A NEW 5000 H MULTI-STRESS TEST PROCEDURE FOR SILICONE RUBBER INSULATORS BASED ON CONTAMINATION AND HYDROPHOBICITY CHANGE SIMULATION

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Abstract: With a wide and increasing application of silicone rubber composite insulators in China and many other countries, long-term performance evaluation of SR insulators are of high significance, and proper multi-stress tests method needs to be studied. Based on the studies of contamination and hydrophobicity change of SR insulators in inland China, high pollution severity with high NSDD (Non-Soluble Deposit Density) and hydrophobicity reduction and transfer process should be taken into consideration in test methods. Existing IEC and other multi-stress test procedures could not provide a satisfactory simulation of the pollution condition and hydrophobicity change process. Based on improvements made to IEC 5000 h test, a new procedure, the THU 5000 h test procedure, is proposed. There are mainly two improvements in the THU 5000 h test procedure; one is to replace the salt fog with mixed pollution fog including both soluble (NaCl) and non-soluble (kieselguhr) pollutant and the other is to provide sufficient time for significant hydrophobicity reduction and transfer. Under the THU procedure, 31 different silicone rubber insulators were tested in five respective 5000 h tests. The improved test procedure has provided a satisfactory simulation of heavy pollution with high NSDD, reproduced the hydrophobicity change process on silicone rubber insulators.

1 INTRODUCTION

Silicone rubber composite insulators (SR insulators) in China were developed in early 1980s, and it has been widely applied to HVAC and HVDC lines of 110 kV and above [1]. Up to now, the total amount of SR insulators used for 110 ~ 500 kV overhead lines is more than 5 million, with more than 300,000 SR insulators in 500 kV HVAC lines and 15,000 in ±500 kV HVDC lines. In addition, in 1000 kVAC and ±800 kVDC UHV lines, nearly 2/3 of all kinds of line insulators (including composite insulators, glass insulators and ceramic insulators) are SR insulators.

Composite insulators used in China are all HTV Silicone Rubber insulators, which have superior performances in heavily polluted areas. Usually, these insulators are used in areas with medium or high pollution severity, and the hydrophobic surface can prevent the formation of continuous water film [1-3]. Although there were researchers having doubts about the hydrophobicity performance of contaminated SR insulators, the field operation experience have proved the effectiveness of SR insulators against pollution flashover [1, 3-6].

Long-term ageing of composite insulators has been a discussing issue for a long time, and their proper ranking and selection have attracted researchers' attention [3, 7-14]. In China, many 500 kV HVAC SR insulators have been used for more than 10 years, and ±500 kV HVDC composite insulators have operated for about 8 years. With the increase of service time, more attention is paid to long-term performances of SR insulators. To evaluate and select SR insulators, proper 5000 h multi-stress test method should be studied, and the method should contain the main stresses in the field and repeat the changing process of SR insulators.

2 POLLUTION AND HYDROPHOBICITY OF SR INSULATORS IN THE INLAND FEILD

From 1998 to 2004, more than 100 insulators were removed from 110 kV ~ 500 kV lines and measured [7]. These insulators, which come from various manufacturers, operated in different areas and in different environment conditions, with service time varying from one to ten years.

2.1 Pollution status in the field

Based on the data from measurement points, the probability distribution of ESDD and NSDD was analysed [7]. According to the statistical analysis result, the 50% cumulative probability of ESDD, NSDD and NSDD/ESDD are listed in TABLE I. For all tested SR insulators, 90% of the shed upper surfaces are with ESDD $\leqslant$ 0.1 mg/cm^2 and 95% with NSDD $\leqslant$ 0.3 mg/cm^2. However, 70% of the shed lower surfaces are with ESDD $\leqslant$ 0.4 mg/cm^2

and 80% with NSDD ⩽1.0 mg/cm^2 (see TABLE II). For the ratio of NSDD/ESDD, upper and lower surface are similar, the 50% cumulative probability result is about 2 ~ 2.5, and 60% of NSDD/ESDD are in the range of 1.5 ~ 4. Moreover, all of the ratio obtained are lower than 9 ~ 10, and there are only 5% larger than 7 [7]. According to the test results, the inland environment is of high pollution with rather high NSDD.

