Experimental Study on Electrical Evaluation of Rotor Insulation System of DFIG for Wind Power Generations

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Abstract – **The failure rate of doubly-fed induction generators (DFIG) for wind turbine generations was relatively higher than that of direct-driven generators, according to statistical data from some wind power industries. The rotor insulation was a relatively weak part of the insulation system for DFIG because it was normally subjected to a PWM impulse voltage during the long-time operation. In this paper, this research focuses on the electrical evaluation based on accelerated electrical aging tests for rotor insulation of DFIG. The accelerated aging tests under the bipolar repetitive impulse with the voltage of 5.3, 6.4 and 7.3 kV were carried out. Some of non-destructive characteristic parameters, polarization and depolarization current were measured periodically during the each interval of cycled aging periods. In addition, the appearance features of the insulation layers at different distances away from the conductor on the aged or failure specimen were observed by microscope. The feasibility and effectiveness of these non-destructive characteristic parameters on the aging status assessments of the rotor insulation system of DFIG are analyzed. The failure times or lifetime of the electrical aging from some specimens were got. Finally, the appropriate selections of the applied voltage levels for the accelerated aging tests were also discussed.**

Keywords: doubly-fed induction generator (DFIG), rotor insulation, electrical aging, repetitive impulse voltage, polarization and depolarization current (PDC)

I. Introduction

Renewable energy sources have long since been recognized as environmental-friendly, sustainable and climate-neutral solution for future power system. With the increasing penetration of renewable energy sources, particularly wind power has now established itself as a mainstream electricity generation source and play an important role in future energy plans [1]. The recent rapid growth in wind power generation indicates that wind power should be seen as one of the main clean renewable energy sources for electricity generation in the global [2]. Increasing wind power generation quantity needs obviously reliable insulation property of power equipment. Since over 70% of the installed turbines utilize wound rotor induction machines(referred to as double-fed induction generators DFIG) [3], DFIG is deemed to be one of the most critical components of wind power systems and its performance directly influences the stability and reliability of wind power generation.

In the actual service conditions, the insulation system of DFIG is stressed by electrical, mechanical and thermal loads during the whole lifetime, which leads to the gradual deterioration of the insulation performance and affects the life of the generator [4]. All these factors will accelerate aging process and affect the operation reliability of DFIG. The rotor insulation was a relatively weak part of the insulation system for DFIG because it was normally subjected to a PWM impulse voltage during the long-time operation [5]. Therefore, it has great significance to evaluate the aging status of rotor insulation accurately.

In this paper, the accelerated electrical aging tests under three voltage levels of bipolar repetitive impulse were carried out and some of non-destructive characteristic parameters were measured periodically, which were similiar to the previous works [6-7]. An electrical diagnostic method known as polarization and depolarization current (PDC) measurement was conducted. A test procedure based on the accelerated electrical aging was established for evaluating the effect on rotor insulation system of DFIG.

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II. Experimental Method

A. Specimens

The specimens of winding bar with iron core slot and winding wire were prepared for modeling the rotor insulation system of 2.5 MW DFIG , as shown in Fig.1. The length of iron core slot of specimen was 80 mm, and the end-winding extended more than 145 mm from the slot end. The test voltage was applied between the top winding wire and the iron core slot. Most of specimens are prepared for accelerated electrical aging tests and the rest as comparison or reference specimens.

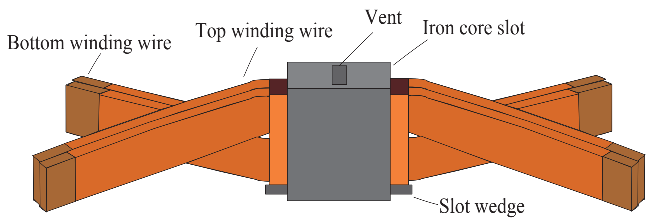


Figure 1. Schematic diagram of specimen for modeling rotor insulation

B. Test setup

The bipolar repetitive impulse voltage generator, with the capacities of repetitive rate of 2 kHz, the peak of 10 kV and the rise time within 0.8 μs, and the test oven with the temperature up to 200 °C were prepared for electrically accelerated aging test.

