Surface Roughness Effect on the Hydrophobicity Characteristic of Operating Composite Insulators

Song Wang
State Grid Beijing Electric Power Company
Beijing, China
e-mail: wangsongcq@139.com

Tian Yuan
China Electric Power Research Institute
Wuhan, China
e-mail: yuantian3@epri.sgcc.com.cn

Jun Zhou, Qian-yu Wang
College of Electrical Engineering
Wuhan University
Wuhan, China

Abstract*—Pretreatment needs to be done before measuring the hydrophobicity of the composite insulators. However, the necessity of such pretreatment is questionable for operating composite insulators. Therefore, surface roughness of light pollution level, heavily pollution level, chalking and the impact of surface roughness on hydrophobicity characteristic (HC) was investigated in this paper. The paper does the research on the result indicated the surface roughness is one of main factor about the pretreatment effect on HC level and static contact angle. The pretreatment effect on HC level and static contact angle seemed to be very obvious and the percentage of static contact angle changed up to 15.3%, as the surface roughness was varied. The R_a and R_{SM} of different pollution level shed percentage change up to 130% and 269%. While R_a and R_{SM} of high surface roughness degree reach up to 3.242µm and 400µm, the hydrophobicity on the composite insulators lost permanent. The surface roughness can lead the water drop to two kinds of states transitions and it can make sample static contact Angle changed up to 31% within 10 minutes, which will also cause the different results of two measurement methods. Surface roughness of composite insulators was suggested as the added parameter in hydrophobicity tests.

Keywords- hydrophobicity; operating composite insulators; surface roughness; static contact angle; HC levels test

I. Introduction

The excellent hydrophobicity of composite insulators makes the contamination resistance in high performance. Compared to porcelain and glass insulators, the hydrophobicity characteristic of composite insulators make small water drops, instead of water film in humid environment, condensed on the surface, which will greatly improve surface resistance of composite insulator beyond doubt. As to wet flashover and pollution flashover of transmission line, the critical voltage in industrial frequency will increase while times will decrease significantly. Thus it can be seen that this characteristic has an important value to ensure the long-term safety and reliability of transmission lines.

Through the examination, hydrophobicity decreases after the pollution flashover accidents of operating composite insulators [1]. As a result, hydrophobicity should be measured according to DL/T 864-2004, in order to replace the insulators in time before hydrophobicity decreases to level HC6. On-site measurement is difficult due to the environmental limit, so the hydrophobicity experiment should be temporarily performed in laboratory. The hydrophobicity characteristics experiment is mainly divided into three parts: classification, recovery and migration.

The silicon rubber jacket is covered with pollution and pulverized powder during the on-site operation, so pretreatment need to be carried out to remove the pollution so as to measure the hydrophobicity of silicon rubber itself. However, the measured results before and after the pretreatment varied a lot. For measurement aims to grasp the hydrophobicity state of composite insulators timely, in-lab hydrophobicity experiment should be performed on the surface within the same practical operating state. In order to analyze the impact of different surface states of silicon rubber jacket on hydrophobicity, in this paper, surface roughness is chosen as a quantifiable parameter to denote the characterization for different degree of pollution and pulverized powder attached to the surface of silicon rubber jacket, as well as pretreatment effect. Introduction of surface roughness measurement can not only provide the basis for hydrophobic classification method, but also remind testers measuring errors due to surface roughness changes which make static contact angle method and hydrophobic sizing method not equivalent. At present, domestic and overseas researches on hydrophobic are mainly concentrated in classification, recovery and migration, while surface roughness of operating composite insulators received less attention.

This paper starts from experimental research about whether the pretreatment of hydrophobic measurement is influential to hydrophobic characteristic of composite insulators, analyzes the relationship between hydrophobic changes and various surface roughness caused by pretreatments, also studies the impact of several types of rubber jacket surface roughness under different pollution situations on hydrophobic characteristics. On this basis, modification suggestions of hydrophobic measurement method referred to DL/T 864-2004 were put forward. The purpose is to make hydrophobic measurement and evaluation methods precisely evaluate the practical operation states of operating composite insulators.

