Hydrogenerator Stator Winding Aging Processes
and the Associated Synergies

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ABSTRACT
This paper examines and discusses the various aging processes in large form wound hydroelectric generator and motor stator windings having thermoset insulation systems. Detailed technical background information is presented to help support the information cited in technical references and the information the author has observed over his 42 plus years of experience. In particular, the impact of start-stop operations and load cycling effects are addressed. This is of particular importance to hydro powerplant owners due to the increased cycling and load changes that have resulted from deregulation and the recent penetration of renewable resources such as wind and solar.

BACKGROUND
To remain competitive and to optimize operations, hydrogenerator owners must be aware of the full cost of the ancillary services they provide. Often, the actual cost of a replacement winding is considerably less than the lost revenue associated with the downtime required to replace a winding that has reached end of life or that has failed in service, and these additional cost also may need to be included. Replacement costs must be considered in pricing ancillary services that would reduce stator winding life. Should a cost be assigned to a loss of stator winding life for requested ancillary services, customers eventually will demand validation of said fees. Unreasonable asset management fees or failure to justify these additional fees may result in litigation as the electric energy industry is very cost conscious, competitive, and highly regulated.

INTRODUCTION
This paper explores the various stator winding aging stressors that may or may not contribute to loss of life and the associated synergies. It also briefly covers variables that impact the quality and life of a thermoset winding associated with the manufacture, installation, and maintenance of stator windings. Detailed technical background information on winding and insulation systems is included because such information should be presented for an all inclusive review pertaining to insulation aging. This background is necessary to properly support the conclusions.
It generally is known and accepted that the primary end-of-life failure mode of stator windings is associated with insulation failure occurring due to insulation deterioration at or near the copper conductors of coils in the front half of coils operating at or near line potential. This deterioration usually results in an in-service failure. However, if serious deterioration is detected prior to failure, the winding may be judged to be at end of life and, therein, scheduled for replacement.

There are several other modes of failure, but they are quite uncommon and not necessarily an end-of-life issue. Failure modes associated with less than adequate (LTA) design, installation, and maintenance are not associated with normal aging of a quality winding and are not addressed in this paper. For example, in the 1970s there were many winding problems and failures associated with loose windings and slot discharges. These problems, for the most part, have been eliminated with redesigned insulation systems and improved maintenance and, therefore, will not be considered in this paper. Failures or aging due to inappropriate operations such as overloading, overheating, mis-synchronizing, etc., also are not addressed in this document.

**AGING PROCESS**

The major aging factors associated with thermoset insulation deterioration are voltage, thermal, and winding current-related mechanical forces.

**Voltage**

The voltage-related deterioration is associated with partial discharges (PD) occurring within voids of critical size or larger within the insulation system. Critical void size for machines operating at or above 6.9 kilovolt (kV) is between 0.005 and 0.06 centimeters (cm) depending on void location [1]. The voltage aging stressor is at work only when the winding is energized and only when voids within the insulation become significant in size due to other aging factors (manufacturing defects aside). Thus, voltage is not considered a cycling loss of life factor, but it becomes an aging factor once large voids develop within the insulation. Other stressors result in significant aging and/or failure well before electrical trees can even begin to form within an insulation system. Thus, electrical tree formation is not an aging issue.

PD can erode everything within an insulation system except for the glass and mica materials. PD produces relatively conductive nitric acid type byproducts within the voids. The conductive byproducts appear as greenish to greenish-gray powder adjacent to the copper. As the integrity of the insulation adjacent to the copper is damaged, or essentially shorted due to PD and other aging factors, the conductive byproducts result in the PD and PD-related damage progressing outwards from the copper. This reduces the effective insulation thickness and is the cause for an increase in the high voltage capacitance of a winding as observed in direct current (dc) ramp and sometimes in the power factor (PF) test results if the PF test is performed at sufficiently high test voltages. This outward progression also may be why PD monitor readings sometimes stabilize once a certain discharge magnitude is reached.