The aging characteristics or dielectric parameters of the model specimens were diagnosed or measured respectively through Schering bridge, high resistance meter, partial discharge detection device, power frequency test transformer and the others. The microstructure analysis of insulating material was taken by microscope.

C. Test conditions

The selected test conditions were described as following:

Electrical stress: The electrical stress for accelerated aging tests was based on the maximum repetitive impulse voltage measured on the rotor terminals in actual 2.5 MW DFIG in the field, as shown in Fig.2. So the maximum phase to ground (or iron core) repetitive impulse voltage of 1.35 kV peak (or 2.7 kV peak to peak), U_{pm}, was defined as a reference of the repetitive impulse voltage. The specimens were applied at three repetitive impulse voltage levels (level I, II and III), which were respectively 3.9, 4.7 and 5.4 times of the U_{pm}. The testing repetitive rate or frequency of bipolar repetitive impulse voltage was selected as 2 kHz, same as actual PWM repetition rate of DFIG.

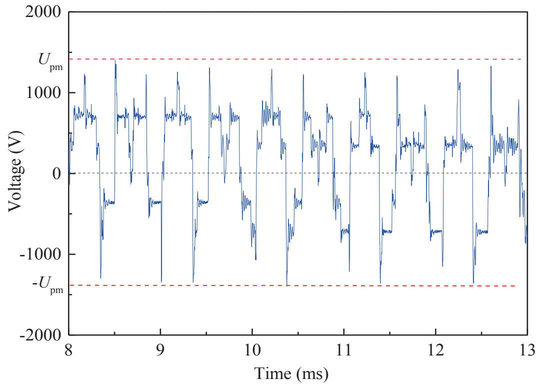


Figure 2. Waveform of phase-to-ground voltage in 2.5MW DFIG

The level of the repetitive impulse voltages, accumulated aging time and diagnosis interval for the three levels are shown in Table I. In addition, the five specimens in each test voltage level for electrical aging tests were prepared, which were named group I, group II and group III, respectively, corresponding to three test voltage levels from level I to level III.

TABLE I. LEVELS OF REPETITIVE IMPULSE VOLTAGE FOR THREE LEVELS

Level	*Voltage (peak)*	*Expected aging time*	*Diagnosis interval*
I	±5.3kV	1200 hrs	500 hrs
II	±6.4kV	500 hrs	100 hrs
III	±7.3kV	100 hrs	100 hrs

Thermal stress: In the level I, II and III, the specimens exposed at a temperature of 180 °C in combination with electrical stress during the aging tests.

III. RESULT AND ANALYSIS

According to the above test process, the measurements of some characteristic parameters of aged and un-aged specimens have been carried out. Also the visible and microscopic physical features for aged specimens have been analyzed.

Under the test voltage of level I, three of five specimens with group I failed within the maximum accumulated test time of 1500 hrs. One failed specimen lasted the electrical aging for about 1220 hrs and the other two lasted for 770 hrs (shortest aging time) under the repetitive impulse voltage of ±5.3 kV. The rest two samples exceeded 1500 hrs (longest aging time, and beyond the expected time of 1200 hrs). The average failure time of five specimens exceeded 1150 hrs. For level II, all of the specimens failed, and the longest time to failure was 730 hrs under the repetitive impulse voltage of ±6.4 kV. The shortest time to failure was 130 hrs and the average failure time of five specimens are about 400 hrs. The samples of group III had reached the expected electrical aging time of 100 hrs as presented in Table I, and not failed.

During the aging duration, each diagnostic interval for aging characteristics or dielectric parameters of the specimens were carried out before the electrical failure occurred. The diagnosis results are presented as follows.

A. Dissipation factors

The dissipation factors of specimens were measured at room temperature under power frequency (50 Hz) AC voltage of 1 kV. For group I and group III, the relationship between the dissipation factors and the aging time are shown in Table II and Table III, respectively. For group II, the relationship between the dissipation factors and the aging time is shown in Fig.3.

