Evaluation Method of Insulation System for Wind Turbine Generator Based on Accelerated Multi-factor Ageing Test

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Abstract- **With the rapid increasing of the amount and capacity of wind power generation worldwide, the operation reliability of wind turbine generator (WTG) became more and more important due to its high repairing cost. In this paper, a procedure based on the accelerated multi-factor aging test was firstly established for evaluating the insulation system of offshore WTG. The specimens for modeling the stator insulation system of megawatt class WTG were prepared. The repetitive impulse voltage, temperature change, steady damp heat, salt mist and vibration, were applied, in turn, to the specimens for periodical ageing test, and at least 5 periods of ageing tests were conducted. At two intervals of each period, some non-destructive diagnoses have been carried out to monitor the change. The relationships of the dielectric properties of insulation system with the aged time have been obtained. The residual breakdown voltages of specimen were measured, and the micro-structures of insulating material were also analyzed. The testing results show that the environmental factors play an important role in the deterioration of insulation materials, and the cooperative effect would produce between the environmental factors. Finally two primordial evaluation methods of insulation system for WTG available for the offshore and onshore environments based on accelerated multi-factor ageing test are proposed.**

Keywords: **Wind turbine generator, Stator insulation system, Ageing, Multi-factor**

I. INTRODUCTION

With the decrease of coal, oil and gas sources, energy problem becomes more and more important. Wind power has now established itself as a mainstream electricity generation source, and will play a central role in an increasing number of countries' immediate and longer term energy plans. The global source of wind energy available is about 20 TW, which is 10 times as much as hydro energy available on the earth [1].

The Global Wind Energy Council and Greenpeace International presented the Global Wind Energy Outlook for 2012, and showed that after 15 years of average cumulative growth rates of about 28%, the global total has increased by more than 40 times over that same period. The Global Wind Energy Council's 2012 market statistics show the new global total at the end of 2012 was 282.5 GW.

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With the fast increasing of the amount and capacity of wind power generation in the world, the operation reliability of WTG became more and more important due to its high repairing cost. According to the statistics data [2], the annual failure rate of WTG in service has reached 0.05~0.1, especially for those of exceeded 2MW. The insulation system of WTG would be subject to the repetitive impulse voltage stress generally when the converter was used, thermal and mechanical stress when the temperature changed widely due to frequently operation, and other multi-environmental factors like as high humidity and heavy salt fog specially for offshore [3], and all these factors will accelerate aging process and decrease the operation reliability of WTG. Li [4] did experimental research on insulation system used in direct-drive wind turbines with different impregnating resin and magnet wires. Chen [5] carried out salt mist and thermal cycling tests to wind generator coils. Ding [6] and Liu [7] investigated the aging characteristics of stator insulation of wind turbine generator under repetitive impulse voltage.

The studies on evaluation method of insulation system of WTG, especially accelerated multi-factor aging have been rarely reported. So it is necessary to carry out the accelerated multi-factor aging test on insulation system of WTG.

In this paper, a test procedure based on the accelerated multi-factor aging was established for evaluating the effect of multi-factor on insulation system of WTG. The multi-factors of repetitive impulse voltage, temperature change, steady damp heat, salt mist and mechanical vibration will be applied, in turn, to the specimens for at least 5 periods of accelerated ageing tests. Finally, two primordial evaluation methods available for the onshore and offshore WTG are proposed.

II. EXPERIMENTAL METHOD

A. Specimens

The specimens of winding bar with iron core slot and double-layer winding wire were prepared for modeling the stator insulation system of 2MW WTG, as shown in Fig. 1. The length of iron core slot of specimen was 200mm, and the end-winding extended more than 100mm from the slot end. The thickness of stator main insulation, corresponding to the rated voltage of 0.69kV, was 0.8mm. The test voltage was applied between the top winding wire and the iron core slot. Total eight specimens are prepared, five of them for accelerated multi-factor aging test and the rest as comparison or reference specimens.

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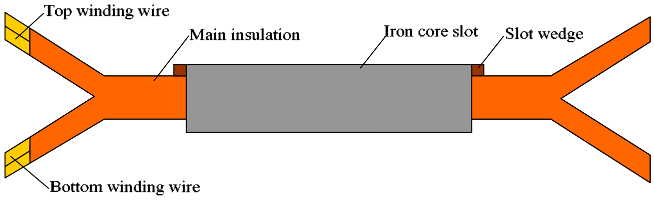


Fig. 1 Schematic diagram of specimen for modeling stator insulation

B. Test setup

The repetitive impulse voltage generator, with the repetition rate or frequency of 5~20kHz, bipolarity, peak of up to 10kV and peak-peak rise time of 0.8μs, and the oven with the temperature of up to 200°C were prepared for combined electrical and thermal stress test.

