Improved Requirements for Stress-Grading Systems at Hydro-Québec

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I. INTRODUCTION

For a number of decades, manufacturers have been using stress-grading coatings to control the electric field in stator end windings. To avoid partial discharges (PDs) into the air, i.e., the corona effect, the electric field along the surface of the end-winding coating must be kept below the dielectric breakdown field of air.

When properly designed and applied, the coating drains electrons to ground within acceptable limits, avoiding deterioration of the insulating or semiconductive material.

Such coatings are tricky to design and implement since their resistivity must vary non-linearly with voltage. Proper electrical bonding with the semiconductive coating must also be ensured since poor contact would concentrate most of the electric field in the air around the junction and may lead to long-term deterioration of the bar's ground-wall insulation, causing a phase-to-ground fault.

In recent years, inspections have revealed traces of white powder at the junction of the semiconductive and grading coatings of a number of Hydro-Québec stator windings. The white powder results from surface discharges attacking and decomposing the insulating material and by air ionizing around the bar. Such defects were even seen on stator windings with only four years of service (see Figure 1).

On-site corrective action must be taken to remedy the deterioration before it becomes critical. This entails shutting down generating units, which is clearly undesirable in an increasingly competitive market for electricity sales.

Hydro-Québec thus decided to tighten requirements by adding very precise provisions in its technical specifications to ensure that new stator windings would not have the same type of problems [1].

Figure 1 – Signs of discharges on a winding after just four years of service

Past research by Hydro-Québec's research institute, IREQ, was used to specify the severity of damage [2;3]. This was useful both in ensuring uniform inspection criteria company-wide and in providing clear and precise instructions to maintenance staff. Such preliminaries were crucial given the size of the Hydro-Québec generating fleet: 341 hydroelectric generating units in 54 generating stations and five units driven by gas turbines or other means. Installed capacity totals 35,170 MW.

To determine the criteria manufacturers would be required to meet, laboratory tests were conducted on several stator bars of various types. This paper presents the approach taken and the new criteria developed.

Those new criteria will ensure that future stator windings are designed and manufactured to meet quality standards high enough for the junction to last at least as long as the service life of the stator windings.

II. DESCRIPTION OF THE PHENOMENON

Laboratory test results and exhaustive on-site inspections by IREQ have provided a basis for hypotheses to explain how junction deterioration could lead to breakdown as observed in the lab [2;3].

Several bars were subjected to accelerated ageing tests at 20 kV. Figure 2 is a photograph taken in the lab of a bar whose junction was artificially degraded.

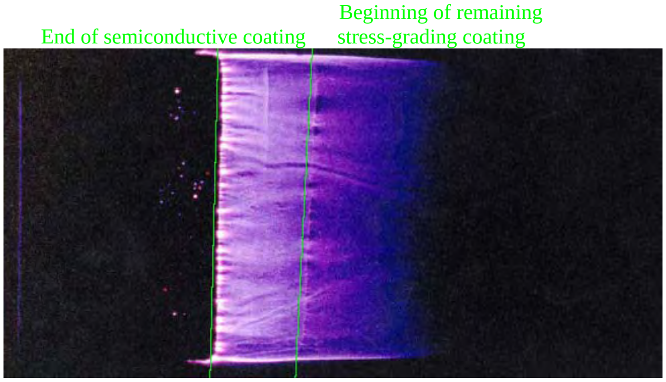

Figure 2 – Corona effect at a degraded junction subjected to 20 kV in the laboratory

In the laboratory, breakdowns occurred inside the slot near the slot exit. The same kind of defect was observed earlier in generators with fairly marked signs of the corona effect. At the time, however, we were unable to associate the defects with deterioration of the junction. The hypothesis put forward to explain this phenomenon is that when the junction has completely deteriorated, the overall surface current from PD activity exceeds the ohmic resistance of the semiconductive paint. The current is near-uniformly distributed around the bar between the paint-paint junction and the iron substrate, and the current density is too weak to burn the semiconductive coating. Ground contact in the slot, however, is much less uniform due to the rough surfaces and inevitable gaps between the bar and the sides of the slot. Furthermore, since the coating has a much higher resistance at very high frequencies than at 60 Hz, the PD current would tend to drain to the iron as soon as it enters the slot. Discharge currents will thus drain to ground at just a few spots. The local current density can therefore be very high and can raise the temperature above the acceptable limit for the coating, thus causing it to burn. This will cause the corona to appear in the slot and may lead to breakdown of the ground-wall insulation.