From Table II, it can be seen that the dissipation factors of group I increased first and then gradually reduced. Table III shows that the dissipation factor of specimen changed a little due to the short aging process. It is found that the long-term combined electrical and thermal stress can cause increase in the dissipation factor of specimens from 0.01 to 0.06 with the increase of aging time as seen in Fig.3. Comparing with group I, it can be found that the higher voltage level at a longer aging duration have a significant impact on the insulating material of specimens.

TABLE II. DISSIPATION FACTORS OF GROUP I

Aging time	**Sample Number**					
	13#	***15#***	***16#***	***17#***	***18#***	***Average***
0	0.0086	0.0104	0.0107	0.0093	0.0103	0.0099
500 hrs	0.0134	0.0149	0.0112	0.0097	0.0210	0.0140
1000 hrs	0.0610	/	0.0257	/	0.0358	0.0408
1500 hrs	/	/	0.0400	/	0.0403	0.0402

TABLE III. DISSIPATION FACTORS OF GROUP III

Aging time	**Sample Number**					
	1#	***2#***	***3#***	***4#***	***5#***	***Average***
0	0.0142	0.0113	0.0087	0.0113	0.0097	0.0110
100 hrs	0.0041	0.0058	0.0047	0.0128	0.0085	0.0072

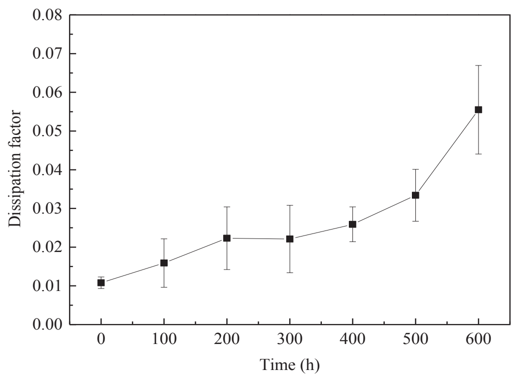


Figure 3. Dissipation factors of the group II vs aging time

B. Insulation resistances

The insulation resistances of specimens were measured at room temperature under DC voltage of 1 kV. The relationship between the insulation resistance of specimens and the aging time are shown in Table IV, Table V and Fig.4.

TABLE IV. Insulation Resistance Of Group I

Aging time	Insulation resistance (×10[12] Ω)					
	13#	*15#*	*16#*	*17#*	*18#*	*Average*
0	11.0	13.0	19.0	14.0	15.0	14.4
500 hrs	1.25	1.00	3.20	1.20	1.50	1.63
1000 hrs	1.15	/	2.40	/	1.25	1.60
1500 hrs	/	/	1.20	/	1.00	1.10

TABLE V. Insulation Resistance Of Group III

Aging time	Insulation resistance (×10[12] Ω)					
	1#	*2#*	*3#*	*4#*	*5#*	*Average*
0	12.0	12.0	13.0	11.0	15.0	12.6
100 hrs	2.80	2.20	2.90	2.10	1.70	2.34

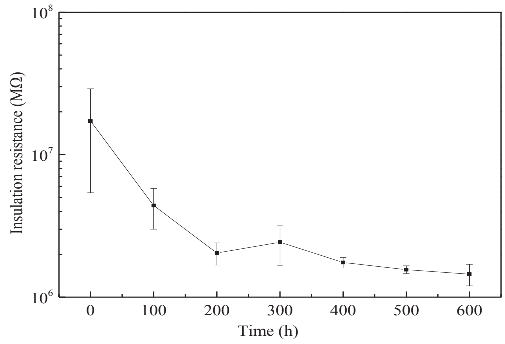


Figure 4. Insulation resistance of the group II vs aging time

From Table IV and Fig.4, it can be seen that the insulation resistances of specimens decrease with aging time in general. The Table V illustrates that in the initial stage of the aging tests, the insulation resistance increases with the application of the combined electrical and thermal stresses, which was attributed to the effect of the thermal cure. The insulation resistances of the specimens are sensitive to the degradation of the insulating materials during aging tests.

C. Partial discharge inception voltages

The partial discharge inception voltages (PDIVs) were measured at room temperature under 50 Hz AC voltage, and the corona inception voltages (CIVs) were measured at room temperature under 2 kHz repetitive impulse voltage. The relationships of PDIVs and CIVs of group II specimens with the aging time are shown in Fig.5.