TABLE I
50% CUMULATIVE PROBABILITY OF ESDD, NSDD [7]

Pollution Severity	Shed Upper Surface (mg/cm^2)	Shed Lower Surface (mg/cm^2)
ESDD	0.04 ~ 0.05	0.2
NSDD	0.14	0.5
NSDD/ESDD	2 ~ 2.5	

TABLE II
CUMULATIVE PROBABILITY OF ESDD, NSDD AND NSDD/ESDD [7]

Pollution Severity	Shed Upper Surface		Shed Lower Surface	
	Range (mg/cm^2)	Percentage	Range (mg/cm^2)	Percentage
ESDD	⩽ 0.1	90%	⩽ 0.4	70%
NSDD	⩽ 0.3	95%	⩽1.0	80%
Ratio of NSDD/ESDD	60% in the range of 1.5 ~ 4 5% large than 7, and all lower than 10			

2.2 Hydrophobicity change in the field

Figure 1 shows the measured results of the hydrophobicity status of over 30 SR insulators in the field. These insulators operated in different environment conditions, with service time varying from one to ten years. It is obvious that the hydrophobicity of most sheds is about WC2 ~ WC4. It also shows that the shed upper surfaces are generally more hydrophobic than the lower surfaces. According to the investigation, hydrophobicity status is more corresponding to the specified environment, and less correlated with the years in service [2, 15, 16].

In the field, hydrophobicity status of SR insulators is changing over time. In rainy or foggy days, hydrophobicity of SR insulators may reduce due to the discharge activities and wet pollution. However, it recovers afterwards because of hydrophobicity transfer property. Hydrophobicity transfer here refers to the phenomenon that hydrophilic pollutant on the SR insulator surface gradually becomes hydrophobic. It seems that the hydrophobic property has “transferred” from the silicone rubber to the pollution layer. For clean silicone rubber surfaces, the change of hydrophobicity refers to the reduction and recovery of hydrophobicity. However, for polluted silicone rubber surfaces, hydrophobicity recovery refers to hydrophobicity transfer.

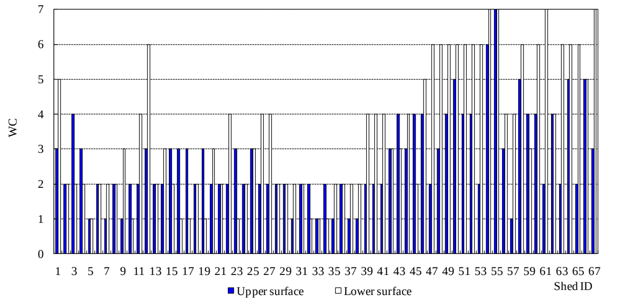

Figure 1. Hydrophobicity status of upper or lower surfaces of SR insulator sheds after years in service [7]

Note: These test sheds are from more than 30 SR insulators and the insulators are located at different areas of China and the distance between them varies from several hundred kilometers to more than 3000 kilometers.

With the variation of wet and dry weather, the hydrophobicity status repeats the reduction and transfer cycle with contamination process, and the hydrophobicity performances of SR insulators gradually become worse in the field [2, 15].

2.3 Discussions on the IEC 5000 h test method

Figure 2 shows the 5000 h multi-stress test procedure adopted by IEC 61109, IEC 62217 and CIGRE 142 [17, 18, 19]. The stresses listed in the procedure cover the main stresses in the field. This procedure simulated the pollution by salt fog, but did not simulate the non-soluble pollution that often deposits onto the SR insulator surface in inland areas. Meanwhile, the procedure did not provide sufficient time for the hydrophobicity reduction and transfer process. China EPRI had conducted multi-stress tests under IEC standard and the test results of SR insulators from different manufactures show almost no difference, however their performances are actually different in service.

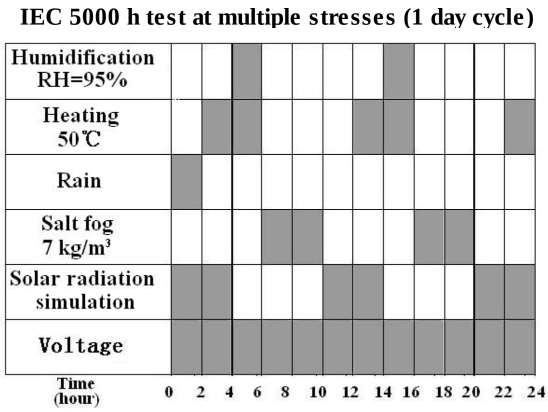

Figure 2. IEC 5000 h test at multiple stresses procedure (1 cycle)[18]

Based on the above analysis, existing IEC multi-stress test procedures is not aim for the inland service environment, and could not provide a satisfactory simulation of the high pollution field condition with high NSDD, and reproduce the hydrophobicity change process on SR insulators.

3 THE NEW PROCEDURE – THU 5000 H TEST PROCEDURE

Based on the above analysis, modifications were made to the IEC 5000 h test method, and a new multi-stress test procedure, the THU 5000 h test procedure, is suggested by Tsinghua University (THU for short), The new procedure is shown in Figure 3.

