Development of Stator Winding Insulation for New-Type 4-Pole Turbine Generators

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Abstract

We recently developed and supplied 4-pole turbine generators with a newly adopted the salient solid poles design. This development is for the increase of power and for higher efficiency.

This 4-pole turbine generator is for 75MVA capacity model which is our largest production turbine generator model. In order to obtain a further compact design and higher efficiency, we developed a stator winding insulation system.

By adopting thin materials and field grading, we reduced the insulation thickness of stator coils by more than 10% compared with our conventional model. Further, we developed a new insulation system that ensures a useful life of 20 years or more according to the IEEE 1553/IEC 60034 evaluation. In addition, the stress caused by the change in the structure of the stator end winding was evaluated, and we confirmed sufficient reliability.

1 Preface

We recently developed a 4-pole turbine generator featuring the newly adopted salient solid poles design. The purposes are to increase the power and obtain the higher efficiency(1). In order to realize the compact design and higher efficiency, we had to decrease the thickness of insulation used for the protection of coils. Insulation is an important factor that directly affects the durability of electrical equipment.

In the case where stator winding insulation is increased to improve durability, the space factor in the slot is lowered. This leads to an increase in the stator core size and deterioration of the efficiency.

This paper introduces the stator winding insulation systems. These are specifically for the turbine generator models with the rated voltages of 6kV, 11kV, and 13kV. Such insulation systems were developed for the 75MVA class 4-pole turbine generator model.

2 Stator Winding Insulation

2.1 Outline of the Stator Winding Insulation System

Fig. 1 shows 75MVA class stator coils. We put these coils into the model core made with iron. After

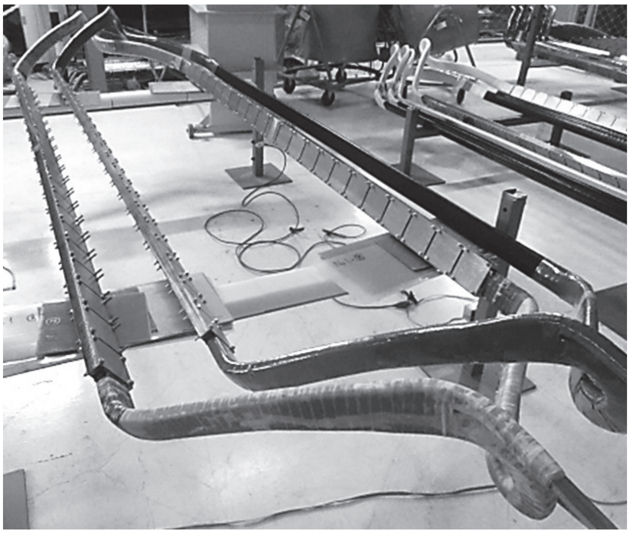


Fig. 1 75MVA Class Stator Coils

This shows the stator coils for 75MVA class 4-pole turbine generator. These are our largest coils.

degassing the coils in the vacuum tank, we fill them with resin and impregnate by pressurizing. In the last step we cure the impregnated coils, the manufactured medium-voltage stator model coil. [This coil impregnating process is called Vacuum Pressure Impregnated (VPI) system.]

Fig. 2 shows a schematic cross-sectional view

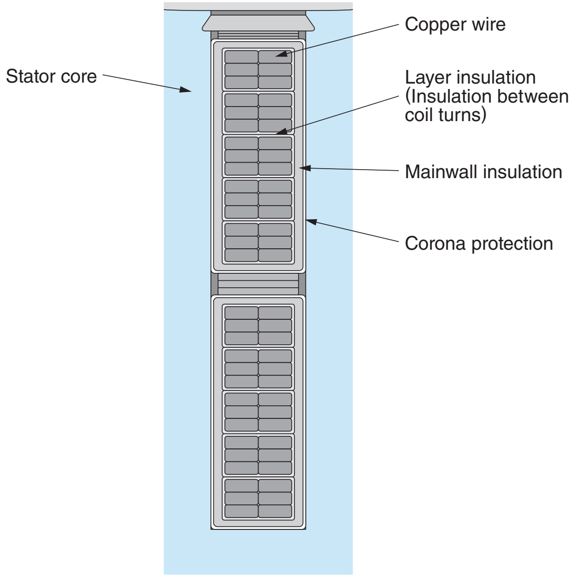


Fig. 2 Schematic Cross-Sectional View of Coil in Stator Slot

A cross-section of coils inserted in the stator slots is shown. The winding insulation is composed mainly of layer insulation, mainwall insulation, and the corona protection.