Programmable environmental test chamber with adjustable temperature range of -70°C~150°C and relative humidity range of 20%~98%, salt spray test chamber with salt mist settlement of 1~2mL/(80cm^2·h), mechanical vibrator with the frequency range of 1~600Hz and amplitude range of 0~5mm, were prepared for the tests of temperature change, steady damp heat, continuous salt mist and mechanical vibration.

C. Test procedure and conditions

The test procedure was established for evaluating the effect of multi-factor aging on insulation system for WTG, as shown in Fig. 2. The test was carried out for at least 5 periods. In each period it consisted of 200h combined electrical and thermal ageing, 10 cycles of change of temperature, 96h steady damp heat, 48h continuous salt mist and 1.5h mechanical vibration.

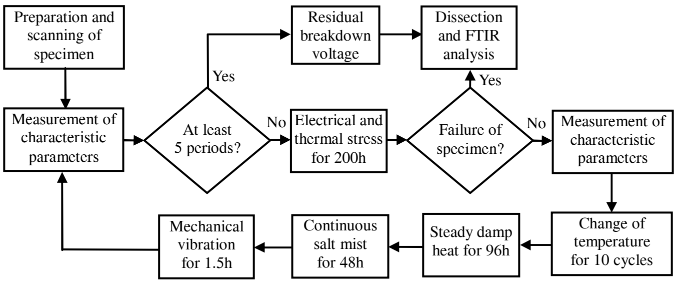


Fig. 2 Procedure of multi-factor aging test

The selected test conditions were listed as following:

1) *Combined electrical/thermal stress:* The repetitive impulse voltage with the repetition rate or frequency of 10kHz, peak of 4.5kV and rise rate of more than 2000V/μs was applied to the specimens. The specimens exposed at temperature of 120°C.
2) *Temperature change factor:* The highest and lowest test temperatures were selected as 120°C and -30°C, respectively, and the maintained time in each temperature was 3h. The converting time from highest temperature to lowest temperature was about 2h, and conversely was about 1h.
3) *Steady damp heat factor:* The steady relative humidity of 93% and temperature of 40°C were maintained in the test chamber.
4) *Continuous salt mist factor:* Salt mist settlement was controlled at about 1.3mL/(80cm^2·h) in the salt spray test chamber.
5) *Mechanical vibration stress:* The mechanical vibration stress with the frequency of 100Hz and amplitude of 0.2mm was applied.

At two intervals of each testing period, some of non-destructive diagnoses or measurements were carried out to monitor the change of ageing characteristic or dielectric parameter of specimens, including dissipation factor, insulation resistance, partial discharge inception voltage and corona inception voltage. After aging test, ac residual breakdown voltages were measured in air ambient at room temperature, and the destructive contrast tests, infrared (IR) analysis and micro-structure observation, between aged and un-aged specimens were conducted.

III. RESULT AND ANALYSIS

The accelerated multi-factor aging test of specimens has been conducted for 5 periods with the cumulative time of more than 2000h according to the established test procedure. At each period, the characteristic parameters of aged specimens are measured for twice, one after the combined electrical and thermal ageing, and another after a full period. Some of the testing results are shown as following.

A. Dissipation factors

The dissipation factors of specimens were measured at room temperature under power frequency (50Hz) ac voltage of 2kV. The relationship between the dissipation factors and the aging period is shown in Fig. 3.

From Fig. 3, it can be seen that the dissipation factors of specimens increase with the multi-factor aging period and then after each combined thermal and electrical stress the dissipation factors of specimens fall off again. The dissipation factors of specimens behave a trend of increasing with the aging period, and the maximum dissipation factor of specimen is about 0.16.

From the changing rule of dissipation factors, it can be found that environmental factors, especially the moisture, have a significant impact on the insulating material of specimens, then the following thermal stress could dry or remove out the moisture and recovery the dielectric properties of insulating material.

B. Insulation resistances

The insulation resistances of specimens were measured at room temperature under dc voltage of 1kV. The relationship between the insulation resistance and the aging period is shown in Fig. 4.

From Fig. 4, it can be seen that the insulation resistances of specimens increase after the combined thermal and electrical stress and decrease after the environmental factors in each period. On the whole, the insulation resistances of specimens increase primarily with ageing period and then decrease lastly with ageing period.