THU 5000 Hours Test (2 days cycle)

Test Stress	Parameters	Period 1 0-24 h	Period 2 25-48 h
High Voltage	AC or DC		
Rain	⩽10 μS/cm	←30 sec 60 sec→	
Humidification	RH ≈ 95%		
Heating	(50 ± 1) ℃		
Polluted Fog	NaCl and Kieselgur		
Solar Radiation Simulation	0.85-0.95 kW/m^2		

Figure 3. THU 5000 h test procedure, this figure shows 1 cycle (48 h) of the test, and each cycle is divided into 2 periods (24 h each).

(1) The modifications on ageing stresses: In this new procedure, NaCl and kieselguhr simulate soluble and non-soluble pollutant. Pollution fog will bring NaCl and kieselguhr onto the upper surfaces and lower surfaces of the sheds of the test insulators. However, the specific parameter of pollution fog depends on the simulated environment condition. Therefore, the polluted fog parameter should be adjusted before the test and sometimes a preparation test should be taken to obtain a proper pollution simulation. Non-soluble pollutant is important in the process of hydrophobicity transfer [2, 7, 15]. The process is very slow if the pollution contains the soluble part only. However, it is much faster if the pollution contains both soluble and non-soluble parts, especially when the NSDD is larger than ESDD of the pollution.

The other main ageing stresses to SR insulators (such as high voltage, rain, UV radiation, temperature, and humidification) are also applied in the new procedure.

(2) The modifications on stress periods: The suggested time of THU procedure is 5000 hours. This procedure has a two days' cycle, and prolongs the duration of polluted fog (1 day) and UV radiation (1 day) in each cycle. It keeps enough time for pollution accumulation, wetting, discharge and hydrophobicity reduction of test specimens in the fog period. Meanwhile, it also keeps enough time for hydrophobicity transfer during the subsequent UV period.

Thus, the suggested THU 5000 h test procedure is intended to simulate not only the pollution on the insulator surface but also the hydrophobicity change of SR insulators.

4 EXPERIMENTAL SETUP

4.1 Specimen insulators

Under the new suggested multi-stress test procedure, a total of 31 SR insulators were tested respectively in five respective 5000 h tests (Test 1-AC, Test 2-DC, Test 3-DC, Test 4-AC and Test 5-AC). In Test 1-AC, Test 2-DC, Test 3-DC, Test 4-AC, specimens are all new insulators, while in Test 5-AC, 2 among 8 are new insulators and the rest have operated in the field safely for 10 years. In Test 1-AC, 8 SR insulators were tested and one of them was a failure insulator in service. In Test 2-DC, 8 SR insulators were tested for 5000 h. Test 3-DC and Test 4-AC were conducted at the same time for 5000 h, with 4 specimens under AC voltage and 4 under DC voltage, and the separate chamber design makes it possible to apply different voltage in the two chambers (test equipment is described in Section 4.2). In Test 5-AC, 1 among 8 insulators is a new insulator, while 4 among 8 were tested with field pollution on the sheds and 3 among 8 are tested with the pollution washed completely.

4.2 Equipment and parameters

The new test procedure has a simpler stress arrangement than IEC and other procedures. Therefore, if the equipment is able to conduct the IEC 5000 h test, it is also able to conduct the new 5000 h test procedure.

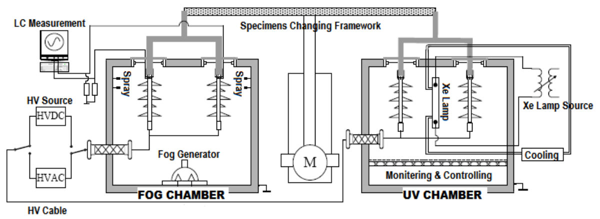

Figure 4. 5000 h multi-stress test equipment in Tsinghua University, with fog chamber and UV chamber separated.

In our research, the tests were conducted in 5000 h multi-stress test equipment in Tsinghua University. This test equipment separated the fog chamber from the UV chamber, and the test stresses (see Figure 3) are applied respectively in the two chambers: the first 24-hour period of a cycle is conducted in the fog chamber, and the second 24-hour period is in the UV chamber. Both the Fog and UV chambers have 4 testing jigs, and 8 specimens in the two chambers are exchanged by a mechanical changing framework between periods. The test equipment is illustrated in Figure 4.

