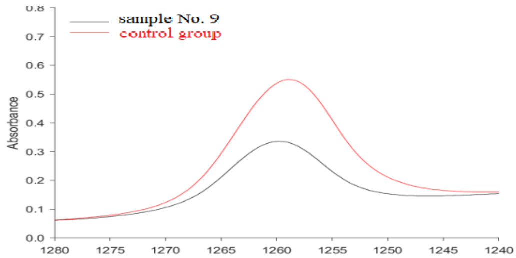


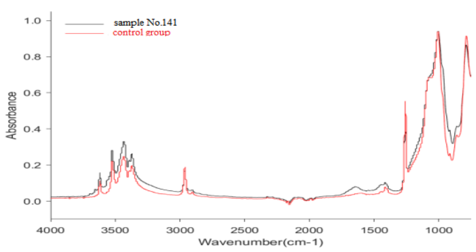
Figure 4: Infrared Spectra of Sample No. 9 and Control Group (Left)

Figure 5: Infrared Spectra of Sample No. 9 and Control Group in the Si–CH_3 Wavenumber Range (Right)

As illustrated in Figure 4, the absorption peak heights of side-chain-related groups in Sample No. 9 were significantly lower than those of the control sample. To facilitate the observation of the functional group absorption peaks in the sheds of each sample, the infrared spectrum corresponding to the wavenumber range of Si–CH_3 was enlarged, as shown in Figure 5. Specifically, the absorption peak value for Si–CH_3 in the control group was 0.54, whereas the sample's absorption peak value was 0.33, indicating a decrease of 38.89%. For Si–$(CH_3)_2$, the control group had an absorption peak value of 0.88, while the sample exhibited a value of 0.72, reflecting a decrease of 18.18%. This demonstrates that shed contamination causes the breakage of Si–CH_3 and Si–$(CH_3)_2$ groups, thereby affecting the hydrophobicity of the sample. Additionally, the hydroxyl content in the silicone rubber samples was higher than that in the control group, potentially due to the addition of a substantial amount of inorganic filler $Al(OH)_3$ in the silicone rubber. Trace elements in the atmosphere induce corrosion of composite insulators, leading hydroxyl groups to undergo complex processes such as dehydration and cross-linking, thereby increasing their content.

(2) FTIR Analysis of HC3 Samples

Sample No. 141 has an operating voltage level of 110 kV and has been in operation for 10 years. Its hydrophobicity level is HC3, and the pollution level is c. The infrared spectra of Sample No. 141 and the control group are shown in Figure 6, with the Si–CH_3 wavenumber range enlarged in Figure 7.



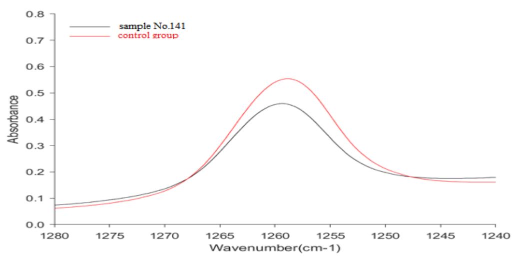


Figure 6: Infrared Spectra of Sample No. 141 and Control Group (Left)

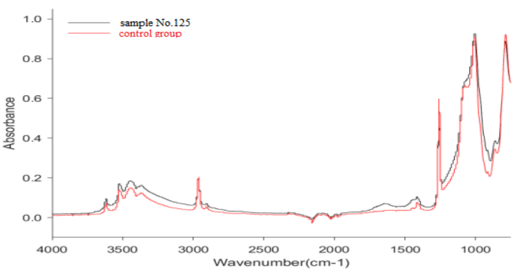
Figure 7: Infrared Spectra of Sample No. 141 and Control Group in the Si–CH_3 Wavenumber Range (Right)

As illustrated in Figure 6, the absorption peak heights of side-chain-related groups in Sample No. 141 are lower than those of the control sample. The infrared spectrum corresponding to the wavenumber range of Si–CH_3 is enlarged in Figure 7. Specifically, the absorption peak value for

$Si–CH_3$ in the control group is 0.55, whereas the sample exhibits an absorption peak value of 0.42, indicating a decrease of 23.63%. For $Si–(CH_3)_2$, the control group has an absorption peak value of 0.90, while the sample shows a value of 0.84, reflecting a decrease of 6.67%. This suggests that under a c-grade pollution level, the $Si–CH_3$ and $Si–(CH_3)_2$ groups remain relatively intact, and the hydrophobicity of the sample is correspondingly maintained at a relatively good level.