II. THE SURFACE ROUGHNESS MEASURING METHOD

Surface profile method was commended in this paper as the surface roughness measuring method. Surface profile is the intersection between plane and actual surface as shown in fig.1. The measuring method is to detect the surface of composite insulators using a stylus in order to obtain the surface profile and calculating parameters.

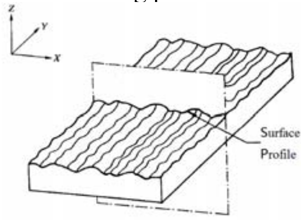


Figure 1. Surface Profile

Where surface profile parameters include amplitude, distance, hybrid, curve and related parameters. This paper focuses on the amplitude parameters and distance parameters. As the profile peak and profile valley of the composite insulator surfaces are randomly distributed, amplitude parameters can be denoted as R_a using the arithmetic mean between sampling lengths of profile peak and profile valley showed below:

$$R_a = \frac{1}{l}\int_0^1 \left|Z(x)\right| dx, \quad (1)$$

where l denotes the sampling length, $Z(x)$ denotes the vertical coordinate.

Meanwhile, distance parameters can be denoted as R_{SM} using the mean value of profile element width within sampling length X_S as shown in fig.2:

$$R_{SM} = \frac{1}{m}\sum_{i=1}^{m} X_{S_i}, \quad (2)$$

where X_{Si} denotes the width of i_{th} unit, m denotes the number of profile element width within sampling length. Profile element is the combination of profile peak and profile valley.

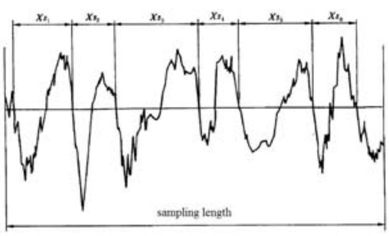


Figure 2. Profile Element Width X_S

During the experiment, surface roughness of each rubber jacket should be taken as the mean value of three times measurements, and the stylus force should be less than 0.5*N*.

III. TESTING EQUIPMENT AND SAMPLES

Under the requirements of the relevant standards [3], watering can is chosen in hydrophobic classification method (HC). Hydrophobic Angle measurement uses optical contact Angle measuring system of type CAM200. In addition, type A Shore durometer is selected, so as type TR-200 surface roughness instrument shown in Fig. 3 and the sampling length is set as 0.8mm.

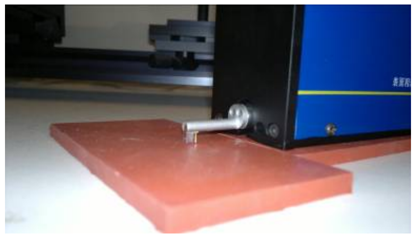


Figure 3. Surface Roughness Instrument

In this paper, 15 operating composite insulators are chosen from 12 different voltage grade lines various from 100kV to 500kV in 12 different provinces, where operating environment includes eight typical climate regions [1], and five major domestic manufacturers are contained. Sampling points of rubber jacket are all on the high voltage terminal.

IV. TEST RESULTS AND ANALYSIS

A. Hydrophobic Characteristic and Static Contact Angle Before and After the Pretreatment of Rubber Jacket [4]

There are two different opinions in electric power industry about whether pretreatment should be required on the surface of rubber jacket during hydrophobic measurement: some people think that pretreatment is needed to reduce the interference of pollution for hydrophobic measurement; while others hold that in order to master the hydrophobic characteristic of operating composite insulators, pretreatment is not required so as to keep the surface state of rubber jacket the same as practical operation.

