Laboratory Investigation on Hydrophobicity of New Silicon Rubber Insulator under Different Environmental Conditions

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Abstract—In order to find out the hydrophobicity loss while soaking in distilled water, hydrophobicity recovery after soaking, hydrophobicity transfer through different contaminations, hydrophobicity loss under icing and hydrophobicity recovery through contaminated iced new silicon rubber surfaces based on hydrophobicity loss, recovery and transference property of silicon rubber, laboratory studies were carried out. The hydrophobic characteristics were studied by STRI hydrophobicity classification guide and measuring the static contact angle along the silicon rubber surface. The experimental results showed that hydrophobicity loss rate is much slower while soaking new SIR in distilled water as compared to recovery at different temperatures. It is found that the new silicon rubber material surface cannot lost its hydrophobicity completely even soaking for eight days at room temperature but, recovered it completely with different rates at different ambient temperature variations. Hydrophobicity transfer rate through pollution layer at different contaminations under different temperatures is also discussed. Therefore, for this purpose hydrophobicity transference through four different contaminations under different temperatures were carried out artificially in laboratory. In the last part of this paper hydrophobicity loss under icing condition and hydrophobicity recovery through icing surfaces under different conditions at different environmental temperatures, humidity and wind speeds are considered.

Index Terms—silicone rubber, hydrophobicity, static contact angle, pollution, icing

1. INTRODUCTION

WORLDWIDE silicon Rubber insulators have been developed for out-door insulation since the 1960’s. They were widely used from the 1980’s and the usage increased rapidly in the 1990’s [1-3]. These are used to support the outdoor transmission line conductors to separate them electrically from each other. In the early days, insulators were made of ceramic and glass materials.

The primary impetus for their increased acceptance by the electric power utilities is their substantial advantage compared to inorganic insulators. The characteristics like Light weight, easy installation, comparable or wet withstand voltage, improved contamination performance, improved resistance to vandalism, improved handling of shock loads and high hydrophobicity [4-5] have made SIR insulators superior over non-ceramic insulators.

Hydrophobicity of SIR insulator is its resistance to water from flowing on its surface. A surface is highly hydrophobic if it resists water flow which is dropped on it and is least hydrophobic if dropped water flows in form of tracks on its surface. The hydrophobic surfaces are water repellent, in contrast with hydrophilic surfaces which easily get wet [6] when exposed to water. In general, it is considered that the hydrophobicity transference originates from the migration of low molecular weight (LMW) polysiloxanes which exhibit a broad molecular weight distribution of siloxane components. The siloxane components comprise fluid silicones (oil-like consistency with molecular weight < 25000) as well as silicone polymer with various backbone chain lengths [7-9].

Hydrophobicity can be described by static contact angle ($\theta_c$) on the material surface that a liquid drop makes on the solid surface when its interface meets it. Surface is said to be hydrophobic, when $\theta_c > 90^\circ$, hydrophilic when $\theta_c < 35^\circ$ and partially wettable when $35^\circ < \theta_c < 90^\circ$ [4, 6] as shown in Fig. 1(a, b).

Fig. 1 Water drop schematic diagram on (a) Hydrophobic surface (b) Hydrophilic surface

The static contact angle of water droplet on the surface of SIR was measured and STRI hydrophobicity classification guide 3, 2005 both were used in the evaluation of hydrophobicity. Polymeric materials are badly affected by environmental stresses like UV-radiations, heat, contaminations, moisture, etc. [4, 10]. There are internal and external factors both
influencing the characteristics of LMW. The internal factor mainly depends on the batch formulation of the polymer compound, while the external factors are manifolds, e.g. the type of pollution, the environmental conditions and so on [7,11-12]. The effect of these external factors like soaking, pollution, icing and temperature on hydrophobicity loss, recovery and transfer on new SIR surface are studied in detail in this paper.

2. TEST SAMPLES AND FACILITIES

2.1 Test Samples

The new silicon rubber insulator was provided by Xiangfan Guowang composite insulators Co, Ltd. Table 1 gives its basic parameters. SIR slabs and weather sheds with the size of 50mm×50mm×4mm and 130mm diameter were uniformly cut from SIR insulator to analyze static contact angle and HC level respectively. FXBW4-110/100 silicon rubber insulator is shown in Figure 2.

Table 1 – Basic data of the FXBW4-110/100 SIR Insulator

<table>
<thead>
<tr>
<th>Insulator Type</th>
<th>Rated Voltage</th>
<th>Structure Height</th>
<th>Sheds Diameter</th>
<th>No. of Sheds</th>
</tr>
</thead>
<tbody>
<tr>
<td>FXBW4-110/100</td>
<td>110</td>
<td>1240±15</td>
<td>160</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>130</td>
<td>14</td>
</tr>
</tbody>
</table>

Dimensions:
Voltage (kV); Diameter (mm)

2.2 Test Facilities

Static contact angle measurements were carried out by using laboratory ramé-hart contact angle goniometer. A static contact angle was captured when a thermodynamic equilibrium was reached between the three phases: solid, liquid, and gas.