A 35 kV, 10 kVA, single-phase transformer is used to provide ac high voltage, and a full wave rectifying circuit is used to provide dc high voltage. The voltage stress is selected according to IEC 61109 annex C [17]. It is normally 34.6 mm/kV (calculated as phase to ground value for ac case and line to ground value for dc case).

Pollution fog is generated from the mixture liquid of NaCl and kieselguhr, and the reason for selecting kieselguhr as non-soluble component of pollutant is that it is frequently used as artificial pollution and is optimal for hydrophobicity transfer [15]. It contains 2 g NaCl and 1 g kieselguhr in one-litre de-ionized water (The amount of NaCl and kieselguhr in one-litre water could be changed to simulate different pollution conditions when necessary.). The conductivity of fog liquid is about 3.6 ~ 3.8 mS/cm. Kieselguhr is added to the salt fog as non-soluble component in order to simulate the contaminated areas with high NSDD. The actual generated fog is 0.34 ~ 0.42 L/(h•m^3). A centrifugal fog generator engenders the pollution fog. Continuous stirring of the liquid is necessary in order to avoid the deposition of kieselguhr.

Nozzles mounted above these specimens, each specimen surrounded by three nozzles, provide the artificial rain. The conductivity of water is lower than 10 µS/cm. Since rain has effects of wetting the pollution and pouring the pollution, the rain phase is applied twice. The rain phase at the end of fog period is to wash out part of the pollution on insulator surface, especially the pollution at the upper surface of the shed. The pollution ratio of upper surface and lower surface could then be controlled to the expected value. The adopted time of rain is only 1 min. In addition, 30 seconds' rain will be adopted right after the specimens are exchanged from the UV chamber to the fog chamber in order to shorten the wetting time.

Heating temperature is (50±1) ℃ in the test procedure, and the relative humidity is about 100% due to the continuous water spray, which is also used to cool the wall of the UV chamber.

The simulated UV radiation is provided by a Xenon arc lamp with an output of 6 kW. The spectrum of Xenon arc lamp is very similar with the solar spectrum between 300nm and 750 nm wavelength. The irradiation intensity of Xenon light is controlled between 0.85 and 0.95 kW/m^2 and is continuously measured with a radiometer. The distance between the Xenon lamp and test specimens is approximately 48 cm according to IEC 61109 [17].

5 RESULTS AND DISCUSSIONS

5.1 Pollution accumulation

Pollution gradually accumulates on the SR insulators in 5000 h test. For example, in Test 1-AC (polluted fog generated from mixture of 2 g NaCl and 1 g kieselguhr in one litre de-ionized water), NSDD and ESDD of the specimens at 144 h, 240 h, 480 h, 720 h, 2500 h and 5000 h were measured. Figure 5 shows the change of NSDD, ESDD and the radio of NSDD/ESDD respectively.

It could be found that the pollution on the surface is gradually accumulated and has a tendency of saturation after 2500 h. The ESDD and NSDD value are close to the pollution level measured from the field. The NSDD and ESDD of the lower surfaces of the sheds are both higher than those of the upper surfaces. The ratio of NSDD/ESDD is steady after 2000 h as shown in Figure 5, with a range of 2 ~ 4. During 5000 h, the ratio of NSDD/ESDD of upper and lower shed surfaces are very close to the measured results in the fields (See TABLE I) [4].

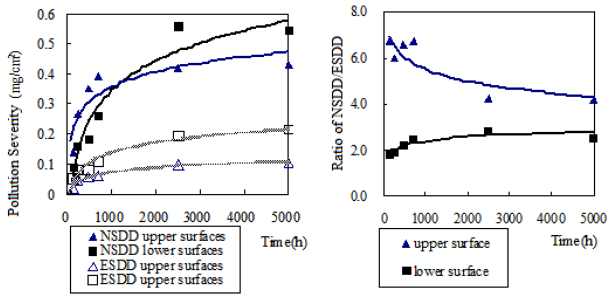

Figure 5. NSDD, ESDD and the ratio of NSDD/ESDD changing with time in Test 1-AC [4]

The new procedure simulates the levels and the ratio of ESDD/NSDD of pollution in inland environment. Both the target pollution severity and the ratio of NSDD/ESDD are close to the values of operated insulators. Therefore, the environment condition has been repeated by the new 5000 h multi-stress test procedure.

5.2 Hydrophobicity change

Hydrophobicity evaluation is according to IEC standard [20]. All new insulator specimens are WC1. The hydrophobicity of SR insulators gradually decreases due to long-term wetting, corona and discharge in the polluted fog chamber, and is recovered when exposed to UV radiation and high temperature.