In this paper, half the surface of every rubber jacket gets pretreated while other half remains the same, and the results of hydrophobicity test are presented in tab.1. In this table, A1, A6, A9, A14, A15 are operating in the light pollution level (equivalent salt deposit density is lower than 0.006 mg/cm^2, non-soluble deposit density is lower than 0.2 mg/cm^2); A2, A3, A4, A5, A8, A10, A11, A12 are operating in the heavy pollution level (ESDD is lower than 0.05 mg/cm^2, NSDD is lower than 0.5 mg/cm^2); A7, A13 are operating in chalking composite insulators (ESDD is lower than 0.02 mg/cm^2, NSDD is lower than 1.0 mg/cm^2).

TABLE I. RESULTS OF HYDROPHOBICITY TEST

	Hydrophobic Classification		Static Contact Angle		Shore A
	Pretreated	***No***	***Pretreated***	***No***	
A1	HC3	HC4	121.2	118.8	65
A2	HC6	HC2	140.5	133.1	47
A3	HC1	HC2	126.6	125.2	58
A4	HC2	HC6	126.4	129.7	70
A5	HC2	HC1	121.6	134.3	67
A6	HC2	HC1~2	131.9	136.3	62
A7	HC5	HC2	110.6	119.8	53
A8	HC6	HC6	111.8	128.9	38
A9	HC2	HC2	119.9	128.8	62
A10	HC2	HC2	125.7	128.0	65
A11	HC3	HC1	122.6	131.6	45
A12	HC2	HC1	131.9	115.4	48
A13	HC6	HC1	118.5	123.7	62
A14	HC1	HC1	113.4	115.8	50
A15	HC1	HC1	114.6	113.9	52

From the above table it can be seen that: the hydrophobic classification results with and without pretreatment are opposite, and the static contact angles differ 15.3%, fully illustrated the great impact of pretreatment on hydrophobic classification and static contact angle. Meanwhile, there exists a certain relationship between hardness and its change tendency. As a result, we suggest that pretreatment is not required in hydrophobic measurement of composite insulators. Otherwise, the results cannot match the practical operation state.

B. Roughness Comparison Before and After Pretreatment of Rubber Jacket

Results of roughness test before and after the pretreatment of rubber jacket using type TR-200 surface roughness instrument are listed below.

TABLE II. RESULTS OF SURFACE ROUGHNESS TEST

	Pretreatment		Without Pretreatment	
	R_a	R_{SM}	R_a	R_{SM}
A1	0.764	119.2	0.893	146.8
A2	0.708	298.1	0.458	188.6
A3	0.885	140.2	0.911	204.3
A5	0.876	329.0	0.743	304.2
A6	0.804	193.5	0.758	169.7
A7	1.656	281.0	1.284	114.7
A8	0.677	162.8	0.586	147.9
A9	0.856	135.4	0.826	125.5
A10	0.494	212.8	0.594	132.1
A11	0.985	174.5	0.877	159.8
A12	0.799	258.4	0.533	146.4
A13	3.878	352.2	1.724	95.40
A14	0.296	75.5	0.311	64.40
A15	0.288	66.7	0.293	58.80

a) Light Pollution Level

Before the pretreatment, R_a was between 0.288μm to 0.876μm, R_{SM} was between 66.7μm to 193.5μm, the surface profile is more uniform as shown in Fig.4. After the pretreatment, R_a is between 0.293μm to 0.893μm, R_{SM} is between 66.7μm to 193.5μm.

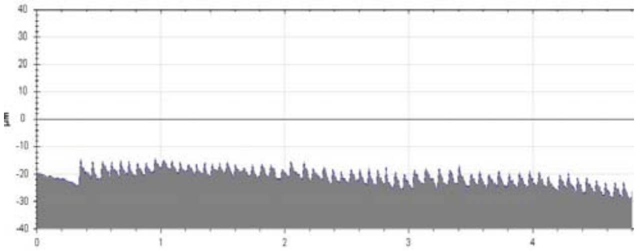


Figure 4. Surface Profile of Light Pollution Level

b) Heavy Pollution Level

Before the pretreatment, R_a was between 0.458μm to 0.911μm, R_{SM} was between 125.5μm to 304.2μm, the surface profile is more uniform as shown in Fig.4. After the pretreatment, R_a is between 0.494μm to 0.985μm, R_{SM} is between 135.4μm to 329.0μm.

c) Chalking Surface

The roughness measurement of seriously pulverized surface profile shows a deeper amplitude parameter (R_a is between 1.284μm to 1.724μm), and a smaller distance parameter(R_{SM} is between 95.4μm to 114.7μm). After the pretreatment, R_a (1.656μm ~ 3.878μm) and R_{SM} (281.0μm ~ 352.2μm) all have obvious increase.