(3) FTIR Analysis of HC2 Samples

Sample No. 125 has an operating voltage level of 220 kV and has been in operation for 10 years. Its hydrophobicity level is HC2, and the pollution level is b. The infrared spectra of Sample No. 125 and the control group are shown in Figure 8, with the $Si–CH_3$ wavenumber range enlarged in Figure 9.



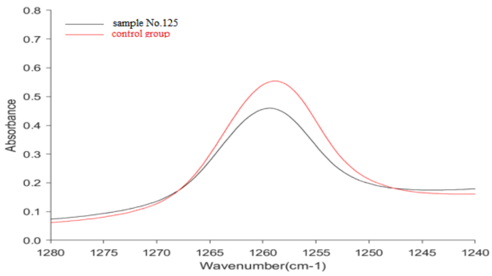


Figure 8: Infrared Spectra of Sample No. 125 and Control Group (Left)

Figure 9: Infrared Spectra of Sample No. 125 and Control Group in the $Si–CH_3$ Wavenumber Range (Right)

As shown in Figure 8, the absorption peak heights of side-chain-related groups in Sample No. 125 are almost identical to those of the control sample. The infrared spectrum corresponding to the wavenumber range of $Si–CH_3$ is enlarged in Figure 9. Specifically, the absorption peak value for $Si–CH_3$ in the control group is 0.52, while the sample exhibits an absorption peak value of 0.46, indicating a decrease of 11.54%. For $Si–(CH_3)_2$, the control group has an absorption peak value of 0.88, whereas the sample shows a value of 0.86, reflecting a decrease of 2.27%. This indicates that under a b-grade pollution level, the $Si–CH_3$ and $Si–(CH_3)_2$ groups are well-preserved, and the hydrophobicity of the sample remains good.

4. Conclusion

Through experimental analysis of 205 composite insulators in the Ningxia power grid, the effects of different pollution levels on the hydrophobicity of composite insulators are summarized as follows:

(a). The decline of hydrophobicity is closely related to operating years and the operating environment. Composite insulators operating under general pollution levels begin to show a decline in shed hydrophobicity after more than 10 years. Those operating under heavy pollution levels for about 5 years exhibit a decline in shed hydrophobicity. Sheds of composite insulators operating for 10 years or more under heavy pollution almost exhibit hydrophilic states, losing hydrophobic properties.

(b). Composite insulators operating under heavy pollution levels can accumulate more pollutants on the surface even in a short operating time, accelerating the aging of the sheds and causing a decline in hydrophobicity.

Additionally, it is noteworthy that due to the excellent hydrophobicity transfer characteristics of composite insulators, some aged samples may still exhibit good hydrophobicity in the spray classification test.

5. Operation and Maintenance Suggestions

Given the harsh natural environment in Ningxia and the impact of numerous highly polluting industrial facilities on air quality—which accelerates the aging and corrosion of composite insulators—the following suggestions are proposed:

(a). For composite insulators in general pollution areas approaching 10 years of operation, the maintenance cycle should be appropriately shortened. Inspections of shed hydrophobicity should be strengthened, and those with declining hydrophobicity should be replaced immediately. For composite insulators in heavy pollution areas approaching 5 years of operation, shed hydrophobicity inspections should be intensified. Combined with visual inspections, those with declining hydrophobicity or powdered sheds should be replaced immediately. For composite insulators in special pollution areas such as heavy industrial zones and areas near chemical plants, the maintenance cycle should be even shorter.

(b). Operation and maintenance units should strengthen maintenance efforts. During power outages or comprehensive inspections, insulators in high pollution areas should be wiped and cleaned. If cleaning is ineffective, dry ice or cleaning agents composed of penetrants, surfactants, and organic carboxylate salts should be used to wash the insulators.

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