COMPARISON OF NEW AND OLD HIGH VOLTAGE DIAMOND COIL ELECTRICAL INSULATION PERFORMANCE FOR HYDROELECTRIC GENERATORS

ABSTRACT

This paper compares high-voltage electrical coils from hydroelectric generators after 38 years of service with newly manufactured replacement coils. The original coils are part of the US Army Corps of Engineers' renovation of the Chief Joseph Dam in Washington State, with 16 generator units (92,920 kVA, 13,800 V) being rewound. Preformed Windings will supply the new coils, designed to sustain decades of renewable energy production. With the average age of hydroelectric power stations in the U.S. approaching 50 years, this paper serves as a reference for the industry of the expected benefits that can be achieved by rewinding of the fleet using resin rich coils manufactured with modern techniques.

Keywords — Partial Discharge, Rewind, Resin Rich, Hydroelectric

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Quality: Our patent-pending ultra-low Partial Discharge (PD) manufacturing processes and in-house high-voltage testing ensure coils of the highest durability, safety, and performance.

Partnerships: We collaborate closely with OEMs, utilities, and service providers across the hydro sector to engineer tailored high-voltage solutions for critical applications.

Service: From R&D and technical design through to scaled production, we deliver a responsive, consultative approach, providing exceptional support to our hydro clients worldwide.

I. INTRODUCTION

This paper aims to inform the industry on the impact of generator operation on electrical insulation, discuss what are good quality indicators for high voltage coils and finally, the benefits of rewinding hydroelectric generators with modern resin rich insulation systems with improved manufacturing methods, giving better control of main wall insulation quality. The generator in question is a hydroelectric generator from the Chief Joseph Dam in Washington State, U.S.A, which has a rating of 92,920kVA at a line voltage (VL) of 13,800V.

This study compares three sets of high-voltage (HV) diamond coils manufactured for the same generator: the original coils removed after 38 years of operation, identical coils stored for 36 years, and newly manufactured coils for the generator's rewind.

The original coils were produced using the vacuum pressure impregnation (VPI) process. In this method, insulation tape is first applied to the coil before being placed in a vacuum vessel to remove air. Heated resin is then introduced under a wet vacuum to fully penetrate the insulation tape, followed by the application of pressure to facilitate resin flow into the coil insulation. Finally, the coils undergo a curing process to solidify the resin.

In contrast, the new coils are manufactured using resin-rich technology. In this process, the insulation tapes are pre-impregnated with resin before being applied to the coil. The insulated coil is then subjected to heat and pressure, enabling the resin to flow and fill voids within the insulation. These conditions are maintained until the resin is fully cured.

The original coil set was manufactured between 1983 (when the project was commissioned) and 1988 and have been manufactured to the specifications of the era. The conductors are manufactured with a brick effect using alternate enamelled and double dacron glass conductor covering. Turn tape and ground wall insulation are comprised of woven glass fabric backed mica tape applied to the coil. The NEW coils are manufactured with a film-backed mica conductor covering, film-backed mica turn tape with woven fabric glass backed mica tape for the ground wall insulation.

The rewind was triggered by high Partial Discharge (PD) measurements on the C-phase of Unit 10. For this study, four coils removed from generator Unit 10 were inspected for signs of operational degradation measured using 3D laser scanning technology and tested for key electrical insulation parameters, including insulation resistance (IR), Tan Delta, and PD. Additionally, the coils were dissected to evaluate the condition of the insulation system at various points along their cross-sectional areas.

PD is widely used as a method for determining the relative residual lifetime of electrical machines based on several factors as discussed in [1]. The primary indicator for ailing coil health is the increase in coil PD levels rising above 90th percentile of the fleet indicating high probability of failure [1]. The paper will present the results of these tests, quantifying the effects of prolonged operation on insulation integrity by comparing the in-service coils with coils stored since their original manufacture. Further comparisons are made with newly fabricated coils, highlighting advancements in insulation materials and manufacturing techniques. Improvements in insulation performance, as evidenced by the enhanced PD are discussed in detail.