**Thermal**

Thermal aging forces are related to the operating temperature of the insulation. The insulation ages at an exponentially (natural LOG) faster rate with respect to an increase in operating temperature. For every 10-degree Celsius (°C) increase in operating temperature the stator...
winding insulation will age (thermally) twice as fast (Arrhenius equation for chemical reactions). Thermal aging is essentially the breaking of chemical bonds due to thermal agitation of molecules. This results in out gassing and the development of voids, reduced adhesion, and eventually in the complete loss of adhesion between layers of the insulation (delaminations). Early delamination may not detract from winding life if it is distributed, not located at the copper, and the insulation remains well compacted and tightly wedged in the slot. While a void involving a wide area is also a delamination; a delamination is not necessarily a void. Once voids are created, serious PD-related damage starts to occur.

The temperature drop from copper surface to ground wall surface (for indirectly cooled windings) is somewhere between 10 and 20 °C. Thus, the hotter insulation adjacent to the copper ages about twice as fast as the average of the ground wall insulation. This is why thermal deterioration usually starts at the copper surface. This partly explains why most multiturn windings fail turn to turn; and, upon dissection, why most of the ground wall insulation is usually in significantly better condition than the insulation nearest the copper. It also partly explains why single turn windings on average last considerably longer than multiturn windings.

A specified insulation class such as temperature Class F means the insulation system will not lose more than 50 percent (%) of original mechanical strength after operating at the rated maximum temperature of 155 °C for 20,000 hours (2.3 years). (The standards say nothing of initial bond strength.) If a particular insulation system exceeds the hour or temperature expectations, but does not meet the next higher temperature class (class H), it is can only be classified as a Class F insulation system, although this insulation may perform better than an insulation system that only just meets the Class F insulation requirements.

A Voith advertising document (currently on the internet) states that the Class F minimum weight loss at end of test shall not be more than 3% of original weight. As stated above, this 3% loss of weight will be concentrated in a thin volumetric strip around the copper conductor. This volumetric strip actually will have a much larger percent loss of weight. To put this in perspective, the percent binder for VPI insulation systems is about 25% by weight and can vary by several percent from coil to coil. As the binder decomposes, voids are formed. Voids also can exist due to LTA impregnation during manufacture. The Vogelsang et al., [2] paper presents data that shows an improperly impregnated winding may only last 10 % of a properly impregnated winding. Most of the deterioration occurs at the higher temperature adjacent to the copper. This is where the voids are concentrated and where the internal electric field strength (and, thus, PD activity) is highest and where it is most important to get adequate impregnation.

Operating a unit at a hot spot temperature of 155 °C does not mean the insulation will only last 2.3 years. First of all, this is simply the 50% loss of strength point and not end of life. In addition, most new windings being installed are Class F and quite often are operated at Class B operating temperatures (130 °C). This is either to maximize winding life or due to other machine component temperature limitations. Many machines also are not operated 24/7 at full load and are conservatively designed and/or operated at much lower temperatures. This further extends winding life. It has been the author’s experience that many of Reclamation hydro machines have a typical operating capacity of 40% and operate at maximum resistance temperature detector (RTD) temperatures of only 80 to 90 °C at maximum load. Reducing the load slightly further reduces operating temperature and greatly reduces the rate of thermal aging. In performing an insulation system assessment, two critical bits of information (not always available) are hours the
machine operated at full load and the full load RTD temperature. Often, many machines with long calendar lives have both low hours and temperatures at maximum load.

**Mechanical**

There are three sources of mechanical forces in a machine. The largest is the radial force acting to bottom the conductors in the slot due to total conductor current. The second largest force is the tangential force in the slot due only to the real component of conductor current and the degree of magnetic saturation in the core tooth tips. The tangential force is concentrated mostly on the conductor strands closest to the air gap. The radial forces are about 10 times larger than the tangential forces. Both forces occur at twice line frequency and tend to create shearing forces within the insulation. One reference [3] states the tangential force or torque on a coil is about 5 to 10% of the machine operating tangential torque. (Most of the tangential torque developed within a machine occurs between the rotor poles and the core tooth tips.) The third mechanical force is due to external vibration. The external mechanical stressors are due to inherent machine vibrations associated with core, rough zones, machine balance, turbine, and similar type of perturbations.

The radial mechanical force magnitude is related to the square of the associated conductor current. The radial forces are even higher when coils in adjacent slots are in the same phase (additive armature reaction flux). Machines with many parallel circuits and multiple turns per coil tend to have lower forces acting on the conductors in the turn closest to the air gap than in other machines. Higher speed machines tend to have greater conductor forces. The internal shear and crush withstand capabilities of a coil are related to the conductor dimensions.