of the coil in the stator slot. As shown in the diagram, coil insulation consists of the following elements:

(1) Layer insulation (Insulation between coil turns)

(2) Mainwall insulation (Coil's ground insulation part)

(3) Corona protection (Prevention of discharges between iron cores)

Of these elements, the mainwall that uses integrated mica tape (or mica paper tape) with glass cloth as the base, is wound at a predetermined number of times.

For a compact design and higher efficiency, a glass cloth that is thinner and superior in mechanical strength was selected as the tape base material. By taping this new tape more than before, the main insulating layer increased in density, and the main insulating layer with a high field and strength was formed, while the thickness of the entire insulating layer was reduced. When the entire thickness is reduced, however, the field grading to the field concentration portion is required more than before. For this reason, field analysis and prototype verification were performed for components other than the main insulation, and appropriate field grading materials were applied to the field concentration part. Fig. 3 shows the analysis of the internal field of the stator core.

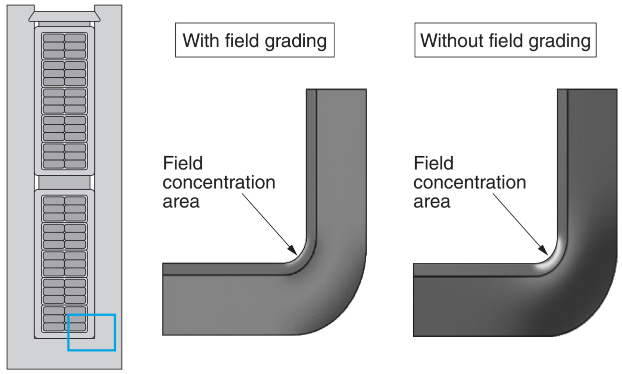


Fig. 3 Analysis of Internal Field of Stator Core

The result of field analysis on the internal stator core is shown. By optimizing the insulation system, the field was relaxed to the field concentration part.

2.2 Evaluation of Stator Insulation Durability

2.2.1 Testing Method

The newly developed insulation system is tested the "electrical aging test ('V-t test' hereafter) "and the "thermal cycling test" to evaluate insulation endurance. The V-t test was carried out in accordance with IEC 60034-18-34. Further, to keep up with an international trend for evaluation, another evaluation was carried out in accordance with the IEEE 1553 Standard stipulated by the Institute of Electrical and Electronic Engineers. The thermal cycling test was commonly performed in conformity to IEC 60034-18-34. After this testing, evaluation of aging was made by the electrical aging test according to IEEE 1553. Table 1 shows aging evaluation standards (applicable standards).

2.2.2 Voltage Endurance Test (V-t Test)

Fig. 4 shows a V-t test result on coils of rated voltage class at 11kV. According to this test result, we have concluded that the insulation endurance can last for more than 20 years at the rated voltage of 11.5kV. We have also made similar testing on coils with the rated voltage classes at 6kV and 13kV.

2.2.3 Thermal Cycling Test

The VPI system assures outstanding insulation diagnostic parameters as described previously because the stator core and coils strongly adhere to each other. Since materials with different linear expansion coefficients are made to stick to each other, however, stresses due to thermal stresses become substantial. Fig. 5 shows the view of thermal cycling test and Fig. 6 shows the temperature conditions for the thermal cycling test. In order to verify the thermal endurance property, a voltage endurance test based on IEEE 1553 in Table 1 was carried out

Table 1 **Aging Evaluation Standards for Stator Coil Insulation**

A list of standards relating to endurance evaluation test is shown. This is needed during the development of stator coil insulation.

