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Study on Reliability of Water Absorption Diagnosis through Precise Water Absorption Test

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Abstract – Accidents caused by water absorption in water-cooled generator stator windings often occur all over the world. The absorption into the insulator of the coolant, which is used to cool down the heat generated by stator windings during operation, leads to the deterioration of dielectric strength, and insulation breakdown. An insulation breakdown may cause not only an enormous economic loss but also a very serious grid accident that would compromise stable supply of electric power. More than 50 % of domestic generators have been in operation for more than 15 years, and water absorption tests performed on 50 water-cooled generator stator windings during a five-year planned preventive maintenance period beginning in 2006 identified water absorption problems in 10 of them, all of which required repair. Because the existing water absorption test detects this problem by utilizing stochastic methods after measuring the capacitances at the final positions of insulation breakdown, its accuracy is limited. This study demonstrates that water absorption can be more accurately diagnosed by utilizing method along with a more precise one.

Keywords: Generator, Stator windings, Insulation breakdown, Precise water absorption test

1. Introduction

General Electric (GE), a generator manufacturer, has pointed to the possible occurrence of insulation breakdown accidents because of coolant leaks and water absorption into insulators. In 1991, it published TIL-1098 (Technical Information Letters, "Test, Inspection and Maintenance Technology for Leak of Stator Windings") in order to improve the reliability of generators and to solve problems in the water-cooled stator windings manufactured by GE [1].

The purpose of the water absorption test for water-cooled stator windings is to prevent accidents by predicting an insulation breakdown through the diagnosis of water absorption into the insulator because of coolant leaks during overhaul periods and by repairing or replacing stator windings that contain moisture. This test locates windings containing moisture that may cause serious accidents such as insulation breakdowns, by decreasing the dielectric strength of the insulator [2]. It must diagnose precisely whether water has been absorbed, evaluating possible errors based on the thickness of the insulator, and the precision and location of the measurement, by utilizing diverse stochastic methods [3].

In this study, we employ water absorption diagnosis of water-cooled generator stator windings, to demonstrate that the reliability of water absorption diagnosis can be enhanced by merging the results of the existing and of a newly proposed test.

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2. Water Absorption Test of Generator Stator Windings

2.1 Structure of generator stator windings [3], [4]

Though generator characteristics differs by manufacturer, a generator should be manufactured with a structure that can withstand the electromagnetic and mechanical forces generated during normal operation as well as any excessive forces, such as abnormal force generated by a three-phase short circuit. The typical structure of a water-cooled generator is shown in Fig. 1.

A water-cooled stator winding has a long structure in the axial direction having a length of 8 to 10 m and is made of a frame, a stator iron core, a coil with a support device, and a hose and header for coolant supply. Spacers and strings, with a retaining ring, are the principal supporting devices of the stator end windings. Some manufacturers also use support devices of the cone type. As the stator support structures differ by manufacturer, the vibration characteristics of the stator end windings vary.

Stator windings are inserted into the slots of the stator iron core that is laminated on the key bar fixed to the stator frame in two layers, and a wedge is used to bind them. The upper and lower windings that come out of the stator slots are tied by adjacent windings of spacers and strings and bound to the inner and the outer rings, as well as winding support devices. Accordingly, the mechanical binding condition of the winding end is relatively poor in comparison to that of the stator slot and leakage of the generator stator coolant, water absorption, and winding abrasion frequently occur at the stator end windings.

In stator windings, many coolant passages are formed in order to cool down the heat generated by the inside copper conductor with flowing electrical current, and the outside is covered by mica-epoxy insulating material, as shown in Fig. 2. The coolant supplied by the stator coolant supply pump flows into the stator winding clip, after passing through the Teflon hose, and cools down the windings that flow along the coolant passages inside the windings. The Teflon hose connection and stator winding clip are the locations in the generator stator windings from which the coolant frequently leaks during operation. The stator winding clip plays not only the role of a coolant chamber for each set of windings but also that of an electrical connector of the upper and the lower windings.