Equation (3) is obtained though the data analysis of amplitude parameter variation R_{a1} and Shore A:

$$R_{a1} = 0.088 ln(A) - 0.1893 \quad (3)$$

R_{a1} denotes the amplitude parameter variation (R_a before pretreatment minus R_a after pretreatment). From equation (3) we can found out that after the pretreatment, roughness R_a in high hardness value decreased, while R_a in low hardness value increased. No matter how hard the chalking surface gets, there will be obvious changes before and after the pretreatment.

C. Relationship between Surface Roughness and HC

As we can see in Fig.5, there is an explicit relationship between hydrophobic classification measurement result and distance parameter R_{SM}.

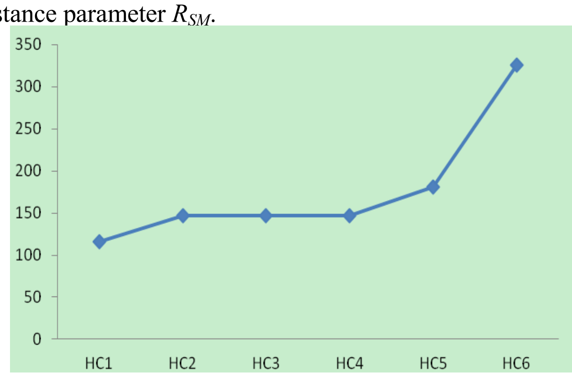
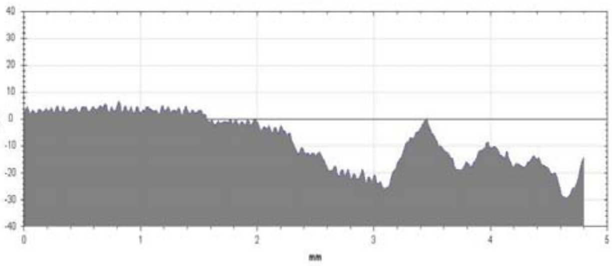
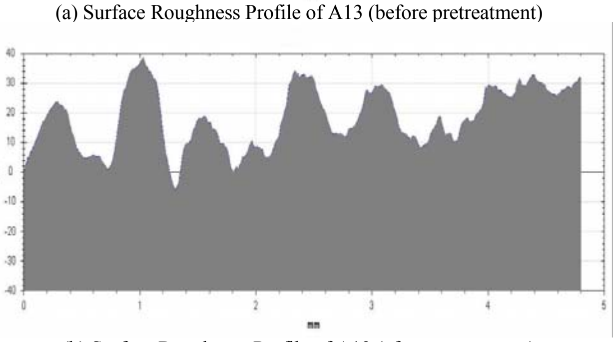