3. TEST METHOD

We found out that three factors mainly influence the surface hydrophobicity change of the tested samples with seasons. They are ambient temperature, precipitation, and deposited pollution property [14]. In order to find out the effect of raining, pollution layer and icing on surface hydrophobicity of new SIR insulator, the detailed procedure is given below.

3.1 Evaluation of Hydrophobicity

The hydrophobicity was evaluated by STRI hydrophobicity classification guide [13] and static contact angle. Referred to [14], about 10-30 ml distilled water was applied to insulator surface in the form of mist from a distance 25 cm ± 10 cm for a period of 20 s to 30 s by using a suitable spray device. Wetted surface was continuously observed and attributes it into one of 7 levels ranging from HC 1 to HC 7, according to the shape of water droplets and the percentage part of the surface which is wetted. HC1 corresponds to the most hydrophobic surface, where only discrete and practically circular water droplets are formed while HC7 corresponds to the most hydrophilic surface, where continuous water film is formed over the whole observed area.

Static contact angle measurements were carried out by using ramé-hart contact angle goniometer. All SIR slabs for contact angle measurements have a dimension of 50mm×50mm×4mm thickness. Deionized water of ~100µS conductivity was used and the drop volume was controlled in the range 20–50µL.

3.2 Soaking of Samples with Water

The different amount of raining may cause the change of hydrophobicity of new silicon rubber surface. In 1st part of this paper, the hydrophobicity loss due to raining and recovery after raining under different temperatures are discussed. Therefore, for this purpose two FXBW4-110/100 silicon rubber insulators were soaked with distilled water for 8 days at standard laboratory environment. While soaking, hydrophobicity loss rate was analyzed at different times up to 8 days. After being soaked with water for 8 days one sample was dried naturally at 7°C~15°C and the 2nd one at 25°C~35°C under relative humidity 40%~80% and hydrophobicity recovery trend was analyzed.
3.3 Artificial Pollution Layers Application

3.3.1 Pre-Conditioning
Before the pollution layer application, 8 FXBW4-110/100 silicon rubber insulators were washed with clean water and left to be dried naturally. The surfaces of the samples were coated by a very thin layer of dry kieselguhr to destroy the hydrophobicity. The adequacy of this layer was checked both visually and by STRI guide to ensure that the surface of the insulator is completely hydrophilic (HC=7) [15-17]

3.3.2 Artificial Polluting
After one hour of preconditioning, the solid layer method was applied to the pollution layer on the samples where sodium chloride and kieselguhr were electric and inert materials, respectively [18, 19]. The non-soluble deposited density (NSDD) of contamination layer was fixed at 1.0 mg/cm$^2$ in all tests and with SDD from 0.05 to 0.5 mg/cm$^2$. The values of SDD/NSDD were 0.05/1, 0.12/1, 0.25/1 and 0.50/1mg/cm$^2$, respectively. Half of the samples were dried at 10°C~25°C and the remaining half at 30°C~40°C in natural environment of Chongqing under relative humidity 40% ~80% and hydrophobicity transference was inspected up to 8 days with different time frames.

3.4 Artificial Ice-Coating Procedure
The ambient temperature distinctly fluctuates not only with seasons in a year, but also with sunrise and sundown during the day [13]. Therefore, it is very important to investigate the trend in hydrophobicity variation on new silicon rubber insulator with sunrise and sundown specially when average temperature varies between -4°C to 12°C in a day.

One clean and three artificially contaminated FXBW4-110/100 silicon rubber insulators were used for this test. The values of SDD/NSDD were 0.05/1, 0.12/1, 0.25/1 and 0.50/1mg/cm$^2$, respectively. After 4 days of naturally drying, the polluted specimens and one clean sample with HC1-HC3 were suspended vertically on the electric hoist at the center of the chamber, and the hoist rotated at one revolution per minute (rpm). At the beginning of icing, the surface of the specimens were wetted by the spraying manually and were covered with 1-2 mm layer of ice to make sure that the pollution layer not get washed away [20].The icing thickness was controlled at 5mm on all samples. All the samples were dried in air at 4°C ~ 8°C and 8°C ~ 12°C from 6AM to 6PM in natural environment of Chongqing under relative humidity (40%-80%) and average wind speed (5 km/h). Finally hydrophobicity recovery trend was analyzed after complete ice melting.

