Multi-stress cyclic testing of Roebel Stator Bars for Hydropower

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Abstract

A multi-stress test rig was built to investigate the effect of many start-stops (load cycling) on hydropower generator insulation. To emulate real-life start-stops, stator bars were subjected to accelerated temperature cycling by circulating a 3.5 kA current and then cooling down with fans while high voltage (service voltage) was applied simultaneously to the insulation. A total of 250 load cycles were applied. Partial discharges (PD) were recorded on-line during load cycling, and after every 50 cycles, off-line dielectric loss and PD measurements were conducted. There was an apparent increase in dielectric losses after they had been subjected to a total of 250 load cycles. During load cycling, the PD level generally decreased with temperature, but there was a temporary increase in the PD activity during temperature rise and fall. This trend can be explained by different thermal expansion in copper and insulating material (epoxy-mica), suggesting that a stator bar that is load-cycled will be exposed to substantially higher PD levels than a stator bar under a uniform load and temperature, leading to further deterioration of the insulation quality.

1. Introduction

Increased penetration of wind and solar power combined with phasing out of nuclear and carbon-based power plants will promote more intermittent hydropower operation to ensure the power grid's stability and maximize earnings. More frequent start/stops will introduce increased thermo-mechanical stresses on the components, especially in materials with different thermal expansion coefficient interfaces. Degradation and aging are thus expected to increase significantly for the stator windings, where copper bars or coils are wrapped with thermoset insulation, i.e., mica-polyester or mica-epoxy. During temperature increase and decrease, the copper in the bar changes its dimension to a larger extent than the insulation leading to thermo-mechanical stresses in the insulation material.

According to IEC 60034-18-34, [1] thermal cycling from the intermittent operation of generators can induce the following defects in the insulation layer:

1. Delamination between layers of insulation
2. Delamination between insulation and conductor
3. Abrasion of the outer surface (outer corona protection, OCP) of the insulation
4. Circumferential cracking of the insulation outside the slot part
5. Mechanical damage due to distortion of the end turns of winding

New generator windings must undergo a load cycling test procedure followed by a long-term high-voltage endurance test where the performance is compared to equivalent non-cycled stator windings to be qualified according to IEC 60034-18-34 [1], and IEEE Std 1310 [2] in North America. Diagnostic tests such as measurement of $\tan(\delta)$ and partial discharge (PD) measurements should also be undertaken, but there are no pass/fail criteria. These tests are proposed to facilitate identifying the dominating process leading to the degradation or failure of the stator windings.

Both $\tan(\delta)$ and PD magnitude have been measured periodically during several laboratory load cycling experiments to estimate the degradation and remaining lifetime of stator windings [3–5]. It has been reported that $\tan(\delta)$ increases with the number of load cycles due to increased thermo-mechanical stress giving delaminations between conductor and groundwall insulation [3]. Another study shows that $\tan(\delta)$ values also increase with the number of load cycles and correspond to a decreased breakdown voltage [4]. In [5], delaminations were observed by tapping on the insulation surface after 300 load cycles, and the PD activity increased correspondingly.

Multi-stress testing, with simultaneous thermal and electrical stress, on stator windings has been performed in [6]. They found that PD magnitude and current increased with the number of load cycles, caused by both increased size and number of delaminations and voids. But, after 1500 load cycles at maximum temperature 122 °C, there was only a small reduction in breakdown voltage. These studies indicate that new stator windings can endure several thousand load cycles.

A recent study [7] of stator bars aged under service with 10,000 start-stops investigated the effect of laboratory load cycling according to IEEE Std 1310, equivalent to IEC 60034-18-34. No delamination was observed before load cycling. After only 20-30 load cycles in laboratory severe delamination was found in companion with a significant increase in $\tan(\delta)$.

The average age of Norwegian hydro generators is approximately 50 years [8]. Even if few failures occur annually, international statistics point to insulation system failures as the root cause [9]. The resilience to harsher and more dynamic loading patterns for these hydro generators, which have been in service for several decades, is unknown. No studies, to our knowledge, have investigated how multi-stress load cycling affects the condition of the insulation in generator bars taken from service, as they have either have been conducted on new stator bars or only have applied thermal cycling. There is thus a need to develop methods that can estimate the degradation and technical state of the insulation system providing real-life stress on the insulation system.