The tangential forces usually are not a problem unless the conductors are designed abnormally close to the air gap. This could become an issue in some up-rated machines having conductors that are moved closer to the air gap (thinner insulation). This issue also can occur in machines that are redesigned to have a larger armature reaction due to an increase in rated current (increased tooth tip saturation).

In cases of extensive deterioration of insulation adjacent to the copper due to thermal and voltage stressors, the tangential forces also can contribute to insulation system deterioration. Tangentially displaced and severely worn conductors have been found in deteriorated windings. The author has observed that, in one instance (Yellowtail Powerplant), the conductors closest to the air gap vibrated tangentially through seven or so layers of ground wall insulation. This coil failed a high potential test at 15 kV dc. In another winding (Flatiron Powerplant), one-third of the front turn conductors were displaced; and the front conductors wore into each other (see figure 1).

The radial (and sometimes the tangential) mechanical force is a major contributor in accelerating insulation system deterioration (delaminations and void generation) once the insulation bond strength and binder volume has been reduced due to thermal aging. Mica and glass materials used in insulation systems are not affected by PD or high operating temperatures. However, when dissecting a deteriorated coil, one usually finds ground up mica and glass. This is due to the mechanical pounding that occurs between the copper conductors and the insulation once resin volume decreases and associated adhesion is lost. This almost always occurs in the conductors and turns closest to the air gap where the mechanical forces are greatest. The strands
closest to the air gap also can run hotter if the coil set back is too small, which would increase thermal aging in this area.

Figure 1. Effects of radial and tangential mechanical forces. Displaced stranding on the left (front of slot) is 10% narrower due to vibration wear. Note PD, thermal aging, and reduced turn-to-turn insulation thickness.

Thermal Expansion

The difference in thermal coefficients of expansion between copper and insulation is of concern to many people. The different coefficients of expansion will result in thermally generated, differential-related mechanical stress between copper and insulation, which could cause the insulation to eventually shear and/or delaminate from the copper or between layers of insulation. Winding suppliers take great effort to match the thermal coefficient of expansion of the insulation system to be as close as possible to that of copper. Manufacturers are reluctant to discuss matching thermal expansion coefficients. However, there have been some inferences that somewhat flexible epoxies and fillers are used to address differential thermal expansion stress and to prevent cracking. A Siemens paper [4] states their insulation “… systems use a mica material capable of withstanding high electrical and thermal loads, together with curable, elastic epoxy resins as bonding material.” No solid evidence, research, or proof that significant differential thermal expansion-related aging occurs could be found in the literature.

Unit Cycling and Start/Stops

While some consider unit cycling, start/stops, and the resulting differential thermal expansion forces between copper and insulation to be a major aging factor there is LTA evidence to support this belief. It is the author’s opinion that the loss of life due to cycling (load changes or start/stops) is a hold over associated with some asphaltic-mica insulation systems. Some, not all, asphaltic-mica insulation designs did experience aging associated with cycling. Thermal ratcheting of the tape layers sometimes occurred when the asphalt heated, expanded, and pushed tapes out of the slot at the upper or lower core boundaries.
Unfortunately, regarding thermoset insulation systems, thermal cycling is still referred to as an aging issue associated with cycling. It is also frequently brought up in dissection reports.

In some dissection reports, cycling is frequently and erroneously cited with little to no scientific basis as the cause for the observed delamination. (During a dissection, it is not always easy to distinguish the difference between delamination and weakly bonded layers of insulation. However, and typically, no mention is made of the extensive and often gross discoloration of the insulation often shown in dissection report photos. The discoloration indicates the binder (epoxy or polyester) has essentially decomposed from the heat-related aging. Epoxy does not melt; it slowly chars (oxidizes), changing color from tan to brown, and finally to a carbonized brittle black substance. Sometimes, what are observed to be delaminations are really extremely poorly bonded tapes, again due to the chemical transformations of most of the binder. Further, in many dissection reports, little to no information is provided as to the thermal age of the insulation. The hours at or near full load and the corresponding RTD temperatures are most important in the dissection-related analysis. (Hours of operation at reduced loads and reduced RTD temperatures of more than 10 °C are not as important as the rate of thermal aging, which is cut in half for each 10 °C reduction in temperature.)