Experience has shown that it may take about 10 years for a white ring to form around the bar once deterioration has started. Deterioration of the ground-wall insulation then begins and, if no corrective action is taken, a fault can be anticipated after a total of 25 to 30 years of continuous service. Other studies mention similar durations for deterioration of the ground-wall insulation due to slot discharges [4], purely electrical activity without vibrations.

III. RESULTS OF VISUAL INSPECTIONS

To achieve comparable results when inspecting generating units at any Hydro-Québec generating station, photographs were selected to clearly show defects at different levels of severity. Maintenance staff could thus assign a priority to each site showing signs of the corona effect.

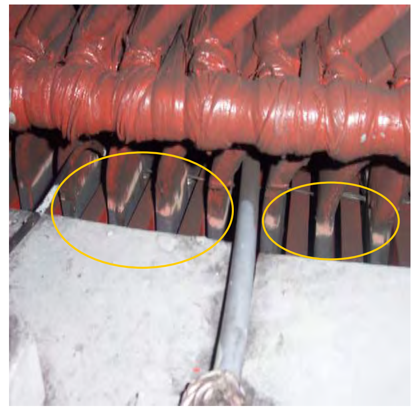

Figure 3 – Priority 1 signs of the corona effect

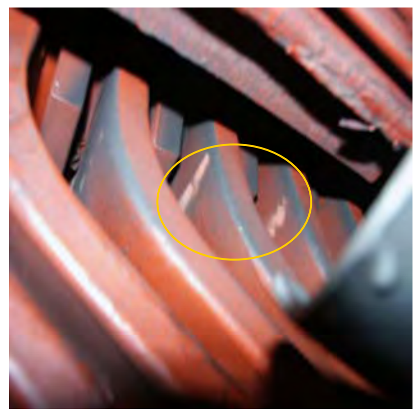

Figure 4 – Priority 2 signs of the corona effect

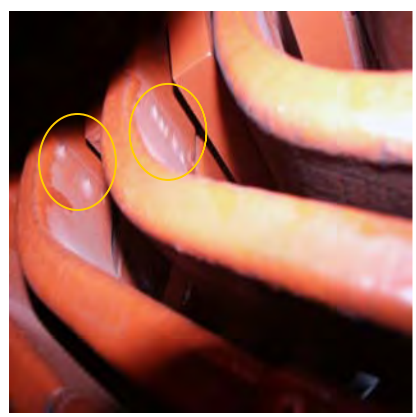

Figure 5 – Priority 3 signs of the corona effect

In-service PD measurements can be used to quantify the intensity of corona discharges at junctions. Such measurements give characteristic discharge patterns skewed toward positive discharges during the negative voltage half-cycle.

Following the inspections, discussions were held with one of our manufacturers so it could propose solutions for future contracts. It proposed using silicon carbide stress-grading tape instead of the paint used earlier.

IV. CORRECTIVE ACTION ON EXISTING WINDINGS

Hydro-Québec has a maintenance tradition that ensures that the generating fleet is always very well poised with enough units in service to meet power system requirements.

A repair program is thus now being developed to correct all bar and coil junctions that show serious signs of deterioration. Developing a repair procedure is complicated by the fact that most windings have a finishing coating of Glyptal on both the junction and grading.

Remaking the contact between the old and new layers of semiconductive and stress-grading paint entails precision on-site sanding and cleaning in cramped quarters and hence requires very skilled and experienced staff exercising high standards of craftsmanship.

On-line PD measurements have confirmed that junctions repaired to date show no signs of discharges.

Windings already manufactured but not yet installed have been corrected using a sleeve over the existing junction [6].

V. LABORATORY ASSESSMENT OF GRADING COATING PERFORMANCE

To better understand the problem of corona effects and the poor initial performance of coatings, IREQ conducted tests with an ultraviolet (UV) camera on spare bars supplied some 30 years ago (Figures 6 and 7). During lab tests on 31 stator bars from three manufacturers and with four kinds of semiconductive and stress-grading coatings, corona inception voltages (CIVs) as low as 5.2 kV were recorded at the stress-grading junction. Such values are clearly unacceptable since bars on the phase side of the stator winding are permanently subjected to 7.9 kV on most Hydro-Québec generators. Some bars, however, had excellent results (see Table 1).

Table 1: Corona inception voltage at the stress-grading junction for different types of insulation and grading coatings

Insulation system	**Number of bars tested**	**Number of generating stations**	**External corona inception voltage (CIV) (8-kV nominal line-to-neutral voltage)**
Type 1	9	3	5.9 kV was the lowest value. Only one bar had a CIV above 8 kV.
Type 2	13	3	5.2 kV was the lowest value. Only 4 bars had CIVs above 8 kV.
Type 3	5	1	12.8 kV was the lowest value. All bars had CIVs above 8 kV and 3 at or above 16 kV.
Type 4	4	1	All CIVs were above 16 kV.