Figure 5. Relationship between HC Level and R_{SM}

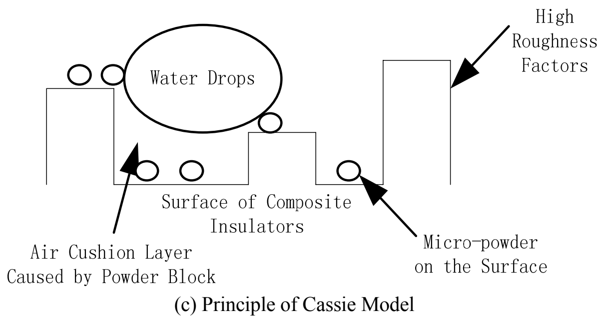
However, relationship between HC level and amplitude parameter R_a is not clear and disperses widely, so the rule similar to Fig.5 cannot be display. After the comparison analysis of profile measured by surface roughness instrument, we think there are two main reasons lead to this phenomenon. Firstly, when the amplitude parameter of chalking surface R_a is higher, surface crack is filled with superfine silica powder and dust. This will make R_{SM} small enough to present homogeneous surface profile (shown in the left half of Fig.6 (a)), similar to light pollution surface (shown in Fig.4), which can prevent water drops from crossing the surface crack filled with superfine silica powder. As a result, the contact angle of ejecting water drops caused by HC level performed as Cassie model (principle is shown in Fig.6(c)) with a great hydrophobicity. Secondly, after the pretreatment (shown in Fig.6 (b)), powder filling the surface crack gets removed, amplitude parameter R_a remains high while distance parameter R_{SM} increases significantly, which lead the ejecting water drops move into surface crack with a poor hydrophobicity.



(a) Surface Roughness Profile of A13 (before pretreatment)



(b) Surface Roughness Profile of A13 (after pretreatment)

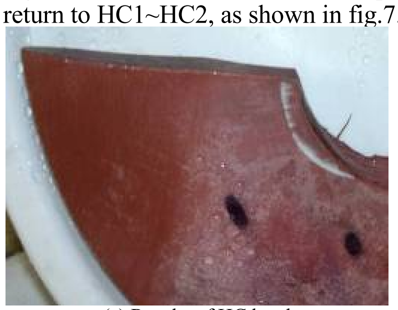


(c) Principle of Cassie Model

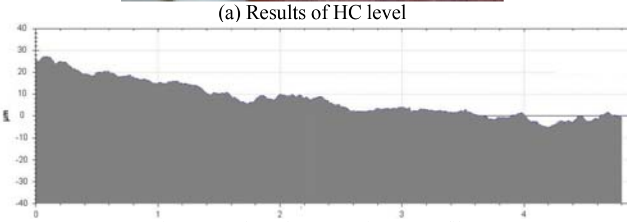
Figure 6. Analysis of Chalking Surface

D. Relationship between High Surface Roughness and Hydrophobic Classification

Sand paper was used on the sample surface to form a partial surface while R_a=3.242*μm* and R_{SM} =400*μm*, as well as a static contact angle descent 89.0°~93.5°. Even when put it in the oven at temperature 30°C for 1 month, surface hydrophobicity cannot restore, while other parts of the sample can return to HC1~HC2, as shown in fig.7.



(a) Results of HC level



(b) Scraped Surface Roughness Profile

Figure 7. Hydrophobicity and Profile (R_a=3.242μm)

When roughness reaches a certain value (R_a≥3.242μm, R_{SM}≥400μm), from the high roughness surface test, we can know that hydrophobicity of material itself cannot play a leading role. At this time, even though the silica hasn't aging, there exists no hydrophobicity.

E. Impact of Roughness on Hydrophobic Recovery characteristic

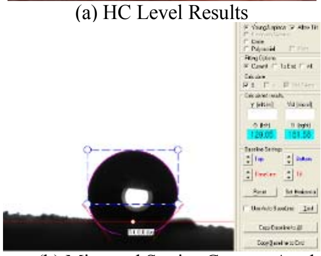
With or without pretreatment, hydrophobic recovery characteristic of rubber jacket differs a lot. After the pretreatment, hydrophobicity of some rubber jackets may recovery in 48h, while those without pretreatment can't. However, during the test, most static contact angles are greater than 90°, result in inconsistency. The surface roughness measurement showed us that, after immersing in deionized water for 96h, there are different degrees of increase in R_a. Those in high values increase a lot while those in low ones are smaller. It should be pointed out that, RSM shows no obvious change.

F. Impact of Roughness on Hydrophobic Migration characteristic

Inert material diatomite used in hydrophobic migration is between 106μm~150μm in diameter, with which surface structure gets more complicated. Size, shape, adhesion and coating way of diatomite particle directly affect R_a and R_{SM}, which will further influence the measurement results.