The author’s experience at Reclamation indicates that frequently start/stopped-cycled generators seem to last as long as units that are not extensively cycled. Reclamation experience indicates temperature and hours at maximum load and mechanical radial forces are the most important aging factors.

This observation is supported by other references. In a Von Roll and Swiss Federal Institute of Technology joint research investigation article [5], the authors state, “Aging is not dominated by electrical stress, but rather by the combination of different stress factors, of which thermal and mechanical wear are the most important.” The article also states thermal aging essentially is the thermal degradation of the binder resin.

In the early 1980s, General Electric built a thermal aging facility to evaluate stator insulation. After 3 years of extensive isothermal and thermal cycling involving thermoset insulation systems (full size coils), one conclusion in their published results [6] was “... cyclic aging of the Class B and Class F insulation systems is less damaging than continuous isothermal aging ...” (figure 2).
Figure 2. Percent Voltage Withstand vs. Isothermal and Cyclic Aging (Taken from reference [6].)

One set of bars was isothermally aged at 170 °C for 3 years, and one set of bars was cycled 12 times a day from 40 to 170 °C over a 3 year period for a total of about 13,000 cycles. The bars were maintained at 170 °C for ½ hour during each cycle. 13,000 cycles corresponds to 2 cycles per day for 20 years. (Note if a unit is cycled more than twice a day the winding temperature swings would most likely be reduced as the unit would be restarted before it has a chance to cool significantly.) At the end point the isothermal bars % voltage withstand strength had dropped from a maximum of 108% to 98% of original. The slope showed the voltage breakdown strength might drop to 85% of original (and possibly less) after another 3 years of isothermal aging. The cyclic bars % voltage withstand strength at the end of 3 years had increased to 110% of original breakdown strength. Note the degree of thermal aging at 9 months of isothermal aging is the same thermal aging after 3 years of cyclic aging (1/2 hour at temperature times 12 cycles/day times 3 years equates to 9 months at a continuous temperature). The % voltage withstand at these two points in time are equivalent.

Within the hydropower industry, there are some references to past estimates on the effect of start/stop cycles. Again, these may be a hold over associated with some asphaltic-mica insulation systems, and no hard science was found to backup any of these estimates. In any case, the number of hours cited often does not add up. For example, a major winding manufacturer stated a winding would lose 16 hours of life for each start/stop cycle. This number does not sound reasonable when applied to many Reclamation and other units. It appears most of Reclamation multiturn windings last between 20 and 30 years regardless of how frequently they are started and stopped. For example, the 105-megavoltampere (MVA) Mt. Elbert pump-generating units (74-inch core length) have been stopped and started once or twice a day for 26 years (roughly 33% duty cycle at full load). Unit 1 has multiturn coils, and Unit 2 has single turn coils. Respectively, these units have experienced over 6,600 and 9,100 starts. A loss-of-life calculation based on the 16-hour loss estimate would indicate that these windings should look or test like windings that were operated at 33% duty cycle for 58 and 74 years. Therefore, the 16 hours loss life per start-stop estimate is by no means reasonable.

Various dielectric tests performed on the Mt. Elbert unit indicated slight some aging, but the winding is far from end of life. The Unit 1 multiturn winding (mica and polyester-modified epoxy resin) showed signs of aging when corona probe tested. In 1999 and 2004, the highest Unit 1 corona probe readings\(^1\) were between 40 and 50. In 2009, three coils had corona probe reading between 100 and 120. (Experience indicates multiturn coils with readings above 200 to 300 are in danger of failing. In 2010, the front leg of the coil (second from the line), having a reading of 120, was removed and dissected. The results showed the groundwall insulation was in excellent condition. The ground wall-to-turn interface bonding was weak and showed moderate signs of thermal aging (tan to medium brown binder and major areas of missing binder) in the outer layer of turn insulation. The manufacturer drawing identifies this damaged layer as an inner binder of Dacron tape (possibly added due to tape reversal at this interface). The Dacron tape on the back turn had over 70% of binder missing. There might not have been high intensity PD occurring since this polyester woven tape was white in color and showed no

