Results of Destructive Analysis of Service-Aged Hydrogenerator Stator Winding Insulation

G.C. Stone[1], H.G. Sedding[1], R. Wheeler[1] & A. Wilson[2]

Qualitrol-Iris Power[1], CEATI International[2]
Canada

SUMMARY

The insulation system in form-wound stator windings is exposed to electrical, mechanical and thermal stresses, in addition to factors such as humidity and contamination. These stresses combine to give rise to at least 15 different aging mechanisms, which are described in some detail in [1, 2]. Some of these aging processes are readily identifiable with a visual inspection of the winding. For example, loose windings in the slot (leading to PD), poorly made PD suppression coatings (either the 'semicon" in the slot area or the silicon carbide grading coating just outside of the slot), and endwinding electrical tracking due to contamination, are easily visually identified. However, there are a number of aging processes that cannot be seen by this method. These processes include thermal aging of the turn and groundwall insulation due to operation at high temperature, delamination of the groundwall insulation due to load (thermal) cycling and PD due to voids or other manufacturing imperfections within the groundwall. The only definitive method to assess the degree of aging with these latter failure processes is to remove multiturn coils or Roebel bars from the stator core and dissect them.

In 2008, CEATI International, a consortium of electric power utilities that sponsors research into common problems, initiated a project to determine the state of aging of the stator winding insulation system in a wide variety of hydrogenerators. A number of utilities from North America, Europe and Australia sponsored the research. The project involved removing a few bars or coils from selected hydrogenerator stators, performing some electrical tests on these bars and coils, and then dissecting segments isolated from each of the coils or bars. Coils/bars were removed from 10 hydrogenerators from 9 utilities (3 from Europe and 7 in the USA). The bars and coils came from machines that were being rewound due to failure, old age or uprating. In cases where the coils/bars were not damaged during extraction from the generator, off-line electrical tests were performed and compared to the condition of the groundwall insulation, as determined by dissections. Only one of the windings had essentially unaged insulation. All the rest showed various degrees of thermal or thermo-mechanical aging. Only one of the 10 windings also showed severe aging due to surface partial discharge. The coin tap test was a good predictor of the degree of thermal and thermo-mechanical (load cycling) aging. The PD test was a good predictor of the coils/bars that had any of the three types of aging. This proposed contribution presents the results from the dissections, and discusses the causes of the aging that was found.

KEYWORDS

Stator winding, insulation, dissection, delamination, diagnostic tests

hsedding@qualitrolcorp.com

INTRODUCTION

The stator winding insulation system in form-wound stator windings is exposed to electrical, mechanical and thermal stresses, in addition to factors such as humidity and contamination. These stresses combine to give rise to at least 15 different aging mechanisms, which are described in some detail in [1, 2]. Some of these aging processes are readily identifiable with a visual inspection of the winding. For example, loose windings in the slot (leading to PD), poorly made PD suppression coatings, and endwinding electrical tracking due to contamination, are easily visually identified. However, a number of aging processes cannot be seen with a visual examination of the winding. These include thermal aging of the turn and groundwall insulation due to operation at high temperature, delamination of the groundwall insulation due to load (thermal) cycling and PD due to voids or other manufacturing imperfections within the groundwall. The only definitive method to assess the degree of aging with these latter failure processes is to remove multiturn coils or Roebel bars from the stator core and dissect them. Clearly this is an invasive, destructive process.

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MACHINES INVESTIGATED

Over an 8-year period, coils or Roebel bars were made available for this project from 10 hydrogenerators or pumped-storage units. Table 1 shows a summary of the machines the coils/bars came from. The machines ranged from about 50 MVA to 160 MVA. The rated voltage ranged from 10.5 kV to 18 kV rms, phase to phase. The oldest coils operated for 56 years without an in-service failure, and accumulated 425,000 operating hours. The newest coils came from a machine in operation for only 6 years that had experienced an in-service failure after only 5000 operating hours. With the exception of machines 1 and 5, all the coils/bars used relatively modern mica paper tapes bonded together with epoxy, using either the VPI or resin-rich manufacturing methods. Six machines were defined as peaking units, that is they tended to operate for just a few hours per day and thus saw many start-stops (load cycling). Four machines were mainly base load, and saw relatively few load cycles.