A multi-stress test rig was built to investigate the effect of many start-stops, i.e., load cycling, on the degradation of the stator winding insulation. To verify and demonstrate the rig's abilities and get reference measurements, new Roebel stator bars with wet bands (resin rich) mica-epoxy mainwall insulation and a nominal phase voltage (U_0) of 7.4 kV were tested in this work. The focus was on two main tasks for experiments with load cycling: i) A better understanding of how stresses/forces degrade the insulation during simultaneous load cycling and electrical stress, and ii) how do these stresses affect the insulation condition after many load cycles?

2. Equipment and methodology

2.1. Load cycling rig

In Fig. 1 (a) a sketch of the load cycling rig is shown, whereas Fig. 1 (b) shows an image of the physical implementation. We constructed the rig in a manner to be as flexible as possible so that it can accommodate different types/sizes of stator bars. The model stator was thus constructed of steel plates clamped with bolts around each stator bar. The stator bars were connected in series and formed a current loop at ground potential. AC current was provided by a split-core transformer, as seen in the front in Fig 1 (b). The model stator steel plates, which were isolated from the steel frame, were energized with high voltage (HV) from a medium voltage transformer, seen to the right in Fig 1 (b). This approach enabled temperature sensors to be inserted in the conductor (at ground potential) to provide accurate temperature measurements for regulation and control. Industrial fans were installed in the supporting steel frame and provided cooling. The test rig was controlled by a PLC system, and current and temperatures were logged at the center of the bar, at the end of the straight part, and in the end windings in both conductor and surface of the insulation.

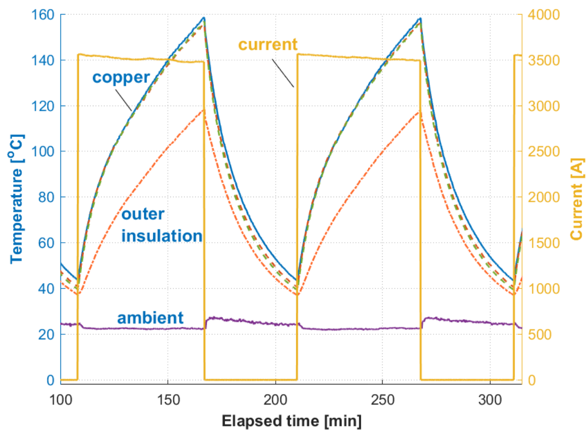
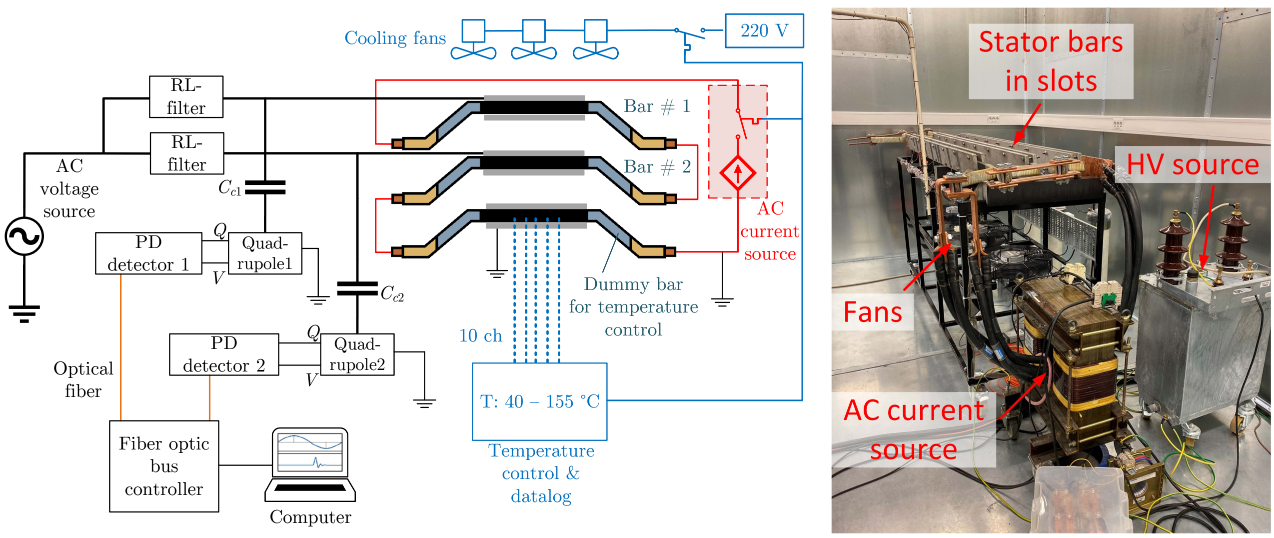


Fig. 2 – Load and temperature in the conductor, stator bar surface, and ambient during load cycling.