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\(^1\) Corona Probe Calibration to charge transfer is not possible; thus, a relative figure of merit is typically used.
signs of damage to the tape fibers. In the interstices of the woven tape no residue was found where the resin was missing. There are several possibilities why the deterioration was limited to the Dacron tape layer. The remaining turn insulation was intact, well bonded, slightly discolored in spots, and well bonded to the strand insulation. There were two very minor green spots (1/2 inch long) on the enamel strand insulation of two different strands. This indicated some very minor PD was occurring. There were no signs of mechanical-related distress in the well consolidated turn bundles. Thus, this level of deterioration would be more typical of the actual age of the winding, 26 years, than the adjusted age using 16 hours per start/stop of 58 years. Essentially the 16 hour /start-stop loss of life assumption does not correlate well with reality based on dissection observations and a multitude of dielectric test data.

Many large P-G units and motors do not seem to have a long winding life. This most likely is due to the large mechanical forces generated in the windings when started across the line. Some large P-G units and motors that are across the line started will have stator winding startup currents that are 4 or more times greater than rated current. This current does not raise the coil temperature beyond rated as the startup period is of short duration. However, across the line starting typically results in mechanical forces that are 16 or more times larger than mechanical forces generated at rated current. Thus, frequent across the line starts of P-G units and motors will substantially increase the rate of mechanical-related damage of thermally aged/weakened windings. The Mt. Elbert P-G units are started in soft start mode to limit starting current to less than rated current.

Even if cycling and start/stops was shown with hard science to be an aging factor, generators started and stopped frequently (more than twice per day) probably see reduced thermal cycling. Thus, the number of cycles and start/stops are not always cumulative. This is due to the thermal cooling time constant associated with the mass of the frame, core, and winding. A machine that remains online and load-cycled also will see reduced temperature changes when load cycled. This is due to the core loss-related heat generated from an excited core. For example, the recently rewound G-5 13.8-kV, 125-MVA generator at Grand Coulee had a no load core and windage and friction heat loss of 1160 kilowatts (kW) and a full load copper loss of 333 kW. The change in temperature from spinning at no load to full load would be less than 40% of a cold start. Thus, generators that are started and stopped less than one or two times per day and having limited full load run time most likely would see the largest thermal excursions.

Another point often made without merit is the concern that during a cold start, there are damaging thermal expansion-related shearing forces developed due to differences in the coefficient of expansion between copper and insulation. The magnitude of this stress is proportional to the associated temperature differential imposed across the insulation and on the actual temperature of the insulation at the time of the start. Regarding both the temperature and the differential, it has been shown that there is considerably less shearing force developed during application of a step increase from zero to rated current than during normal operation. This is due to the specific heat capacity of the copper conductors being quite high. That is, it takes considerable time for the copper to reach a steady state temperature for a step increase in current. This effect limits the temperature differential between the copper and the adjacent insulation, and across the insulation.

Test data shown in figure 3 and taken from a paper by Doctors Morin and Bartnikas [7] on accelerated life testing illustrates this very important key point. The coils were in a mock steel
core with cooling vents, forced cooling fans, packing, and wedges. As can be seen in the plot, a step increase of rated current will result in a considerable time delay for the copper to reach steady state temperature conditions. Further and most importantly, the plot shows the thermal expansion-related stress is a maximum at the high temperature steady state full load operating point. This differential temperature is constant for a given machine current and is proportional to the machine current.

In an independent and unrelated Reclamation funded research investigation performed by Siemens [8], the same results were obtained and are shown in figure 4 (taken from Bethge et al. [8]). These test bars were installed in a frame and laminated core mock up also with vents, forced cooling, slot packing, and wedging. The temperature rise period during heating was similar to a machine in service. However, the forced cooling cycle was considerably shorter than what occurs in service and, thus, deemed more stressful. Maximum copper temperature was set to be 20 °C higher than would occur in normal service. This resulted in a 30 °C drop across the insulation rather than the typical 10-30 °C drop that will occur in service. The bars were subjected to 60 days of full load cycling (4,324 cycles). This is about 12 years involving daily start/stops. Power factor tip-up and dc ramp test results were identical to initial test results. Average shear strength test results (to push 4 strands out of the consolidated bar were 4 newtons per square millimeter or 9,000 lbs/inch² which was 15% less than for a new bar and in accordance with the manufacture’s predicted value. There were no tape separations, voids, or delaminations found during subsequent dissections. Tapping on the bars indicated there was no delamination.