4. RESULTS AND ANALYSIS

4.1 Effects of Soaking on Hydrophobicity
The test results of soaking of new SIR samples with distilled water showed that new SIR insulator surfaces offer a strong resistance to hydrophobicity loss. It is found that surface hydrophobicity of SIR insulators gradually decrease from HC1 to HC3 and contact angle from 110° to 65±2° while soaking with distilled water at room temperature for eight days (Figure 5 and Figure 6) and recover to HC1 and 110° with different ambient temperatures (Figure 7 and Figure 8). The hydrophobicity recovery rate was recorded to be different at different ambient temperatures. It is also found that increase in temperature gradually increases the recovery rate because migration rate of LMW increases due to increase in ambient temperature. Figure 9 and Figure 10 give the pictures showing the hydrophobic decrease while soaking and recovery at 7°C~15°C on the surface of clean new SIR insulators.
Figure 7 HC Level over time for Hydrophobicity recovery at different temperatures after being soaked in distilled water.

Figure 8 Static Contact Angle over time for Hydrophobicity recovery at different temperatures after being soaked distilled water.

Figure 10 Pictures showing the hydrophobic recovery distribution on the surface of new SIR weather shed after being soaked in distilled water for 196Hrs and dried at 7°C~15°C

4.2 Influence of Pollution Layer on Hydrophobicity Transfer

Figure 11 and figure 12 show the effects of NaCl with different contents on hydrophobicity transference of new silicon rubber insulator surface at 10°C~15°C. The tested results show that hydrophobicity transference rate becomes slow with increase in SDD or NSDD. Figure 13 and figure 14 also show the same effects of NaCl with different contents on hydrophobicity transference at 30°C~40°C. Figure 15 gives the pictures showing the hydrophobic tranfer on the weather sheds of new SIR insulators after eight days of hydrophobicity transfer with SDD/NSDD are 0.05/1, 0.12/1, 0.25/1 and 0.50/1mg/cm². It is found that the pollution severity has a great impact on hydrophobicity transference. The low temperature and high relative humidity were found to have obvious depressed effects on the rate of hydrophobicity transference. It is found that new silicon rubber samples with low SDD/NSDD, high ambient temperature and low relative humidity, exhibited good hydrophobicity.

The test results showed that the contaminated surfaces change from hydrophilic to hydrophobic steadily. It is found that after 6~10 hours of transfer time, the pollution layers exhibit contact angle greater than $70\pm5^\circ$ with HC2-HC3 and levels off at $100^\circ$~$130^\circ$ with in 24 ~ 48 hours at 30°C~40°C but this hydrophobicity rate is found a bit slower at 10°C~15°C. Pollution layers gain contact angle of $50\pm3^\circ$ with HC3-HC4 after 6~10 hours of rest time and levels off at $80^\circ$~$90^\circ$ with in 24 ~ 48 hours at 10°C~15°C. After 96 hours of transfer time, all the combination of SDD and NSDD, hydrophobicity level begins to level off at the range of HC1~HC2.
The tested results show that surface hydrophobicity of the tested samples gradually decreases to the worst state with ice accumulation on polluted and clean surfaces. In order to investigate the hydrophobicity recovery though ice covered surfaces, all the samples were dried in air naturally at 8°C ~ 12°C. Initially, all the samples were inspected just after the complete ice melting at 8 A.M. It is found that contaminations
got partially cleared from the polluted surfaces after complete ice melting. It is investigated that all the samples exhibited the worse hydrophobicity state of HC7-HC6 with immeasurable contact angle. All the samples were inspected again at 1 P.M and 6 P.M. It is found that the clean sample exhibited good state of hydrophobicity (HC2-HC3) with 75±3° to 80±3° at 1 P.M and HC1 with 98±2° at 6 P.M dried in air under the temperature range of 8°C ~ 12°C with relative humidity (40%~80%) and average wind speed of 5 km/h. The test results showed that recovery rate though contaminated surfaces are very slow as compared to clean surface. Contaminated surfaces recovered hydrophobicity to HC3-HC6 with 35±3° to 60±3° under the same environmental conditions as described above at 6 P.M. Figure 16 and figure 17 show the effects of temperature rise on hydrophobicity recovery through 5mm thick ice surfaces (clean and contaminated) with 8°C ~ 12°C temperature variation, regarding the HC Level and the contact angle as a function of elapsed time respectively.

Figure 18-19 also show the same effects at 4°C ~ 8°C. The tested results show that hydrophobicity rate is recorded much slower at 4°C ~ 8°C as compared to recovery rate at 8°C ~ 12°C with same environmental conditions of humidity and wind. It is noticed that clean surface recovered hydrophobicity HC5-HC6 with 30±3° to 40±2° at 1 P.M and HC3 with 60±2° at 6 P.M. The worst hydrophobicity recovery rate was investigated in case of contaminated surfaces at 4°C ~ 8°C. Partially contamination surfaces recovered hydrophobicity to HC5-HC6 with 15±3° to 35±2° at 1 P.M and 20±2° to 45±3° at 6 P.M. Figure 20 gives the picture showing the hydrophobic distribution of clean and polluted specimens with SSD/NSDD are 0.05/1, 0.12/1, and 0.25/1mg/cm² at 6PM under 8°C ~ 12°C.