Standards	Test items	Testing specifications
IEC 60034-18-32	Electrical aging test (V-t test)	Product life is estimated based on the results under below 3 conditions. (1) Insulation breakdown time: about 100h (2) Insulation breakdown time: 1000h or longer (3) Insulation breakdown time: 5000h or longer
IEEE 1553	Electrical aging test (V-t test)	Schedule A: 2.17Un-400h or longer Schedule B: 2.53Un-250h or longer Un: Rated voltage
IEC 60034-18-34	Thermal cycling test	(1) Testing method: ・Heating – cooling test ・Room temperature (30～50℃) ～ Heat resistance class ・500 cycles or more (2) Evaluation method: ・Nondestructive test (tanδ, corona discharge, etc.) ・Withstand voltage test (2Un + 1kV – 1min), Surge test ・V-t test
※References IEEE 1310	Thermal cycling test	(1) Testing method: ・Heating – cooling test ・40℃～temperature classification ・500 cycles or more (2) Evaluation method: ・Nondestructive test ・Withstand voltage test, Surge test ・V-t test

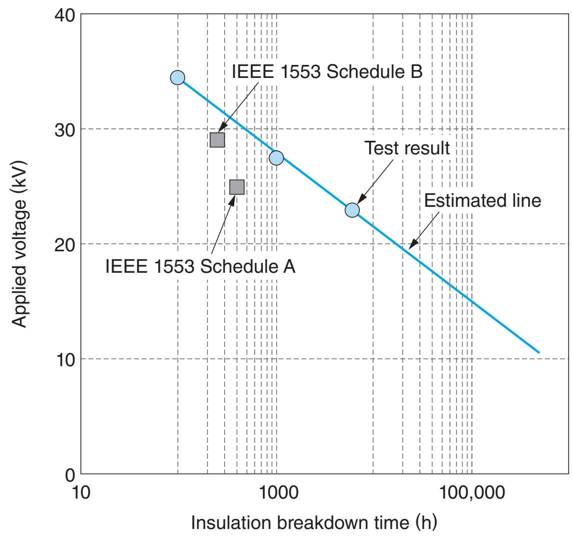


Fig. 4 **V-t Test Result on Coils of Rated Voltage Class at 11kV**

The results of the long-term voltage endurance test (V-t test) is shown. It was performed on coils for rated voltage 11kV class and capacity 75MVA class generator. The results conform to IEEE 1553. According to IEC-based evaluation, it was evaluated and has the durability at 11.5kV for more than 20 years.

on the stator model coils after passing through the specified thermal cyclic program. It was made under a condition where a single test cycle is a process of

Fig. 5 **Thermal Cycling Test**

The energized thermal cycling test is shown conforming to IEC 60034-18-34. It simulates thermal elongation of coils during machine operation.

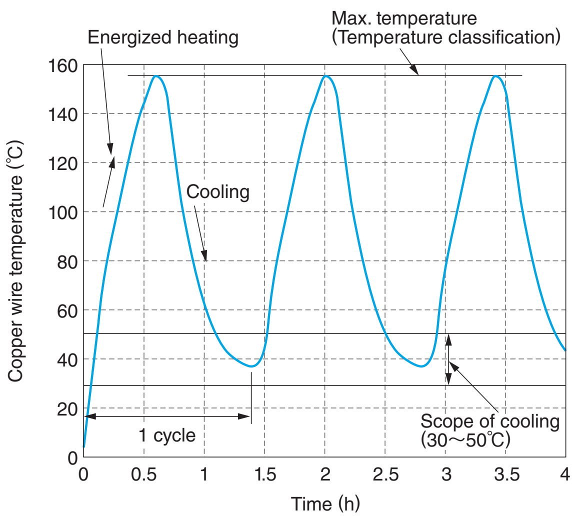


Fig. 6 **Temperature Conditions for Thermal Cycling Test**

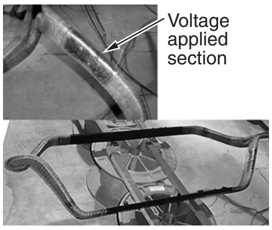
Specific thermal changes are shown and were measured during the thermal cycling test as per **Fig. 4**. We conducted at least 500 cycles under the room temperature (30～50℃) temperature classification (In case of Class F: 155℃).

thermal changes: from room temperature then 155℃ and back to the room temperature.