In another unrelated Reclamation study, thermal expansion tests were performed on 7 coil samples: 2 new samples taken from 2 new coils, 4 well-aged samples taken from the Flatiron generator that failed in service (figure 1), and 1 well-aged sample from a Glen Canyon unit. On the two new coil samples there was no differential expansion between copper and insulation indicating the expansion of the copper was restrained by the insulation for these well bonded coil sections. In addition there was no difference in expansion between copper and insulation for one
aged coil (Flatiron unit1, neutral, back of slot coil sample). This shows that this test sample also was well bonded. In the other 4 aged coils the insulation expanded to the same degree as in the well bonded samples; however, the copper expanded about twice as much than the copper in the coils that were well bonded. These samples were from line end coils and/or from the top slot. This indicates the bond strength in these samples has eroded as the copper expansion is no longer being restrained by the insulation. These results support that PD in line-end coils and/or the higher mechanical forces that exist in the front of slot coil legs significantly contribute to the eroding of the insulation bond strength. Thermal cycling forces had little to no impact as the Flatiron neutral, back of slot sample was exposed to the same degree of thermo cycling as the other 3 Flatiron samples and yet remained well bonded.

Only one reference in the available literature could be found linking thermal cycling to delamination. This paper by H. Zhu and D. Kung of Power Tech Labs [11] addresses acoustic monitoring of one 13.8-kV epoxy mica bar under accelerated life testing per IEEE standard 1310-1996 (Recommended Practice for Thermal Cycling Testing of Form Wound Stator Bars and Coils for Large Generators). The acoustic energy level increased by a factor of 700 during thermal cycles 14 through 19. Thereafter, the energy dropped back to the initial precycling levels. Dissipation factor (DF) at 8 kV increased from 1.5% initially to 5.5% after 50 thermal cycles and the 2- to 8-kV tip-up went from 0.75 to 4.5%. Initial capacitance at 4 kV decreased from 3.6- to 3.1-nanofarads after 50 thermal cycles. The paper states that most of the acoustic signals occurred during the cooling periods. This agrees with another reference paper [12] that states insulation suffers more damage in compression than in tension, which is a typical property of tapes, ropes, wires, etc.

Unfortunately, the Zhu and Kung paper appears to focus on using acoustic signals to detect delamination during thermal cycling tests. Using the results of this work to relate thermal cycling to delamination is not justified. The rather limited information and documentation presented, and the lack of delamination location and size, are of concern and reason for discounting this paper at this time. From a photo one can only guess that the delamination is at least eight layers removed from the copper. The insulation does not appear to have uniform layers of insulation thickness and seems to have a very high percentage of epoxy. The coil was not constrained/wedged in a test fixture. Since others having performed accelerated life tests have not observed and reported such large changes in capacitance, DF, and tip-up, nor are such changes seen in actual machines, one must conclude that the electrical test results may be indicative of something other than the delamination identified by acoustic monitoring. These rather unusual test results would certainly be cause for coil rejection.

**Accelerated Life Testing**

The industry accepted standard accelerated life test is valuable, appropriate, and useful in making comparisons to other products that were tested under similar conditions and provides insight as to comparative quality of an insulation system. These tests also lend credence to the position that cycling has little to no impact on aging. The test coils are thermally cycled anywhere from several hundred to several thousand cycles, usually with accelerated voltage aging and wedged in simulated cores with current applied to expose the coils to mechanical forces. Many windings may be subjected to less start/stop cycles in their entire lifetime than in accelerated life testing. Dissection results of acceptable quality coils show no delamination.
It is also the author’s experience, and of primary importance, that dissection and test results of accelerated life tested coils bear absolutely no similarity to service aged coils because thermal aging is not included in the testing. (Realistically, thermal aging cannot be accelerated because the temperature of the test specimen must be kept below the insulation system glass transition temperature.) Often, the test coils show slightly higher power factor or PD, but these test results also are not realistic as the accelerated voltage aging test levels excite small voids and cause related damage. This does not occur at rated service voltages. When these coils fail during test, they fail due to the formation of electrical trees; this, too, is not an inservice aging-related failure mode. Another concern is that, in many accelerated life tests, the coils are not restrained or wedged in a core or similar clamping assembly. Finally, forced cooling to quickly reduce test temperature (figure 3) is a much more severe thermal cooling cycle than what occurs in service.