The measured results indicate that the PDIV of the group II specimens has decreased from 2.1 to 1.2 kV (r.m.s) and has a descent rate of 43%.The CIV at AC of 50 Hz has a trend of averaged 34% drop rate, from 2.45 to 1.61 kV (r.m.s). The CIV at repetitive impulse voltage of 2 kHz has a trend of averaged 41% drop rate, from 3.62 to 2.14 kV peak with the aging time.

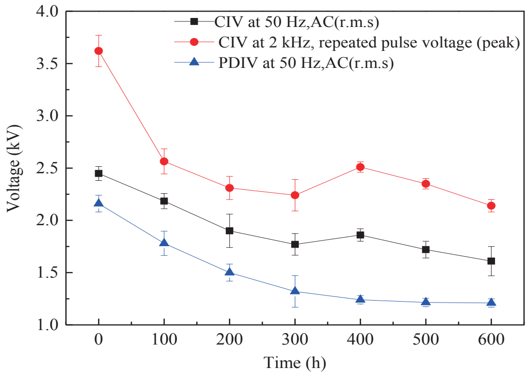


Figure 5. Inception voltages of group II specimens vs aging time

D. PDC

The polarization current measurement was performed by applying a DC voltage step on the dielectric materials, and depolarization current was measured by removing the DC voltage source incorporating with a switch which turn on to short circuit at the under tested objects [8].

The measured PDCs of modeling rotor insulation specimens after different aging time are shown in Fig.6 and Fig.7, respectively. With the increase of aging time, the amplitude of all the PDCs increased. By analyzing the variation characteristics of the PDC after different aging time, it can be found that the PDC curves move above to the left with the increase of aging time. Comparing with the un-aged specimen, the depolarization current curves of aged specimens with different voltage levels and aging durations are very close to in the later stage of testing.

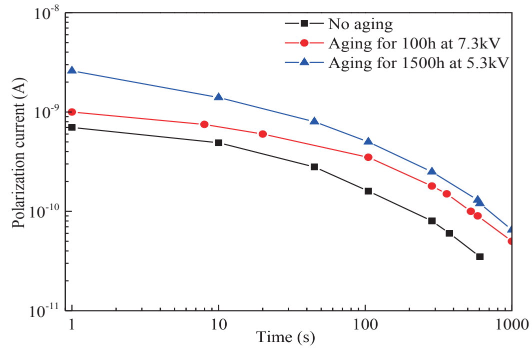


Figure 6. Polarization current of specimens under different aging time

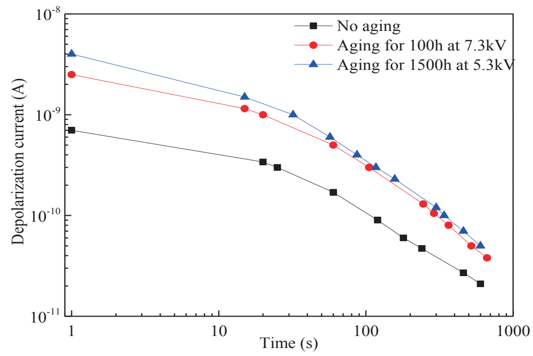


Figure 7. Depolarization current of specimens under different aging time

E. Lifetime

By utilizing two parameter of Weibull distribution [3] to evaluate the experimental data, the corresponding failure time with the failure probability of 63.2% is chosen to be the failure time of insulation. Under the temperature of 180 ºC, the lifetime of specimen insulation with the applied 2 kHz repetitive impulse voltage (peak) is shown as Fig.8.