These 10 machines had a range of methods for supporting the coils/bars within the stator core slots. In some cases, the slot support seemed to be just simple flat wedges and side packing. One machine used a ripple coat of conductive silicon rubber that gave an interference fit in the slot. Some machines also had conductive putties to keep the coils/bars secure in the slot.

A total of 34 coils or bars were removed from stator windings for dissection.

TESTS ON COILS/BARS BEFORE DISSECTION

After uncrating the coils or bars, an overall visual inspection of the specimens was performed. In particular, bars and coil legs that were obviously cracked or damaged as a result of removal from the stator were identified. Such defective coil legs and bars were not subjected to any electrical tests. In addition, the surface condition of the coil/bars was examined, especially for signs of insulation system abrasion due to movement in the stator slots, and the presence of any surface PD activity (white areas). A “tap” test was then done at many locations along each coil leg or bar by striking a coin against the specimen and listening for a hollow sound. This test gives an

initial indication on whether the insulation is delaminated and/or the groundwall has separated from the copper conductors.

The insulation resistance of each un-cracked coil/bar was measured using a Megger MIT 1020/2, at either 5 kV or 10 kV dc, according to IEEE 43 or IEC 60034-27-4. If the insulation resistance test was above about 5 GΩ at room temperature, the polarization index test was not performed, since it tends to be inaccurate. In a many cases, a DC ramp test (IEEE 95) or other hipot test was performed to about 2 times the rated phase to phase rated voltage. The off-line partial discharge (PD) test at rated line to ground AC voltage (IEEE 1434) was then performed on damaged bars/coils. Two PD instruments were used. In a few cases a PD test in the wideband mode in the low frequency range (40-800 kHz) was done using a PDTech DeltaMaxx with a 1 nF detection capacitor. The PD magnitudes were in units of pC. A very high frequency (VHF) PD test was also performed with an Iris Power TGA-B using an 80 pF detection capacitor. These readings were recorded in mV.

Table I: Characteristics of the Machines with Dissected Coils/Bars

No.	Winding Age (years)	Ratings	Insulation Type*	Operation Mode	Operating Hours	Coil or Bar
1	56	100 MVA 13.8 kV	Polyester Mica splitting, VPI	Base	425k	Coil
2	42	167 MVA 13.8 kV	Epoxy Mica VPI	Peaking	190k	Bar
3	37	100 MVA 18 kV	Epoxy Mica VPI	Peaking	93k	Bar
4	37	68 MVA 18 kV	Epoxy Mica RR	Peaking	138k	Bar
5	37	87.5 MVA 10.5 kV	Epoxy Mica splitting, VPI	Pump Storage	175k	Bar
6	27	47.8 MVA 13.8 kV	Epoxy Mica RR	Mixed	103k	Coil
7	27	109 MVA 13.8 kV	Epoxy Mica VPI	Mainly base	192k	Bar
8	16	163 MVA 13.8 kV	Epoxy Mica RR	Both	54k	Bar
9	13	132 MVA 15 kV	Epoxy Mica VPI	Peaking	59k	Coil
10	6	126.5 MVA 14.4 kV	Epoxy Mica VPI	Peaking	5k	Coil

*VPI = Vacuum Pressure Impregnation, RR = Resin-Rich

DISSECTION PROCEDURE

To assess the general condition of the insulation system, segments were cut from the bars and coils. Usually 3 or more segments were cut from a coil leg or bar. In almost all cases some of the segments were from each leg/bar at the point where it exits the slots. Often, this included the first bend outside of the slot. In addition, segments were cut from the coil leg/bar inside the slot – often at locations where the insulation sounded clearly as "solid" or "hollow" in a coin tap test.