3 Insulation on External Part of Stator Core (End Winding)

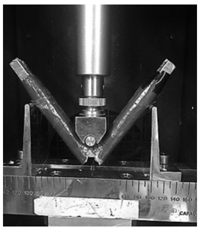
3.1 Outline of End Winding Insulation

The inner insulation for the stator core is made as stated above. Regarding the end winding insula-



(a) End winding V-t test

(c) End winding model thermal aging test



(b) End winding 3-point bending test

(d) End winding model 95%RH moisture absorption test

Fig. 7 Stator End Winding Insulation Endurance Test

Processes of insulation performance evaluation test are shown. This testing was conducted on stator winging coil ends and is a model sample. Evaluation was carried out in regard to energized lifetime, thermal endurance property, mechanical strength, and moisture resistance. We confirmed sufficient performance.

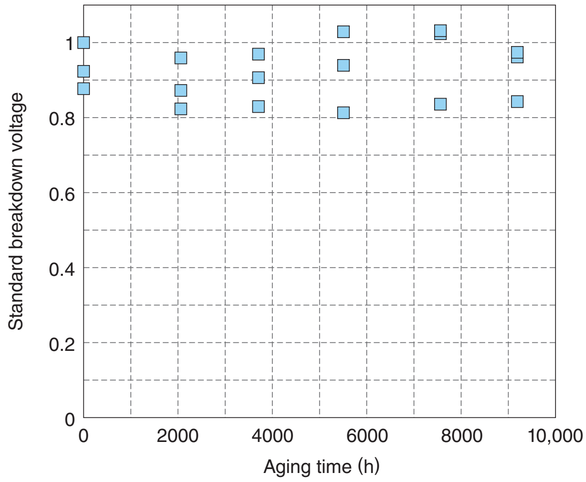


Fig. 8 Thermal Aging Test on End Winding Model Sample

After conducting thermal aging on the end winding model sample, short-time insulation breakdown test was carried out. This test assumes that the highest breakdown voltage of the sample before the test is defined as 1.0 level. The breakdown voltage at a level of 0.8 or higher was still secured even after the aging test. We concluded that the product has ample thermal endurance.

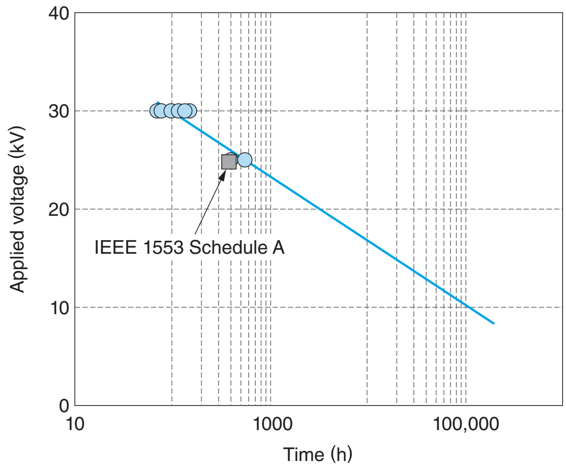


Fig. 9 V-t Test on Stator End Winding

A result of V-t test on stator end winding is shown. Since it is necessary to perform an evaluation in consideration of probable insulation damage caused during coil forming, the object of testing was not a model sample but a winding.

tion for the external part of the stator core, we took measures against moisture and contaminants. With the rise of more compact and light-weight design models, the markets now call for better coil forming accuracy and better cooling performance. In order to improve aforementioned characteristics, we insulated the end winding by using a tape with high shrinking and sealing capability.