In order to emulate real-life start-stops, stator bars were subjected to accelerated temperature cycling by inducing current up to 3500 A and then cooling down with fans and HV simultaneously. A complete temperature cycle from 40 – 155 °C and back to 40°C took approximately 90-100 minutes, in accordance with IEEE Std 1310. This test protocol is significantly more stringent than



(a) Illustration of the constructed load cycling test set-up. **(b)** Image of the constructed load cycling test set-up.

Fig. 1 – Multi-stress load cycling rig built for on-line and off-line tests.

a usual start/stop in a Norwegian hydropower plant, where the maximum temperature usually is 80−90 °C. To emulate the stator core, stainless steel plates were clamped on the sides of the stator bars. Three stator bars were simultaneously heated and cooled. Two bars were simultaneously electrically stressed under HV, while the third bar was at ground potential, allowing direct temperature measurements as a reference. The measured conductor temperature was used to regulate the auto start-stops in the test rig.

A total of 250 cycles (1 cycle = heating + cooling) were applied. During the load cycling, partial discharge (PD) in each bar was recorded on-line on individual channels. After every 50 cycles, the insulation conditions of the bars were characterized using dielectric loss and PD measurements (off-line). The testing scheme is shown in Fig. 3.

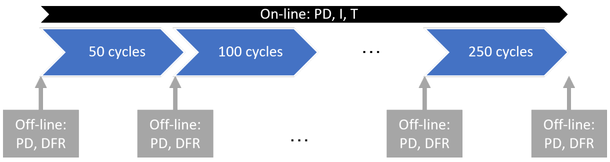


Fig. 3 – Outline of the testing scheme.

2.1.1. Partial discharge measurements

PD measurements were performed according to IEC 60270 [10], using an Omicron MPD 600 system and 800 pF coupling capacitors. During load cycling, the two bars energized with HV were electrically isolated by RL-filters in the high frequency (HF) band, as shown in Fig. 1(a), thus allowing for separate PD measurements of each stator bar (without crosstalk) during load cycling. At intervals of 50 load cycles, the end connections were removed, and each stator bar was measured off-line to also investigate inception voltage (PDIV) and voltage dependency of PD-parameters.

2.1.2. Dielectric loss measurements

Dielectric frequency response (DFR) was measured at intervals of 50 load cycles with a GE-Programma IDA 206 Insulation Diagnostic Analyzer connected to a Trek HV amplifier. RMS test voltages were 140 V and from 0.2 U_0 to 1.2 U_0. Since the stator bars were situated in the test rig during the measurements, placing a guard at the end-corona protection (ECP) was not possible. Hence the losses in the ECP were included in the measurements, which can cause a significant increase in measured losses [11]. Only relative changes should thus be studied rather than the absolute values from the measurements with different guarding arrangements.

2.1.3. Test objects

The test objects in this study were pristine Roebel bars with 2.3 m slot length and rated at $U_0 = 7.4$ kV (phase-to-ground). The mainwall insulation system is resin-rich epoxy-mica, and ECP was painted following the supplier's guidelines. Three stator bars were load-cycled. One bar served as a reference for temperature measurements and was not at HV potential, while two bars were at HV potential simultaneously denoted G009 and G010 in this study.

3. Results and discussion

3.1. On-line PD

In Fig. 4 the PD-magnitude and PD repetition rate, n, for stator bar G009 and conductor temperature for the reference bare during two complete load cycles are shown. It can be observed that both magnitude and intensity are largest during increasing or decreasing temperature, with peak magnitudes of 6.5 nC and 7.3 nC, respectively. The PD magnitude stabilizes at 50 pC above 140 °C, while there is no plateau at low temperatures. Since the PD magnitude is much larger during temperature change than at steady-state levels at room and elevated temperatures (not shown here), the observed effect was likely caused by the formation of voids or changes in the geometry of existing voids within the insulation. As the stator bar heats up, there is an elongation that is not reflected in the thermoset insulation, and voids increase in size or the formation of new voids occurs. Likely competing mechanisms at high temperatures are the increased conductivity and pressure increase, which promote a decrease in PD magnitude. At a certain temperature, one or both of these mechanisms will cause a reduction in PD magnitude, approximately at 100 °C in the current experiment. As the temperature drops, the pressure in the voids and conductivity in the insulation and void wall decrease, and thus the PD activity increases again.

The increased PD activity during large temperature changes manifests that load cycling without simultaneously applied HV will not represent the realistic stresses the mainwall insulation undergoes during start/stops in a hydropower station. Since only the thermo-mechanical effects are engaged, and this can lead to an over-optimistic conclusion regarding the lifetime of generator windings.