The segments were about 10-15 cm long, and were rough cut using a fine-blade portable band saw. A diamond saw and polishing of the segment ends was not performed since failure channels through the insulation were not present. In all cases at least one axial cut was made on the narrow edge of each specimen. If the groundwall tape layers could not be separated or the groundwall did not easily separate from the conductor bundle, then a second axial cut was made on the opposite narrow edge of the segment. Then manually, or using a knife or a chisel (depending on the ease with which the layers could be separated), the semicon tape (if present) and the groundwall layers were one by one pealed back until the conductor stack was reached. For coils, special care was taken to examine the turn insulation.

During this process, the integrity of the bonding between tape layers was observed, and if the mica tapes were made from large mica splittings or mica paper. Any wrinkling of the tapes (which tends to create local voids within the insulation system) was also noted. Examination for evidence of PD was also made. Partial discharge tends to cause the resin between tape layers to turn to a white, yellow or grey dust. If PD is occurring adjacent to the copper conductors, it also tends to turn the surface of the copper green due to oxidation. High PD activity over many years also leads to burning of the insulation in the immediate region. The bond between the copper strands or turns (in coils) to the groundwall was noted – since a poor bond in the absence of discolouration is a sign that the debonding may be due to either generator load cycling or a poor manufacturing process.

RESULTS

Table II provides a summary of the test results on the bars/coils before dissection, as well as a summary of the dissection findings. Of the 10 machines, only one machine (No. 10) shows no significant signs of any form of aging. It had experienced an in-service failure, but this was likely due to localized debris or a localized manufacturing flaw.

The other 9 machines all showed signs of either long-term thermal aging or thermo-mechanical aging caused by load cycling. In these 9 machines, one or more (usually all) of the dissected segments showed various degrees of poor bonding between the groundwall and either the turn insulation (for coils) or the copper strands (for the bars). In the cases with the worst bonding, the line-end coils/bars also exhibited local burning and PD. Two of the machines (Numbers 1 and 6) had such severe deterioration of the turn insulation that the windings were in fact at the end of life and an in-service failure could have happened at any time (Figures 1-2). In spite of the evident turn insulation deterioration on these two machines, the groundwall insulation itself was relatively unaged, that is there was still good bonding between the groundwall tape layers and there was little sign of discolouration due to operation at high temperature. A burning odour was only noted near the conductors.

Only one machine (No. 5) exhibited significant deterioration of the stator bar surface in the slot (Figure 3). Aging, leading to abrasion of the groundwall due to vibration of coils/bars in the slots, or PD acting on the stress relief coatings, was not present in the 9 of the hydrogenerators. This low percentage of stators with surface insulation problems is in contrast with the findings of hydrogenerator failure surveys [3,4] that showed that issues in these locations are common.

Table II: Summary of Findings

No.	IR* (GΩ)	VHF PD		Tap Test	Dissection (worst coil/bar)
		PDEV (kV)	***Qm (+/- mV)***		
1	3	-	290/246	mainly hollow	groundwall tapes poorly bonded together. Turn insulation destroyed by severe PD, burning. Minor PD attack on semicon. Conductors fell apart. At end of useful life
2	>100	4	14/13	some hollow areas	groundwall reasonably well bonded. Moderate bonding to conductor stack. No PD attack
3	>100	2.5	107/109	a few hollow areas	groundwall well bonded. Moderate bond to conductor stack. Minor PD at stack
4	>100	3.5	39/78	mainly hollow	groundwall well bonded. Poor bond to conductor stack. No PD. Some overheating at stack. Minor PD attack on semicon
5	30	1.5	450/500	50% hollow areas	groundwall moderately well bonded. Poor bond to conductor stack. considerable burning and PD attack at the stack. Moderate PD attack/burning on semicon
6	>100	5.5	212/143	mainly hollow	groundwall moderately well bonded. Poor bond to turn insulation conductor stack. considerable burning and PD attack at the stack. Conductors fell apart. At the end of its useful life
7	-	4.5	11/29	solid	groundwall well bonded. Moderate bond to the conductor stack. Minor PD attack at the stack
8	>100	5.7	72/81	not relevant (CRTV coating)	groundwall well bonded. Moderate bond to the conductor stack. Some overheating at the stack
9	>100	5.2	3/22	some hollow areas	groundwall moderately well bonded. Poor bond to conductor stack. PD attack and burning at stack
10	>100	6.3	22/22	solid	groundwall well bonded. excellent bond to conductor stack. No sign of PD or burning anywhere

Figure 1: Photographs from the dissection of a segment from Coil A1 from Machine 1. Machine 1 had seen 56 years of base-load operation, but did not experience an in-service failure. Once the axial cut through the groundwall was made, the turns and strands from Coil A1, slot exit (connection end) fell apart. The turn insulation was burned and there was extensive PD attack.