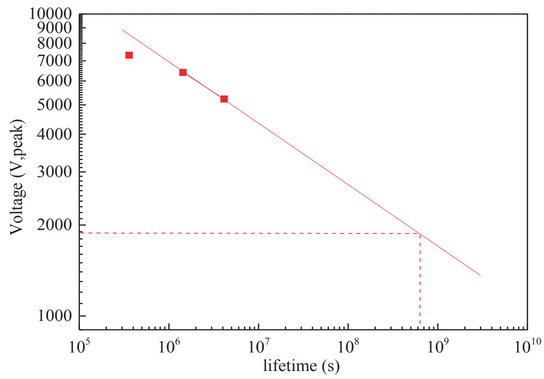
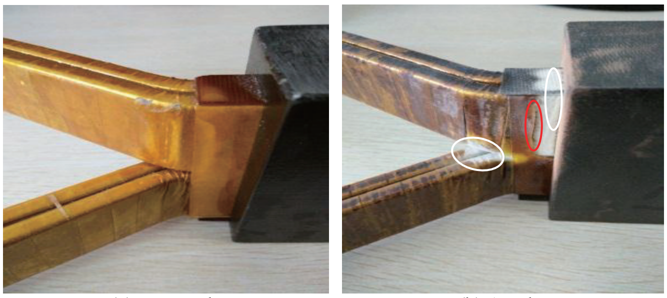


Figure 8. Relationship between repetitive impulse voltage and lifetime

According to the extrapolation curve of repetitive impulse voltage with the lifetime, the expected lifetime of the insulation system have been analyzed. The remaining safety factor was usually taken as 1.2 to 1.5. In this test, it was set to 1.4. It shows that under the voltage level of 1.4 U_{pm} (about 1.89 kV peak), the electrical lifetime of specimen can reach to 20 years, as marked in Fig.8, which could be satisfactory to the industry application in general.

F. Appearance features

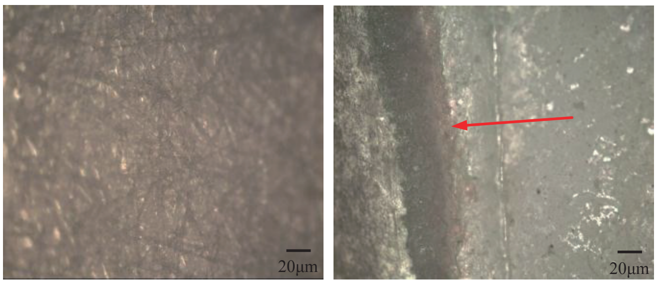
Fig.9 demonstrates the pictures taken from the 1220 hrs aged group I specimen and the un-aged one, respectively. After aging tests, the insulating layer of specimens changed from bright yellow to dark grey. The white glass fibers have been exposed and accompanied with some powders, as marked in Fig.9 (b) with the white circle. In addition, the insulating layer of specimens near slot end emerged cracks, as marked in Fig.9 (b) with the red circle.



(a) Un-aged (b) Aged

Figure 9. Appearance of un-aged and aged specimen

Fig.10 shows the microscopic pictures of the main insulation near to the slot end of the un-aged and aged specimens. It is found that after the aging process the color of the insulating material became white from the light yellow. The insulating material of the specimen near to the slot edge occurred the obvious cracks and was damaged, as marked in Fig.10 (b) with an arrow. The partial discharge or corona can make the specimen's insulation surface corrode and lead to degradation of varnish component in composite insulation.



(a) Un-aged (b) Aged

Figure 10. Microscopic photos of insulation surface (×40)

Fig.11 shows the dissection picture of the failed specimen during the electrical aging test. From Fig.11, it can be seen that the insulation of specimen sustained serious erosion and breakdown point turned black near to the crook. It meant that because of the severe field distortion around the crook, the generated micro-cracks or high field intensity resulted in the partial discharge and became a relatively weak part of the insulation system.

Figure 11. Photographs of failed main insulation appearances

IV. CONCLUSION

Based on the results of electrically accelerated aging tests under repetitive impulse voltage with the model rotor insulation of megawatt-class DFIG, some conclusions can be made as following:

(1) In the electrically accelerated aging tests, three voltage levels of bipolar repetitive impulse were selected, which are higher than the PDIV and make the same failure mechanism within the range of the applied test voltages. The partial discharge was seen as one of the key aging factors.

(2) The visible corona under the repetitive impulse voltage with a short rise time mainly occurred on the surface of end-winding near to the slot end edge during the electrical aging tests. So it is important to enhance the winding insulation on this location.

(3) The polarization and depolarization current moves to the increasing trend with the aging time. In addition, the depolarization current curves of different aging time and level are very close to in the later stage of testing for aged specimens.

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