Figure 16 Hydrophobicity recovery curves through 5mm ice thickness surfaces (clean and contaminated) with 8°C ~ 12°C temperature variation, regarding the HC Level as a function of elapsed time.

Figure 17 Hydrophobicity recovery columns through 5mm ice thickness surfaces (clean and contaminated) with 8°C ~ 12°C temperature variation, regarding the contact angle as a function of elapsed time.

Figure 18 Hydrophobicity recovery curves through 5mm ice thickness surfaces (clean and contaminated) with 4°C ~ 8°C temperature variation, regarding the HC Level as a function of elapsed time.

Figure 19 Hydrophobicity recovery columns through 5mm ice thickness surfaces (clean and contaminated) with 4°C ~ 8°C temperature variation, regarding the contact angle as a function of elapsed time.
Based on the above test and analyzed results, the following conclusions were obtained in this paper:

1. The new SIR insulator surfaces offer a strong resistance to hydrophobicity loss while being soaked in distilled water and it cannot lose its hydrophobicity completely and this concept means that pollution has very significant effect on hydrophobicity. It can gradually decrease to HC1 to HC3 and contact angle from 110° to 65±2° while soaking in distilled water at room temperature for eight days and recover to HC1 and contact angle 110° with different ambient temperatures.

2. The hydrophobicity recovery rate is recorded higher as compared to loss in clean water and it can gradually increase with increase in ambient temperature.

3. Pollution performance of new SIR insulators is tied closely to their hydrophobicity property. The pollution severity has a great impact on hydrophobicity transfer rate. Low SDD or NSDD, low relative humidity and high ambient temperature can result in good hydrophobicity transfer.

4. Ice accumulation on new SIR insulators can gradually decrease to worst status of HC7 with immeasurable contact angle but with sun rise hydrophobicity can gradually recover however it depends on pollution severity, environment temperature variation, humidity and wind speed.

5. It is found that the clean sample exhibited good state of hydrophobicity (HC2-HC3) with 75±3° to 80±3° at 1 P.M and HC1 with 98±2° at 6 P.M dried in air under the temperature range of 8°C ~ 12°C with relative humidity (40%~80%) and average wind speed of 5 km/h. The test results showed that recovery rate though contaminated surfaces are very slow as compared to clean surface. Contaminated surfaces recovered hydrophobicity to HC3-HC6 with 35±3° to 60±3° under the same environmental conditions as described above at 6 P.M.

6. It is noticed that clean surface recovered hydrophobicity HC5-HC6 with 30±3° to 40±2° at 1 P.M and HC3 with 60±2° at 6 P.M. The worst hydrophobicity recovery rate was investigated in case of contaminated surfaces at 4°C ~ 8°C. Partially contamination surfaces recovered hydrophobicity to HC5-HC6 with 15±3° to 35±2° at 1 P.M and 20±2° to 45±3° at 6 P.M.

7. Static contact angle in combination with HC level to compensate each other is found to be more effective for the description of the hydrophobicity of new SIR insulators.

8. In future, the effect of soaking on hydrophobicity loss of high temperature vulcanized (HTV) new silicon rubber in saline solutions of different conductivity can be carried out as a function of time and temperature. The recovery of hydrophobicity of high temperature vulcanized (HTV) new silicon rubber in air after being soaked for specific time in saline water solution of different conductivity can also be studied.

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REFERENCES


Chengrong Li, Linjie Zhao, Jun Xiong, Shuqi Zhang and Jisha Yao, “Influence of Seasons on Hydrophobicity of Silicone Rubber Insulators in Semi-wet Warm-temperature Zone of China”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 15, No. 4; August 2008


Xingliang Jiang, Jihe Yuan, Zhijin Zhang, Jianlin Hu and Lichun Shu, “Study on Pollution Flashover Performance of Short Samples of Composite Insulators Intended for ±800 KV UHV DC”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 14, No. 5; October 2007

“Artificial pollution tests on high-voltage insulators to be used on a. c. systems”, IEC 60507, 1991.

Xingliang Jiang, Yafeng Chao, Zhijin Zhang, Jianlin Hu and Lichun Shu,” DC Flashover Performance and Effect of Sheds Configuration on Polluted and Ice–covered Composite Insulators at Low Atmospheric Pressure “, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 18, No. 1

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