Most hydrophobicity of sample rubber jackets cannot migrate onto the surface (shown in Fig.8), while migration situation of new samples is better.

(a) HC Level Results



(b) Migrated Statics Contact Angle

Figure 8. Comparison of Statics Contact Angle in Hydrophobicity Migration

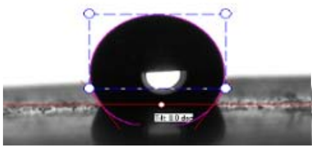
The above test results fully illustrate that surface roughness of composite insulators has a great influence on hydrophobic characteristic.

V. Relationship between Surface Roughness and Statics Contact Angle

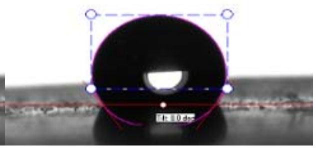
Statics contact angle method is one of the hydrophobicity measurements. During the tests, surface roughness will cause the following problems:

a. Surface roughness lead to obvious statics contact angle lag (shown in Fig.9 (a) and (b)), statics contact angle changed from 126.0° in 10s to 87.0° in 10min.

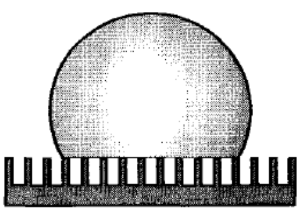
Analysis [4] showed that this is the process classical Cassie model slowly transforming to Wenzel model (shown in Fig.9 (c) and (d)), phenomenon caused by various surface roughness.



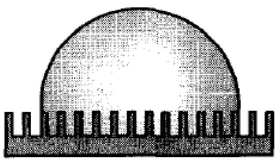
(a) statics contact angle (10s)



(b) statics contact angle (10 min)



(c) Cassie model [2]



(d) Wenzel model [2]

Figure 9. Statics Contact Angle Lag

b. Impact of roughness change on statics contact angle is smaller than HC level. Especially on high roughness surface, measurement results conflict.

Here is the reason. While statics contact angle is in Cassie model, it isn't affected by the amplitude parameter, statics contact angle change a little when roughness changes. On the high roughness surface, quantity and strength of ejecting water in HC level may change the Cassie model to Wenzel model, while statics contact angle remains in Cassie model. All these lead to the conflict. However, on smaller roughness surface, conflict will not be obvious.

c. Statics contact angle shows no classification function.

Under existing standards, $\theta_{av}\geq90°$,$\theta_{min}\geq85°$, just to meet the hydrophobicity ($\theta\geq90°$ should be considered as the hydrophobic surface in chemical category).

VI. Conclusion

a. Impact of surface roughness on hydrophobic characteristic of operating composite insulators is obvious, among which HC level results and distance parameter R_{SM} have obvious corresponding relation, while corresponding relation with R_a isn't ideal due to surface powder filling.

b. Roughness of rubber jacket varied before and after pretreatment, and the trends are all related to hardness. However, no matter how hard the chalking surface is, obvious changes will take place both before and after the pretreatment.

c. There are obvious changes in hydrophobicity and statics contact angle both before and after pretreatment of rubber jacket. As a result, pretreatment should not be put forward before the hydrophobicity measurement of operating composite insulators. Otherwise it will lead to the deviation of measurement results.

d. Measurement methods of statics contact angle and HC level is inequitable, which is common on high roughness surface. In that case, HC level is suggested for its similarity with operating conditions.

e. Surface roughness measurement is suggested in HC level to better correspond the HC hierarchical relationship and degree of aging on rubber jacket.

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BIOGRAPHIES

YUAN Tian was born in 1980, male, Ph.D. candidate. His engineer research direction is insulator testing and anti-contamination of the lines.

ZHOU Jun was born in HuBei, China, on Nov 10, 1980. He received the B.S. degree and Ph.D. degree of high-voltage and insulation technology from Wuhan University, Wuhan, China. His major fields of interest are Power System Operation and Control and LCC technology.