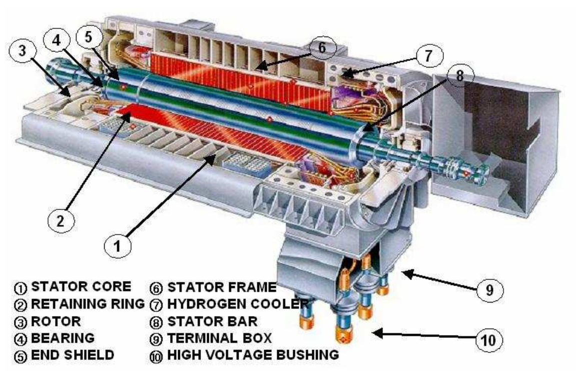


Fig. 1. Structure of generator

(a) Left side (b) Front side (c) Inside of water-clip

Fig. 2. Section of clip to strand of stator

2.2 Existing water absorption test [4], [5]

The water absorption test is a technique that uses a non-destructive method to detect the existence of moisture inside the ground wall insulation that may be generated by leakage of the coolant inside the generator stator windings.

In stator bars, this test measures the capacitance between the sensor (+) and copper (-) pressing the sensor to the mica surface. A condenser is used to store the electricity. If voltage is applied to the two parallel metal plates, electricity is stored in this location, which is called capacitance. If the electrical flow is charged in the storage battery, as shown in Fig. 3, the charges are distributed within the plates. The electric flux is perpendicular to the plates, and a uniform magnetic field is formed in a parallel shape. The capacitance of the parallel plate storage battery is equal to Eq. (1).

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} [F] \tag{1}$$

Capacitance is increased in generator stator windings.

(1) When the area of the sensor is wide or the distance of poles is short and
(2) When an arbitrary material between mica and copper has a large permittivity.

In case (2), a new material for which permittivity is large cannot be added during construction. In addition, the area of the sensor and the distance between the poles are constant. Accordingly, the capacitance is increased only if the water leaks inside bars. As a reference, the permittivity of water is 20 times that of the mica that composes the bar. The water absorption test makes use of these physical phenomena. Through the stochastic diagnosis methods and the measurement of the capacitance of mica, it assesses whether wet bars are present. This evaluation should not be undertaken through the quantitative comparison of the capacitance of bars, because only a small amount of bars is present in the water absorption test. However, the judgment errors for wet bar can be lessened as long as the comparable data are numerous. In addition, if various stochastic diagnosis methods are applied, the accuracy of such decisions can be heightened.

Water absorption is evaluated by measuring the capacitance of all windings and comparing it with the average value, based on the large difference between the dielectric constant of the ground wall insulation of stator windings and that of water. High capacitance means that moisture exists inside the insulator of the windings. In case of wholesome windings, the capacitance shows a standard deviation within 2σ from the average value. If the standard deviation is 3σ or larger, water absorption is generally suspected, and, if it is 5σ or larger, moisture absorption by the insulator of windings is indicated. The advantage of this test is that it can locate the winding with a high risk of hipot failure during operation. When carrying it out, careful attention is required, because the measurement

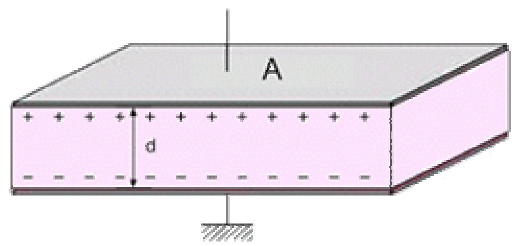


Fig. 3. Capacitance for parallel plate storage battery

sensor and the surface, coating and painting condition of the windings all induce small changes in the capacitance of stator windings. As water absorption diagnosis of stator windings is carried out through the stochastic process, the measurement condition should be consistent.