3.2. Off-line PD

The load cycling was stopped after each 50 load cycle to perform off-line low-noise PD measurements to evaluate if there had been any subtle changes or degradation to the insulation system during the load cycling that was not observed by the on-line assessment. In Fig. 5, the total apparent charge per period, 99 percentile maximum charge, repetition rate, and average discharge are shown for each 50 load cycle.

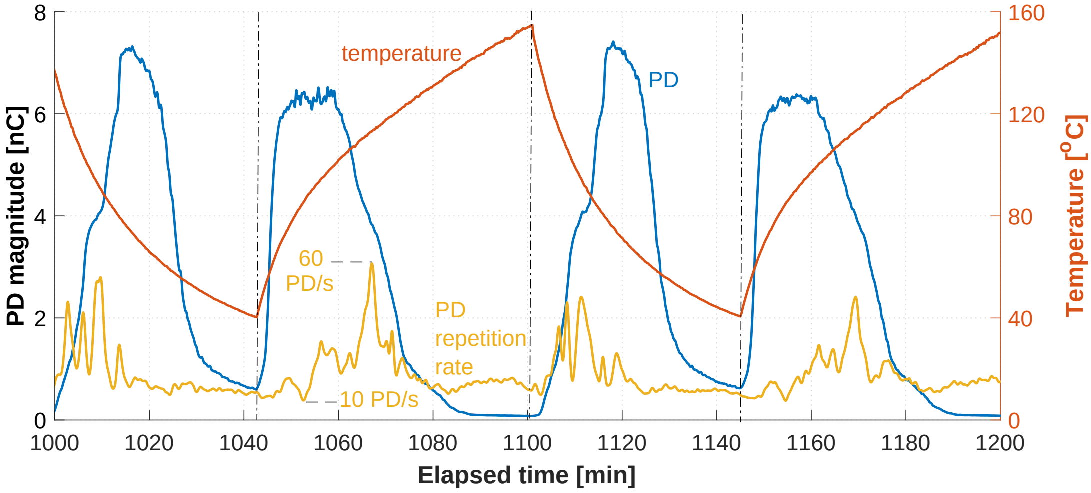


Fig. 4 – PD magnitude and intensity during load cycling.

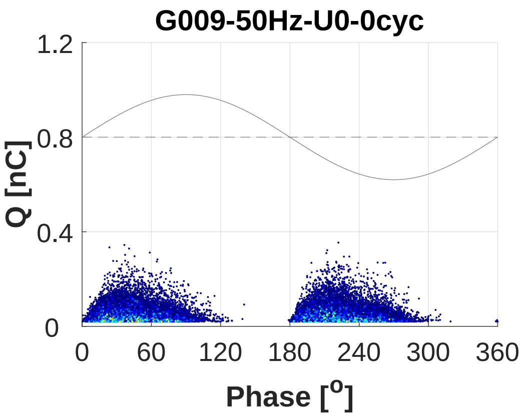
Fig. 5 – Trend of PD parameters after 0, 50, ..., 250 load cycles.

The only observable change in the trend is an increase in the max and average discharge at 150 load cycles. This was caused by a circumferential crack around the end-winding, as shown in Fig. 6. Due to the curvature in the end-winding, there will be variations in mica tape overlap and bonding between layers, which can cause decreased mechanical strength of the mainwall insulation in this region. Combined with the elongation of the copper core, this type of circumferential cracking can be the result. As load cycling proceeded, the increase in PD-activity declined back to normal. A similar trend was observed in the on-line measurements.

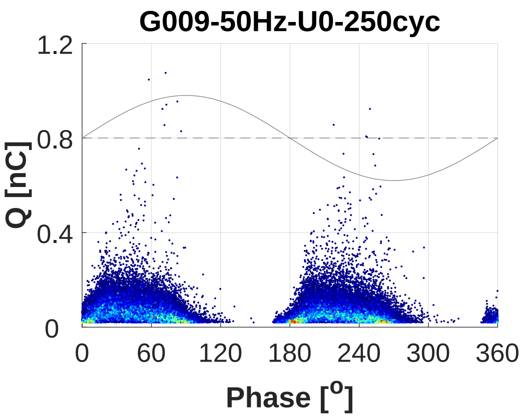
In Fig.,7 the phase-resolved PD (PRPD) histograms before load cycling (a) and after 250 load cycles (b) are

Fig. 6 – Crack in end-winding.

shown for stator bar G009. In these histograms, all PD events are shown and constitute the source data for the trend of PD parameters shown in Fig. 5. After 250 load cycles, it can be seen that there are PD events with a larger magnitude compared to before load cycling. This is consistent with an increase in void size [12]. It is also seen that after 250 load cycles, there are discharges present at the trailing edge just prior to polarity reversal in the PRPD pattern, which is caused by an increase in remnant charges in the voids. The latter can be a change in the electronic states at the surface or merely because larger deposited charges need a longer time to decay to zero. Combined, these observations suggest that there has been a change or degradation in the insulation system of the generator bars. They are not observed in the trend plot because the largest PD magnitudes are very few compared to the bulk of small PDs.