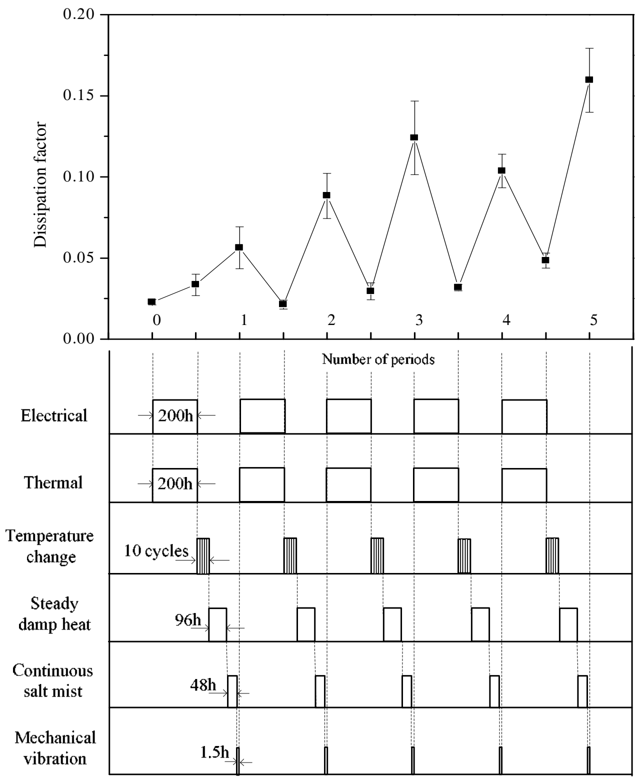


Fig. 3 Dissipation factors of the specimens vs aging period

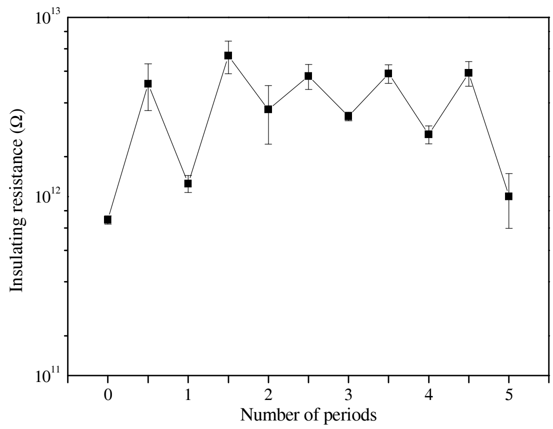


Fig. 4 Insulation resistances of specimens vs aging period

C. Partial discharge inception voltages

The partial discharge inception voltages were measured at room temperature under 50Hz ac voltage, and the corona inception voltages were measured at room temperature under 10kHz repetitive impulse voltage. The relationships of partial discharge and corona inception voltages with the aging period are shown in Fig. 5.

From Fig. 5, it can be seen that the partial discharge inception voltages fluctuate between 2kV and 3kV with the aging period. The corona inception voltage has a trend of averaged 40% drop rate, from 5.3kV peak to 2.6kV peak, with the aging period.

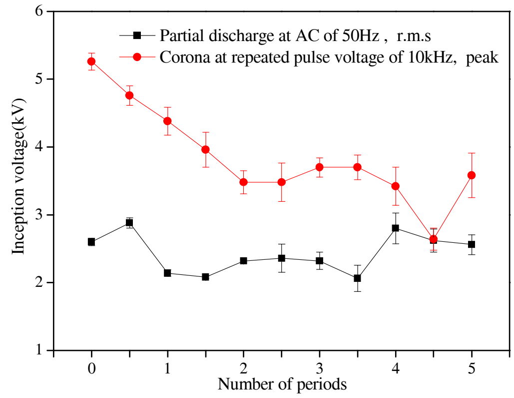


Fig. 5 Discharge inception voltages vs aging period

D. Contrasts of breakdown voltage

The ac breakdown voltages of were measured in air ambient. The comparison of breakdown voltages for aged specimens with that for un-aged specimens is shown in Tab. I.

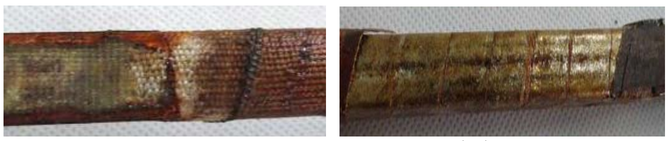
TAB. I BREAKDOWN VOLTAGES OF AGED & UN-AGED SPECIMENS

Specimens	Un-aged			Aged		
Breakdown voltage	45kV	46kV	43kV	26kV	32kV	22kV
Average	44.7kV			26.7kV		

From Tab.I, it can be obviously found that after 5 periods of accelerated multi-factor aging, the breakdown voltages of specimens decreased by an average drop rate of 40%, from the average 44.7kV to 26.7kV,.

E. Appearance features

Fig. 6 shows the appearance pictures of main insulations near the slot end and within the slot, respectively, after the iron core removed.



(a) Near slot end (b) within the slot

Fig. 6 Photographs of main insulation appearances

From Fig. 6, it can be found that, after aging test, the color of insulation surface changed to puce from original pale yellow, the partial insulating varnish near the slot end decomposed and the mica-glass tape exposed apparently.