Figure 6 – UV camera view of the corona discharge at the junction – Case 1

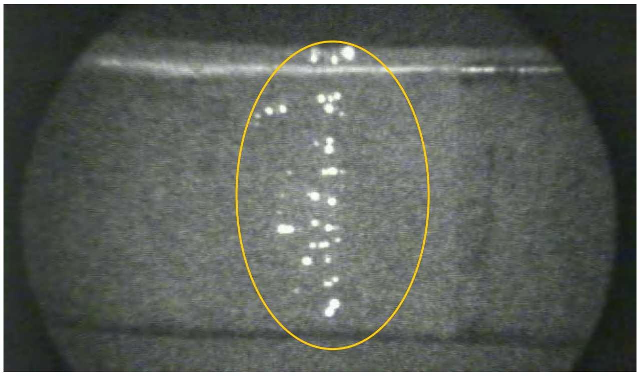

Figure 7 – UV camera view of the corona discharge at the junction – Case 2

VI. IMPROVEMENTS TO STRESS-GRADING COATINGS

After these findings, discussions were undertaken with our manufacturers to see what could be done to avoid such deficiencies in new windings.

Tests by one manufacturer led it to change its manufacturing process. From a traditional stress-grading paint, it now uses a silicon carbide (SiC) tape, which ensures greater uniformity in SiC particle dispersion and in field distribution along the end windings. Tests have shown that the new tape adheres as well to the ground-wall insulation as does the semiconductive tape.

To ensure that future stator windings supplied to Hydro-Québec do not deteriorate due to the corona effect over the 45-year service life expected of them, further requirements have been added to our technical specifications.

VII. RESULTS FROM VARIOUS COMMERCIAL INSPECTION METHODS

Lab tests were conducted to select the quickest and least expensive junction inspection method that achieves the desired sensitivity. We also sought a method that could be used in both factory and generating station. Factory testing involves applying 16 kV AC to the bar at ambient temperature and to check the sensitivity, advantages and drawbacks of each method. Our conclusions for the various methods tested are summarized below.

Capacitive coupler measurements

A phase-resolved partial discharge (PRPD) detection system was used, with two detection ranges: 40–800 kHz and 2–20 MHz. Though trigger thresholds were properly detected for both frequency ranges, it is often impossible to detect the external discharge trigger threshold at the junction since it is much higher than the internal discharge trigger threshold. Also, the method cannot be used for simultaneous detection on several bars.

Ultrasonic measurements

Measurements were taken with the wideband (150-kHz) Ultraprobe using no waveguide. This instrument is sensitive to both internal and external discharges. Since the bars are live, it is impossible to get close enough to distinguish between internal and external discharges. Detection from a distance greatly reduces the instrument's spatial resolution. Furthermore, the width of the conical beam used makes it practically impossible to take simultaneous measurements on several bars.

CoronaProbe electromagnetic measurements

This probe, formerly marketed under the name "TVA", comprises an antenna capturing a 500-kHz to 10-MHz electromagnetic signal. Detection is highly localized, covering an area of only 1 x 5 cm. The dial gauge supplied with the probe could not detect corona discharges. When connected to a PRPD system, however, detection was better than with the preceding methods. It remained difficult, however, to distinguish between internal and external discharges. Since the probe had to be placed close to the discharge site, it was not practical for testing several live bars at the same time.

Naked-eye inspection

The so-called "blackout test" is precise but requires, for each set of bars, a 15-minute wait in complete darkness for the eye to accommodate and become sensitive enough. This is the method that has been used until very recently.

UV camera observations

This is the most sensitive method and can be used to measure several bars simultaneously. It is very safe since there is no need to be near the bars and it can be used under regular lighting conditions. This is the method that was selected.

VIII. NEW SPECIFICATIONS FOR CORONA-FREE STATOR WINDINGS

Factory specifications

Bars must be free of corona discharges at the junction between coatings up to 16 kV AC. For a batch of 501 to 3,200 bars or coils, 80 bars or coils must be tested. This gives an acceptable quality level (AQL) of 0.4% for a double-sampling plan [7]. This AQL gives adequate statistical confidence for the batch.

Double sampling means that if a single sample fails the test, a second batch of 80 bars or coils must be tested. If another defect is found, the entire batch must be checked. Depending on the problem, Hydro-Québec may accept or reject the batch. Generally, the defects detected are caused by scratches in handling or by dirt, and repairs can be made in a few minutes with stress-grading paint or light cleaning.

Figure 8 is the decision tree for double sampling a batch of bars or coils.