For example, in Test 1-AC, hydrophobicity status became better in the 24 hour UV period. Figure 6 shows the results of the hydrophobicity transfer during 24 hours (in the UV chamber) at the 56th cycle [6]. It shows that, the hydrophobicity status recovers to WC1~WC2 after the UV period.

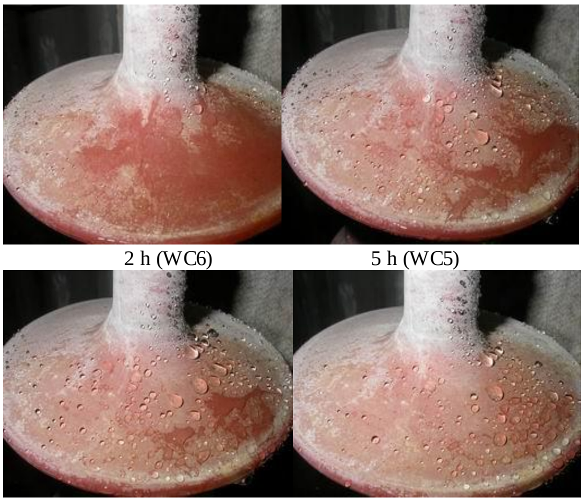

Figure 6. Hydrophobicity change due to transfer property in 24 h (in the UV chamber) at the 56th cycle of the test. First shed of grounded end, B_L in Test 1-AC [6]

Figure 7 gives the hydrophobicity status curve during 24 hours at different test stage. The initial WC values (0 hour's WC value) were not measured and generally judged as WC7 because the hydrophobicity lost significantly in the fog chamber. Meanwhile, no measurement of hydrophobicity prevented the pollution being poured off unnecessarily. In the first 1000 h, insulators recover to WC2 ~ WC3 just need less than 6 hours, and to WC1 ~ WC2 need less than 9 hours (24 cycle = 48 days = 1150 h). It takes more time for insulators to recover to a better hydrophobicity status, such as to WC2. However, it could still recover to WC3 after 5000 hours test due to the superior hydrophobicity performance.

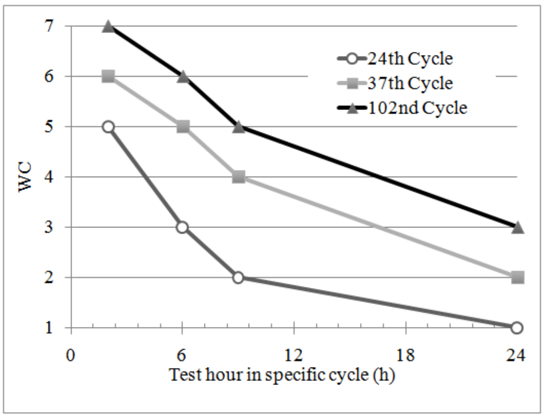

Figure 7. Hydrophobicity changes in different cycles. It takes more time for the insulator to recover to a better hydrophobicity status, such as WC2. Wettability class was measured at first sheds of grounded end of sample insulator B_L in Test 1-AC [6].

Hydrophobicity reduction is also obvious in the fog chamber, and significant loss of hydrophobicity commonly needs less than 10 hours [6]. For all test insulators, hydrophobicity loses in the fog chamber and recovers in the UV chamber. Thus, the hydrophobicity status seems to be "alternating". However, this kind of "hydrophobicity alternating" is also happening to SR insulators in the field with the weather changing.

With the test time increasing, hydrophobicity of SR insulators becomes poorer and the process becomes more quickly if the test SR insulators are of poor hydrophobicity performance, which will suffer severe tracking and erosion in the later cycles of 5000 h test. Thus, hydrophobicity performance of test insulators could be ranked according to the test results.

Therefore, the hydrophobicity change on SR insulators has been successfully simulated and repeated by the new 5000 h multi-stress test procedure.

6 CONCLUSION

1. Hydrophobicity change is a very important process happening on SR insulators in high pollution areas with high NSDD. 5000 h multi-stress test should simulate hydrophobicity change process with a consideration of specific environment condition.

2. An improved 5000 h multi-stress test procedure, the THU 5000 h test, is proposed. Improvements have been made as follows: (1) To replace the salt fog with mixed contaminant fog including both soluble (NaCl) and non-soluble pollutant (kieselguhr), (2) To provide sufficient time for significant reduction of hydrophobicity and discharge activities in fog period and for fully hydrophobicity transfer in UV period.

3. 31 SR insulators of different compositions had been tested in five THU 5000 h tests under the new procedure. THU procedure has simulated the high pollution with high NSDD successfully, and reproduced hydrophobicity change process on SR insulators satisfactorily.

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