3.2 End Winding Insulation Test

There is no definite standard on the evaluation of end winding insulation. As such, we have our own evaluation guideline based on our many years of generator production experiences. Fig. 7 shows the view of insulation endurance test, and Figs. 8 and 9 show the results of thermal aging test and V-t test, respectively. The thermal aging test was carried out under the three conditions of 180℃, 200℃, and 220℃. This is an accelerated aging test which simulates the deterioration of over-20 years operation under the expected operating temperature conditions. As shown in Fig. 8, we conducted the thermal aging test for one year under the condition of 180℃. Compared with the insulation level before aging test, the insulation breakdown voltage was above 80% and ample thermal endurance capability was still preserved. Even in the case of thermal aging tests at 200℃ and 220℃, no remarkable reduction of breakdown voltage was observed. As shown in Fig. 9, it was confirmed that the end winding insulation meets the required endurance characteristics stipulated in IEEE 1553 Schedule A. Judging from both thermal and electrical perspectives, sufficient endurance level was maintained. We are currently still conducting voltage endurance tests. At the final stage, we will make product life evaluation in accordance with the relevant IEC Standard in the same manner as described in above **Section 2**.

Fig. 10 Attached of Acceleration Sensors on Developed Prototype

A view of placed optical fiber type acceleration sensors on the developed prototype is shown. Sensors were attached to the prototype so that no loosening occurred and measurement was not affected, and vibration data from the actual machine was acquired.

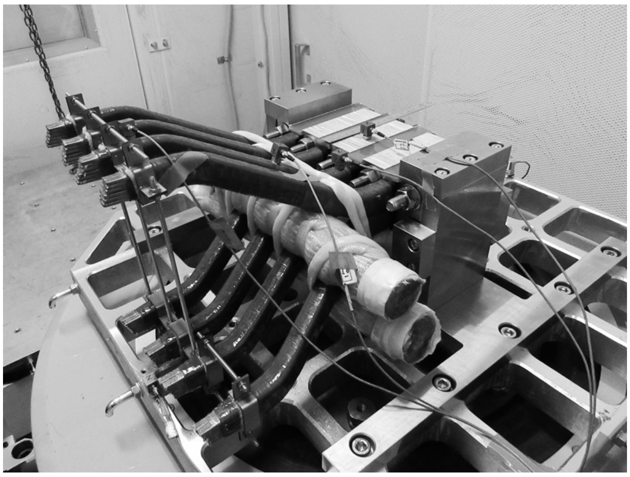


Fig. 11 Vibration Test on Stator End Winding Model

A view of vibration test on a sample and the sample simulated the stator end winding is shown. Reliability was confirmed by conducting an excitation (vibration) test. It simulated the stressed stator core end winding and the binding cord that could cause insulation wear.

3.3 End Winding Model Vibration Test

In recent years, measurement technology has been developed and measurement has become possible in an area that have not been possible before. This created a new need to test such area.

For example, it becomes possible to measure vibrations at medium voltage part area such as coil ends by using non-metallic accelerometers, and the standard IEC 60034-32TS on coil end vibration measurement has been issued. The evaluation between the vibration metrics of coil end and deterioration of coil ends is attracting the industry's attention.

In order to confirm the effect of our insulation systems and cooling technologies, we developed a prototype and conducted evaluation tests. For the improvement of cooling performance, the prototype was provided with many structural design changes in the stator end winding. In consideration of the influence of these changes upon the end winding, we put optical fiber sensor type accelerometers on the developed prototype machine to measure the vibration values during the operation of the real machine. Based on such results, we carried out the accelerated vibration test on the end winding model and confirmed that there was no loose binding nor insulation wear. Fig. 10 shows the attached acceleration sensors on the developed prototype and Fig. 11 shows a view of the vibration test on the stator end winding model.

4 Postscript

Regarding the stator winding insulation system for the 4-pole salient type turbine generator, we worked on the reduction of the insulation thickness and confirmed the resultant endurance property. We also confirmed that the stator winding coil ends have sufficient reliability.

Going forward, we will continue to develop higher performance and quality insulation systems.

《**Reference**》

(1) Ota, Murai, Ishibashi: "4-Pole Turbine Generator," Meiden Review No.167, 2016/No.2, pp.6-10