(a) PRPD histogram prior to load cycling.



(b) PRPD histogram after 250 load cycles.

Fig. 7 – PRPDA histograms before and after load cycling.

3.3. Dielectric frequency response

For both stator bars, there was a clear increase in dielectric losses measured at U_0 after they had been subjected to the 250 load cycles. In contrast, no consistent increase could be seen for the dielectric loss measured at low voltage (140 V), as shown in Fig. 8. Below PDIV, an increase in $\tan(\delta)$ will generally probe the overall increase in conductivity from the degradation of the insulation system. In contrast, above PDIV, there will also be a contribution to losses from the PD current, and an increase in $\tan(\delta)$ is expected. PDIV for epoxy-mica stator bars is usually in the range of $0.6U_0 - 0.8U_0$, see e.g. [13]. This is consistent with increased void size, i.e., more delamination of the mainwall insulation, as reported in the literature [3], and also with the increased PD-magnitude after 250 load cycles as shown in Fig. 7. Degradation of the ECP could also be a source of increased losses, but since it was not possible to guard the ECP in the measurements, the contribution from the ECP could not be isolated.

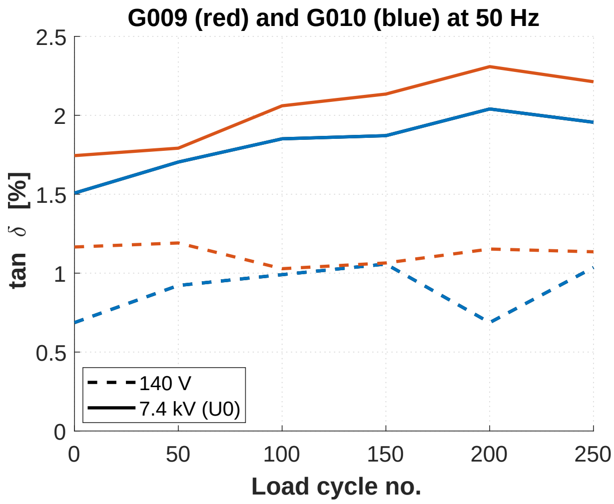


Fig. 8 – $\tan(\delta)$ as function of number of applied load cycles, measured at 140 V (dotted line) and U_0 (solid line).

4. Summary and outlook

A novel multi-stress test rig, with simultaneous thermal and electrical stress, for generator stator bars, has been constructed and demonstrated by completing 250 load cycles with simultaneous application of HV potential on two stator bars.

There is a significant magnitude of PD activity during temperature increase and decrease, showing that there potentially is additional electric-stress induced degradation during load cycling that current IEEE and IEC standards do not probe. Trending PD parameters show little change during load cycling, but careful inspection of PRPD histograms reveal that there are more, but few, PDs with large magnitude after 250 load cycles. This is consistent with the increase in $\tan(\delta)$ measured at U_0 present after 250 load cycles.

Following IEEE and IEC standards, load cycling is done as part of the test and development regime for new stator bars. The test is accompanied by monitoring changes in $\tan(\delta)$, and the acceptance criteria is that no significant change in $\tan(\delta)$ or $\Delta \tan \delta$ should occur – the latter being the difference in $\tan(\delta)$ between to following voltage levels. It is shown in this work that there is, in fact, an increase after 250 load cycles for new, previously unused stator bars. Following IEEE and IEC standards, load cycling tests do not include simultaneous application of HV to the mainwall insulation. Combined with the fact the large magnitude was observed during temperature change, we suspect that the more realistic multi-stress testing is the main cause, and such testing, therefore, should be considered to impose more realistic testing regimes.

The test rig and methods for assessment have now been demonstrated. Future work should focus on accelerated multi-stress ageing of stator bars taken from service in order to investigate how old hydro generators will cope with more intermittent operation. Comparison of load cycling with and without simultaneous HV should be of interest for standardization bodies, as this will address the relevance of the existing standards.

Acknowledgment

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