And more, surface of iron core slot was terribly rusty. It meant that because of the mismatched thermal expansion coefficient, the generated micro-cracks or delaminating resulted in the salt solution or moisture permeating into the interfaces and eroding the inner surface of iron slot.

F. Infrared spectrum analysis

The Fourier transform IR spectrum analyses of aged and un-aged specimens were conducted to observe the chemical change of insulating materials. The compared IR spectrums of insulating material near the slot end are shown in Fig. 7.

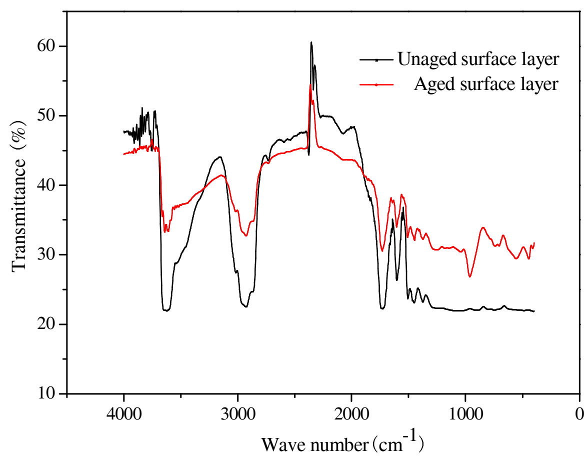


Fig. 7 IR spectrums of insulating materials near slot end

From Fig. 7, it can be seen that there are two absorption peaks of 2953cm^{-1}(-CH_3) and 3504cm^{-1}(-OH) in the spectrum of un-aged insulating materials. For the aged insulating materials, the absorption strength of these two peaks has an obvious reduction compared with that of un-aged insulating materials, which shows the decomposition of surface layers of insulating material, caused by multi-factor ageing.

VI. Evaluation Methods

Until now, no normative or evaluating method available for insulation system of WTG was issued. Based on the above and previous works of authors [6-7] and when the converter was used, two typical evaluation method of stator insulation system of WTG available for the offshore and onshore environments, respectively, are proposed.

A. Evaluation method available for onshore

The insulation system of WTG served in the onshore or cold case will be subject to the repetitive impulse voltage stress generally when the converter is used, thermal and mechanical stress when the temperature changes widely due to frequently change of operating state, and humidity and mechanical vibration of environmental factors. Based on the accelerated multi-factor aging, the insulation system of onshore WTG can be evaluated by following test conditions:

1) *Combined electrical/thermal stress:* The test voltage level of $3U_{pm}$ or $2.5U_{pm}$ will be applied to the modeling specimen for cumulative ageing of 1000h or 5000h, respectively and U_{pm} is maximum repetitive impulse voltage peak generated on the insulation system of WTG. Test temperature is selected as 100°C (or 120°C).
2) *Temperature change factor:* The highest and lowest test temperatures shall be selected as 120°C and -30°C (or -40°C), respectively, and the maintained time in each temperature was 3h. The temperature converting rate can be 1°C/min (or 3°C/min). The cumulative changes of temperature are at least 50 cycles.
3) *Damp heat factor:* The relative humidity of 93% and ambient temperature of 40°C in the test chamber shall be maintained for the duration of at least 240h cumulatively.
4) *Mechanical vibration stress:* The mechanical vibration stress with the frequency of 100Hz and amplitude of 0.2mm is applied to specimen at least 6h cumulatively.

B. Evaluating method available for offshore

The insulation system of WTG served in the offshore or near shore case will be subject to the repetitive impulse voltage stress, thermal stress, and humidity and salt fog of environmental factors. In this case, the extra salt mist will be considered as an ageing factor. Salt mist settlement rate of 1.0mL/(80cm^2·h) and ambient temperature of 40°C in the salt spray test chamber can be maintained at least 240h.

In above two evaluation methods, ageing characteristic parameters including the dissipation factor, insulation resistance, polarization index, partial discharge inception voltage and so on can be diagnosed to monitor the change during the each ageing period or cycle. The ac residual breakdown voltage will be measured if no specimens are failure during the ageing test. The dissection and microscopic analysis or observation of insulating materials are necessary.

V. Conclusion

The specimens have endured, in turn, the combined thermal and electrical stress, temperature change, damp heat, salt mist and mechanical vibration ageing for five periods. The environmental factors, especially the moisture and salt mist, have a significant impact on the dielectric properties of insulating material of specimen. Then thermal stress during the combined electrical/thermal stress ageing could dry or remove out of the absorbed moistures and partially recover the dielectric properties of insulating material. The insulating materials of stator near the slot end are damaged more serious than that within the slot. The mismatched thermal expansion coefficient result in the micro-cracks or delaminating phenomena occurred. Two proposed evaluation methods of insulation system based on accelerated multi-factor ageing are available for the offshore and onshore WTG, respectively.

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