As shown in Fig. 4, the test is performed by selecting the curved part of windings at the end of the stator iron core; manufacturing and taping conditions must be uniform at the measurement point. Because the water absorption route is unpredictable, water absorption is diagnosed by making all possible measurements of the curved sections of the collector and turbine end sides, that is, the top/inner/outer sides of the upper curved sections of windings and the inner/outer sides of their lower curved sections.

(a) Top (b) Inner (c) Outer

Fig. 4. Water absorption test due to measurement position

Because measurement errors such as that of calculating the surface roughness of windings and diagnostic errors from the use of stochastic methods for a very small capacitance always occur in the water absorption testing of water-cooled generator stator windings, we establish such absorption with diverse stochastic diagnosis methods. Specially, we employ a capacitance mapping plot, a capacitance diagram, and normal probability and box plots, in order to minimize diagnostic errors. Fig. 5 shows the result of the stochastic diagnosis performed for capacitance of the outer side of upper windings at the collector end side

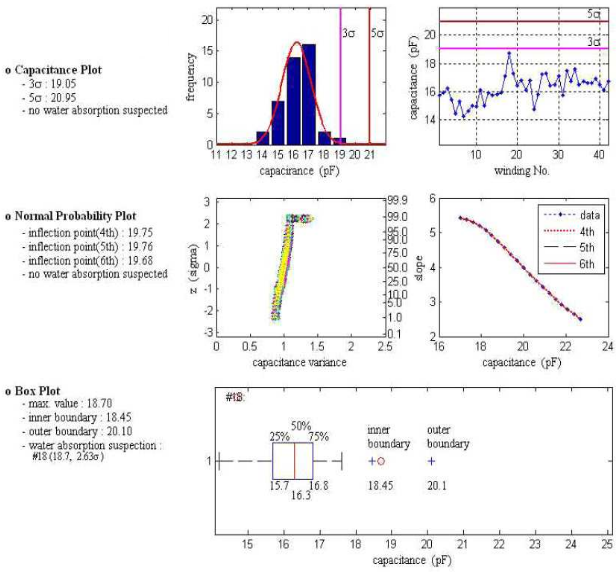


Fig. 5. Water absorption diagnosis results (CET-OUT)

(CET-OUT). Though we can see that the capacitance of winding No. 18 at the collector end side is comparatively higher than those of other windings, we know that this divergence is not sufficient to guide expensive and long repairs, because it has not exceeded 3σ .

Fig. 6 presents a comparison of the results of the tests performed in October 2006 and in September 2010. It indicates that the change in the capacitance of winding No. 18 has increased in comparison to those of the other windings. This change can be used to predict coolant water absorption in winding No. 18.

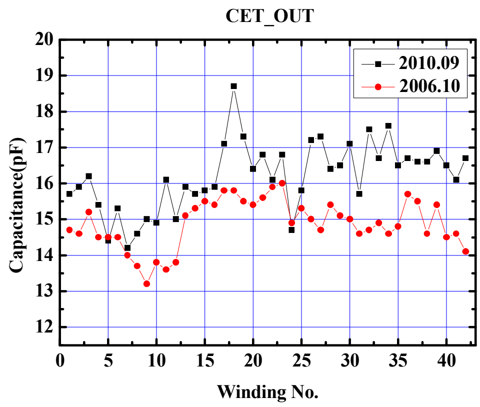


Fig. 6. Capacitance change due to operation (2010.09 vs. 2006.10)

Table 1 lists the results of the existing water absorption diagnosis methods. They indicate that water absorption is suspected in the collector end side's No 18 winding; however, we are not sure of this finding. Accordingly, it is confirmed that existing methods make it very difficult to secure a clear proof of water absorption.