II. VISUAL INSPECTION

The coils received from the Chief Joseph project are split into two categories, GEN coils are from the generator core and have been in service for 38 years. STORE coils have been in storage since manufacture in 1988. NEW coils were manufactured in 2024 at Preformed Windings manufacturing facilities.

The GEN and STORE coils were scanned and compared to the NEW coils to see any differences in the design. Figure 1 shows clearly that the NEW coil has longer projections compared to the original coil sets. It will provide a marginally increased coil resistance. The NEW coils are longer at 2428mm compared to 2280mm for the original coil sets.

Two coils were chosen for dissection one from the generator (GEN3 – due to failure), and one from storage coils (STORE 3). These dissections are compared to the new coil dissection done during the qualification stage of the coil development at Preformed Windings, as shown in Figure 2.

The straight sections of the coils have a good uniform structure and are very comparable to the NEW coil set in terms of uniformity of the copper strands and the insulation of the ground wall is uniform in thickness and has minimal void content to the naked eye.

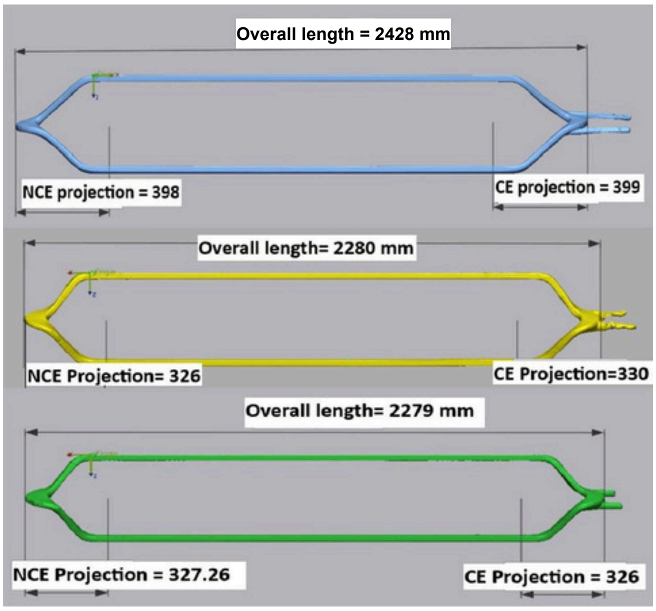


Fig. 1. Comparison of the overall dimensions of the original and new coil sets from laser scans, Top – NEW, middle – GEN, bottom – STORE.

The stress grading dissection cuts show misalignment in the conductors on all coil sets, however the NEW coil has significantly improved copper strand alignment. Also, the level of insulation is more evenly distributed around the circumference of the conductors. The original coil sets show a significant delamination and void content within the stress grading sections, the impact of which will be discussed in more detail further in the paper.

Fig. 2. Dissections of the three coil groups, Top – straight leg portion, Middle – Stress grading region (around the first bend), Bottom – beyond stress grading region.

III. ELECTRICAL TESTING

The three coil groups were tested to measure the quality indicators of the insulation system. The original coil group was checked for insulation resistance prior to other testing to ensure they are safe to do so.

A. Tan-Delta/PowerFactor

Tan Delta is a measure of the insulation dielectric properties as defined in [2] and is an indicator of the quality of the insulation system in the slot area. The testing was done with guard applied approximately 20mm (0.787inch) away from the start of the stress grading region to limit the impact of the stress grading resistance on the outcomes.

The measurements were done with a calibrated Omicron Tando 700 which is widely used within the industry. The tan-delta is measured on the coils at intervals of 20% of phase voltage, Un, starting at 0.2* Un up to 2* Un as indicated in Figure 3.
The results indicate that all groups of coils have good tan-delta measurements relative to the standards applied in [2] apart from STORE3 which has failed on the power factor tip-up specification between (2Un-1.2Un). Coil GEN3 failed during testing at 7.95kV.
Overall, no conclusion can be drawn from the effect of aging on tan delta of dissipation factor, or on the comparison with the NEW coils, apart from the NEW coils have a narrower distribution on the results.