Figure 2: View of turn insulation and conductor stack of coil LC1 from Machine 6. Note that the delamination at the turn resulted in heavy partial discharge attack that further damaged the turn insulation. The green powder is from oxidation of the copper by ozone from the PD.

Figure 3a: Observation of the degradation of the semicon coating of Bar L3-1 from Machine 5 (a motor-generator), which had the lowest PDEV and the highest PD magnitudes. This image also shows local burning and PD attack on the bar surface.

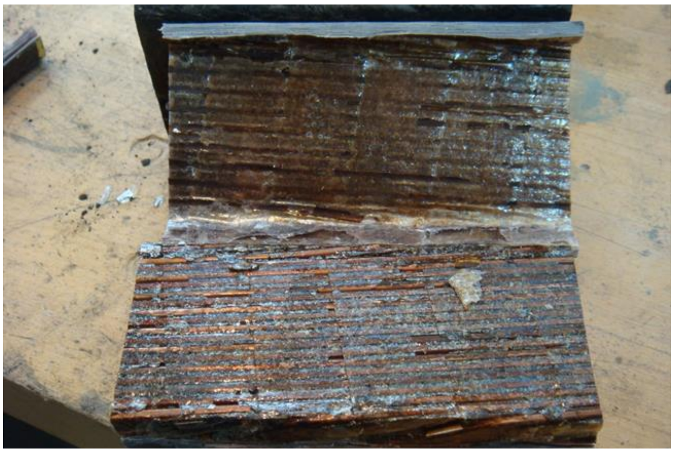

Figure 3b: Burning and PD attack between the groundwall and the copper stack. The green areas are where the PD has corroded the bare copper strands (half the strands were not insulated in this machine).

CONCLUSIONS

In this study, 34 coils or bars from 10 machines that had seen from 6 to 52 years of service were dissected after first being assessed with a variety of diagnostic tests. The main conclusions are:

The most common cause of winding insulation deterioration in these 10 machines was delamination of the insulation, mainly near the conductor stack. Delamination can be caused by long-term operation at high temperature, load cycling and/or insufficient impregnation of the insulation with resin. Comparing Tables I and II, base-loaded machines required more hours of operation to attain a severely-degraded state, in contrast to machines operating in a peaking mode. This, together with the generally good bonding between tape layers and the absence of signs of discolouration or burning in the groundwall insulation itself, tends to suggest load cycling is an important cause of aging in older machines.

In the most severely deteriorated coils/bars, the delamination facilitated partial discharges next to the turn insulation in coils or the conductor stack in Roebel bars. The PD degraded the organic materials and caused localized burning. In multi-turn coil windings, the degraded turn insulation could have lead to turn to turn faults (and very soon after) a ground fault at any time.   That is, the stator windings in Machines 1 and 6 could have failed at any time (and in fact Machine 6 had already experienced in-service failures). The bars in Machine 5 also exhibited significant PD attack at the conductor stack. In Roebel bars, eventually strands shorts will occur which will further increase the bar temperature. Most of the other machines showed less advanced forms of this mechanism.

It was surprising that only one of the 10 machines exhibited any significant issues with loose windings in the slot or significant surface partial discharge activity. Past surveys have indicated that such problems are at least as likely as the thermal aging/thermal cycling mechanisms.

Table II suggests the tap test and the partial discharge test were the best predictors of the aging processes causing delamination in the windings. The insulation resistance test was not useful in predicting the presence and severity of thermal, thermal cycling or surface PD aging processes.

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