Table 1. Suspected bar results from water absorption diagnosis methods

Water absorption diagnosis method	Suspected Bar	
	Collector end	Turbine end
Capacitance mapping	None	None
Probability plot	None	None
Box plot	None	None
Periodic capacitance change	No. 18	None

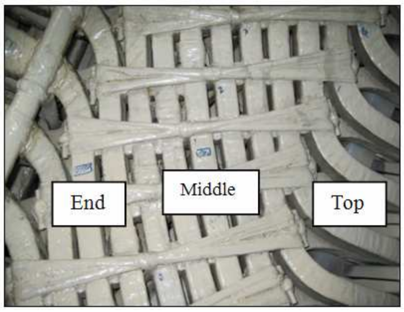
2.3 Precise water absorption test [6], [7]

The reliability of water absorption diagnosis is improved by using water absorption sensors to measure differences in the capacitances of the ends and iron cores of windings at multiple points where water absorption is.

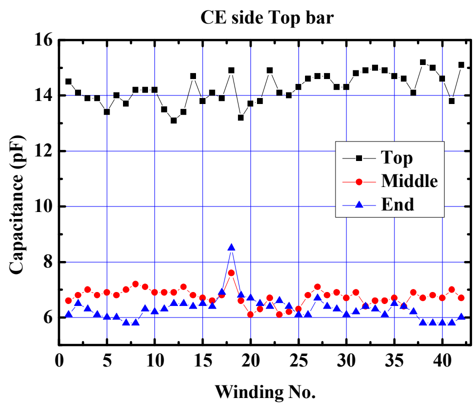
In the existing water absorption test, the diagnosis of water absorption is based on the change of capacitance at the top position that is shown in Fig. 7(a). Generator manufacturers recommend the replacement of windings within a year if water absorption is found at this top position. Thus, such detection indicates a significant likelihood of failure. Generator manufacturers are reluctant to receive orders for just one or two windings because such small quantities cannot be manufactured economically; in addition, such purchases create budgeting problems for electric power companies. Because the capacitance used to judge water absorption is of a 10^{-12} [F] scale, it is also very difficult to be absolutely sure about the water absorption of windings. A more accurate assessment method can resolve this difficulty and prevent unexpected electrical trips of a generator, such as insulation breakdowns.

As shown in Fig. 7(a), the analysis of changes in capacitance can be utilized as an important tool to diagnose accurately the water absorption process along the water absorption route. Measurements of the capacitances at the same positions as the existing water absorption test, that is, at the end where coolant starts to leak, at the middle where water is very slowly absorbed by the capillary phenomenon, and at the top are periodically. Fig. 7(b) shows the capacitances measured at the top, middle and end sections in September 2010. They indicate that the capacitances at the middle and end sections of No. 18 are higher than those of other windings. From this, we can surmise that coolant has leaked from the water clip into the insulator and that water absorption is in progress. The higher capacitance at the end than at the middle means that the amount of water absorbed at the former is larger than that absorbed at the latter, if we disregard the possibility of capacitance variance stemming from differences in the roughness of the insulating paint and the thickness of that insulator from that of the copper conductor, even though the areas of the water absorption sensors are same. Thus, this method enhances the reliability of water absorption diagnosis by measuring capacitances not only at the top but also at the middle and end sections and by entering these findings into a database. In addition, when the water absorption of some windings is suspected, the reliability of its diagnosis can be further enhanced by measuring the capacitances of ± 2 normal windings, at the same position, as those of which water absorption is suspected and comparing the results, as shown in Fig. 8. Comprehensively speaking, the reliability of water absorption diagnosis can bettered by minutely comparing (1) the results of the existing water absorption test, (2) the capacitances measured periodically at the same positions of windings, (3) the change in capacitance measured at each winding position with small water absorption sensors and, (4) the capacitances of windings in which water absorption is suspected.

Fig. 9 compares the capacitances of normal windings Nos. 16, 17, 19, and 20, measured with the above method at the same positions at the upper part of collector section as those of winding No. 18 end in which water absorption is suspected. As shown in Fig. 9, the capacitances measured at the positions of winding No. 18 are all relatively higher than the capacitances of windings Nos 3, 8, 13, 18, 23, and 28. Those measured at the end section are, in particular, far higher than those at other positions.