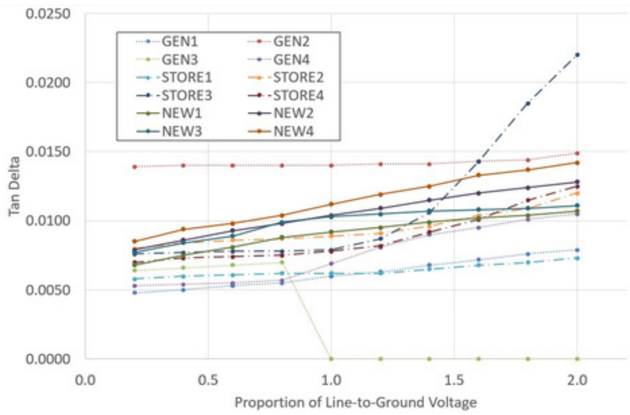
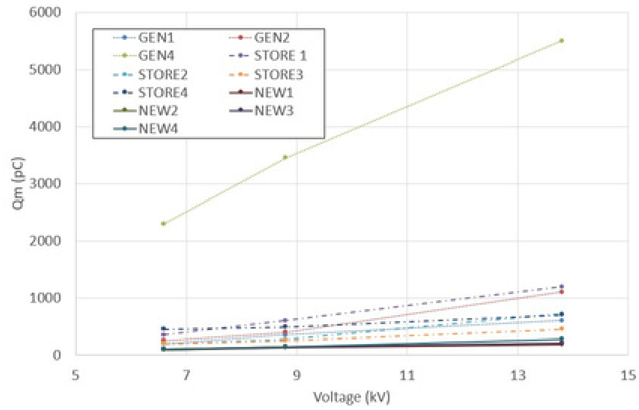


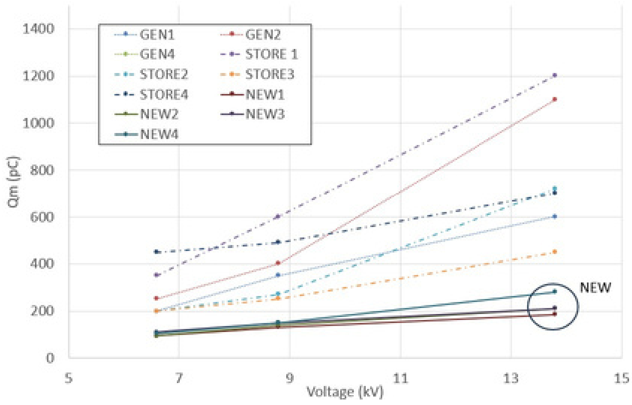
Fig. 3 Dissipation factor measurements on the coils sets.

B. Partial Discharge

The partial discharge was measured on all 3 coil groups to see the impact of in-service lifetime between the GEN and STORE coils. Figure 4 a) shows the measured values of the coils groups including coil GEN4 which has high levels of PD across the range.
If we exclude GEN4, then we can see in Figure 4 b) the values of PD between the GEN and STORE coil groups are similar with GEN1 coil giving remarkable results considering the lifetime. The distribution of the coil measurements suggests that the stored coils already have a significant variance prior to installation of the coils which could result in specific coils undergoing more rapid aging due to the higher initial levels of PD as seen on GEN4.
The NEW group of coils shows reduced levels of PD across the range of voltage measurements and have a far narrower distribution of values. This suggests that an improved manufacturing process allowing for greater control of variance over the whole set of coils, this in turn can improve the overall lifetime of the generator coil sets.



a) Including GEN 4



b) Excluding GEN 4 to give better resolution for the remaining measurements

Fig. 4. Partial discharge measurements across different voltage ranges for 3 different coil groups.