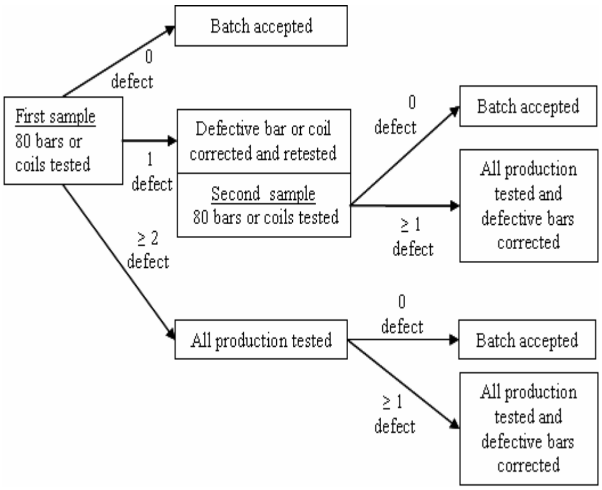

Figure 8 – Double-sampling decision tree for a batch of bars or coils

Generating station specifications

Besides factory tests that ensure that the stress-grading coating itself is of high quality, other testing is carried out at the generating station after the unit has been assembled but just before applying finishing paint. This final testing ensures that defects did not slip in during assembly (scratches, chipped paint, inadequate spacing, mispositioned RTD cable, etc.). During generating station testing, each stator phase is energized while the other two phases are grounded. The test voltage is 12 kV AC at ambient temperature. Spots with visible PDs must be repaired by sanding, cleaning or applying stress-grading paint.

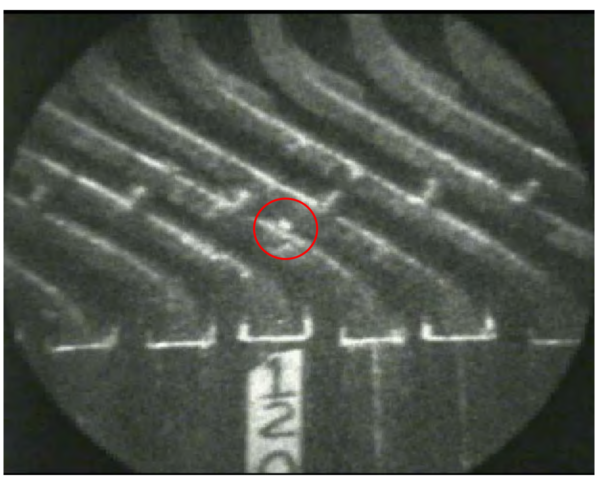

Figure 9 – Sign of the corona effect in the generating station

UV camera specifications

Observations must be made using a camera with adequate sensitivity to ultraviolet radiation of wavelengths shorter than 300 nm (UVB and UVC).

IX. DISCUSSION ON SPECIFICATIONS

Some manufacturers initially preferred 15-minute blackout testing. They feared that the camera would not be sensitive enough. In most instances, both visual and UV camera tests showed that their bars or coils were free of discharges at junctions up to a voltage exceeding 20 kV.

Factory testing made it possible to quickly check product quality. Testing 80 bars by batches of 7 to 10 bars takes about one-half day and is quicker with the UV camera since there is no need for eyes to accommodate to the dark when changing batches.

Applying 16 kV for 15 minutes in the factory has practically no effect on winding service life. According to some authors, it would reduce service life by less than 15 days [4].

Generating station testing takes about one day, including any minor repairs required and subsequent retesting.

Since these specifications were applied, the quality of windings and of their installation has greatly improved. Defects observed are minor and simple to repair. In one generating station, an entire stator recently passed the test on the first run, showing that when the manufacturer exercises craftsmanship, excellent quality results and everyone wins.

X. CONCLUSION

To keep a generating fleet in top working condition, Hydro-Québec's experience both at generating stations and in the lab has shown that corona discharges at junctions must not be neglected.

It is preferable and possible to attack the root causes of such discharges rather than taking corrective action on units once in service. Generating unit outages for repairs, or worse, due to a failures, amount to appreciable loss of revenue. With the stress-grading products available today, there is no reason to tolerate PDs at their junction.

Generator manufacturing is now scattered around the globe. No manufacturer is safe from a problem with a supplier. If a defect is detected after installation, or worse, after commissioning, the economic impact can be costly and negotiations with the customer are bound to be painful.

The small economic impact on purchase price makes it preferable to have specifications that cover the semiconductive/grading junction. The UV camera makes quick checks possible at little cost.

It would be important to have an international guideline on inspection of such junctions to make all manufacturers aware of this issue.

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