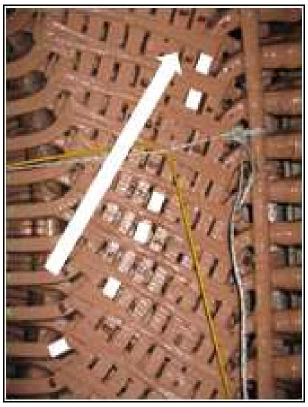


(a) Added measurement position

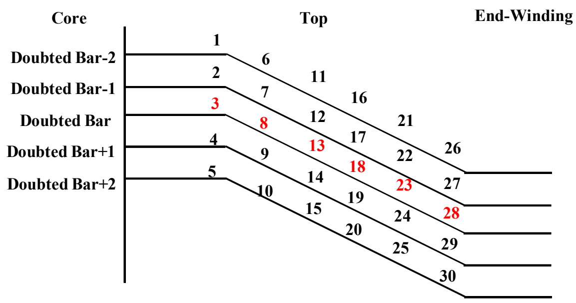


(b) Capacitance change

Fig. 7. Capacitance change at different winding positions



(a) Measurement gap



(b) Measurement position

Fig. 8. Measurement position for precise water absorption diagnosis

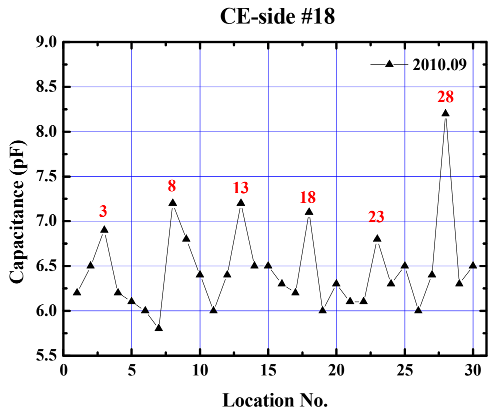


Fig. 9. Precise water absorption diagnosis result

Fig. 10. Water absorption winding due to coolant water leaks

As the supply of coolant started in the water clip, it is evident that coolant has leaked and that water absorption into the iron core side by capillary phenomenon is in progress.

Fig. 10 shows the check for the leak with bubble test after disassembling the insulator at the water clip of winding No. 18 which is located at the upper part of the collector end where water absorption is suspected. We can see small bubbles made by pressure at the leakage. Thus, we can confirm that coolant has leaked at this point and that water absorption into the insulator is very slowly progressing.

This finding reveals the lack of soundness of the existing water absorption test. It indicates that although the leak test has been passed, water absorption is in progress inside the windings, showing that the coolant that has not leaked outside of the windings is being absorbed into the ground wall insulation by capillary action, causing the deterioration of dielectric strength. When we consider that leak and water absorption are in progress in more than 50 % of the stator windings of generators that have been in operation for more than 15 years (the TIL of GE indicates that most domestic 500 MW thermal and 1000 MW nuclear power plants are this old), we can grasp the overwhelming importance of detecting such problems with periodic tests for them in order to prevent fatal accidents which may result from insulation breakdown.

3. Conclusions

The unexpected electrical trips of generators caused by leaks and water absorption in water-cooled stator windings occur throughout the world. As a result, generators can be restored only after enormous expense and many months of labor. Accordingly, a technology that can prevent such accidents in advance is essential for the safe and efficient operation of power plants.

This study demonstrates that while suspicions of water absorption in windings are produced by the existing diagnostic method, it is difficult to decide on whether to undertake generator repairs due to the lack of water absorption data.

Further, we have empirically demonstrated that the reliability of this existing method can be significantly enhanced by analyzing changes in capacitance based on number of service years, the position of windings, and the variances of capacitance of sound and possibly defective windings at identical positions and then employing all findings in a water absorption diagnosis.

We judge that an accurate water absorption diagnosis of water-cooled generator stator windings will greatly reduce unexpected generator accidents caused by coolant water absorption.

Acknowledgement

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