The increased PD in the original coil groups can be attributed to the higher levels of voids and delamination witnessed in the ground wall insulation of the coil in the stress grading area and beyond.
It is interesting to note that only coil GEN4 showed significant signs of aging with higher levels of PD when compared to the mean values of STORE coil group. However, when the PD inception voltage (PDIV) and extinction voltage (PDEV) is reviewed we see a difference between the used and unused coils. Table I illustrates clearly the differences between the GEN and STORE coils which have been manufactured to the same specifications at a similar time, with the only difference being that the GEN coils have seen over 38 years of operational life. We observe a 1.8kV reduction in the mean PDIV for the GEN coils, which would be a result of the aging of the insulation system over time.

IV. REVIEW OF COIL INSULATION

Given the differences in the PD levels between the original coil groups and the NEW coils it was decided to review the coil dissections in detail under a microscope. The purpose is to compare the finish quality of the ground wall insulation in order to understand the differences between the coil groups. The straight section of the coils were reviewed under the microscope and highlighted significant voids and delamination which was prevalent in all cross-sectional cuts from the original coil sets (both GEN and STORE). Figure 5 shows images of the delamination which were measured in the region of 0.15mm (0.006 inch) in the radial direction. The small voids were present in all corners of the slot section dissections from the original coil sets, which would contribute to increased partial discharge levels when compared to the NEW coils.

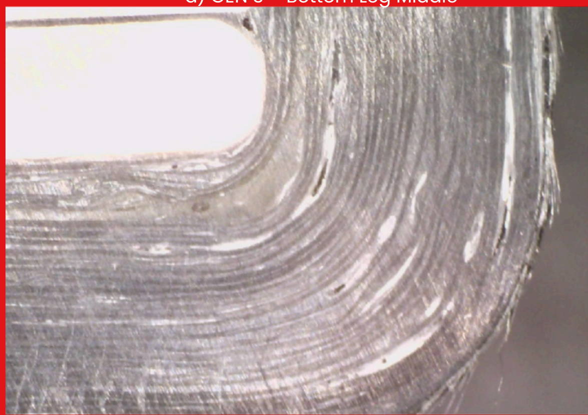
The NEW coil set, in contrast, showed no voids in the straight section.

GROUPS

Coil Group	PD Inception Voltage	PD Extinction Voltage
GEN	3.07kV	1.83kV
STORE	4.87kV	2.8kV
NEW	4.88kV	3.17kV

Table I. Overview of mean PDIV and PDEV for different coil

a) GEN 3 – Bottom Leg Middle



b) STORE 3 – Bottom Leg Middle

c) NEW – Middle of Leg

Fig. 5. Microscope image of coil insulation cross section.

V. CONCLUSIONS & DISCUSSION

Three coil groups, all intended for use in the same hydroelectric generator, have been tested, providing valuable insight into the effects of aging and the impact of different manufacturing techniques on generator coil performance. The tan-delta results indicated good performance across all three coil groups, with the NEW coils exhibiting greater consistency in outcomes. The tan-delta results confirm that the quality of the ground wall insulation in the slot area is good for all coil groups, without revealing insulation quality limitations in the end-winding. However, the original coils displayed a wider variance in results, suggesting that manufacturing control was less rigorous.

PD measurements revealed significant differences between the NEW and original coil groups. These differences can be attributed to the increased delamination and void content in the original coils, as confirmed by dissection cuts. In contrast, dissection photographs of the NEW coils show improved insulation characteristics, with better copper strand alignment and a more uniform ground wall insulation. This uniformity ensures even consolidation around the circumference, significantly minimizing void content and hence improving the PD results.

Through the comparison of the original coils, the tan-delta and PD results in themselves cannot indicate aging effects and therefore estimate lifetime, as mentioned in [4], however PD monitoring can detect when there is a significant increase in PD and therefore potential for failure as seen in coil GEN4.

The Partial Discharge Inception Voltage (PDIV) and Partial Discharge Extinction Voltage (PDEV) results could offer valuable insights into aging effects, with the values significantly lower for all GEN coils, which could indicate aging of the total coils in the generator [5]

The decision to rewind these generators stems from increasing partial discharge trends measured on Unit 10, potentially caused by a few individual coils within the generator, highlighting the need for rewinds to have consistency in the quality of the coils.

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