**Winding Longevity Related Variables**

There are many factors divided in five main groupings that can impact winding quality and longevity. Once a winding is commissioned, only the factors associated with operation and maintenance (O&M) can be managed to maximize winding life. Regarding this paper, it is assumed that the machine is well maintained and properly operated. A partial list of five groupings and associated longevity factors are listed below:

- **Insulation system and coil design** (insulation volts/mil, tape type, % epoxy, mechanical strength, etc.)

- **Manufacturing quality** (cure, glass transition temperature, void size, taping, forming, pressing quality, impregnation, quality control program, etc.)

- **Machine design** (core length, speed, conductor setback, cooling design, radial forces, eddy current loss design, up-rate design, etc.)

- **Winding installation** (quality, handling of bars—one can sometimes hear cracking when moving long, unsupported coils, installation stress, brazing process, keeping water out of coils when brazing, wedging process proper coil end turn spacing, etc.)

- **O&M** (keeping the winding clean, dry, and tightly wedged; avoiding mis-synchronization, overheating, overloading, overvoltage, and switching surges; and maintaining machine balance, alignment and air gap; etc.)

Given all these factors, assigning an expected life to a winding is quite difficult, if not impossible. It has been the author’s experience at Reclamation that a majority of multiturn windings last somewhere between 20–30 years, while some last considerably longer and some considerably shorter. A shorter life of 15–20 years was quite common for some, but not all of the earlier thermoset windings. (There have been many advancements and improvements in quality over the past 50 years.)

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2 This is the temperature at which the binder goes from a glass-like state to a rubbery-like state. Above this temperature, the coefficient of expansion greatly increases, the volume increases, chemical bonds break, and the resin separates from the glass or polyester tapes. Plasticizers are sometimes added when flexibility at lower temperatures is required.
Assuming a quality product and installation, winding life is dependent on insulation system quality, operating temperature, void content, voltage stress level, conductor current, number of turns, wedging, etc. The two most important factors are whether the winding is single turn or multiturn (for reasons stated earlier) and mica tape quality.

In a lab mechanical stress test [9], mica paper did not start to deteriorate until $10^5$ mechanical stress cycles, whereas mica splitting tapes started to deteriorate electrically after only $10^3$ mechanical stress cycles. For an average hydro peaking unit, $10^3$ start stop/cycles are about 2 to 4 years ($10^5$ stop start cycles is about 300 years). The same paper [9] shows the number of cycles to failure increases as the inverse tenth power of the strain amplitude for strain values less than 1. Thus, the lower level mechanical forces due to conductor current occurring 120 times per second over 25 years for a unit having a 40% duty capacity ($10^{10}$ times) could be significant, especially as the insulation system mechanical strength deteriorates due to thermal aging. The mechanical breakdown strength of mica flake layers is not that much higher than the conductor current related mechanical force.

For example, the Glen Canyon generator Unit 2 (multiturn coils, 83-inch long slot, 13.8 kV, 165 MVA) that was rewound in 1977 had signs of significant change when dc ramp tested 2 years later. The insulation was polyester-mica splitting. Top coil leg radial force at rated load when both coils in the slot are in the same phase is 350 kilograms (kg) (770 pounds). These units run at or near full load between 6,000–7,000 hours per year depending on snow pack and runoff in the Rocky Mountains. These units typically operate at 80–90 % load. RTD temperature at rated load is 92 °C. This is very heavy duty service and results in significant thermal aging. However, these units are typically start/stopped only 40–140 times per year. The test results showed a significant increase in winding capacitance around 12 kV dc—most likely due to ionization in or around the turn insulation and perhaps associated with early delamination at the turn to groundwall interface or within the turn insulation. (This change is rarely seen so early in a winding life cycle. A smaller capacitance change may be detected sometimes, but to a small degree and typically after significant aging has occurred over many years.) Dissection of the coils that failed in service after 23 years of service showed massive deterioration of the strand and turn insulation and major discoloring (thermal aging) of the groundwall insulation. It appears it took many more years of deterioration before the turn-to-turn insulation actually failed in service after roughly 150,000 hours.

Resins adhere better to glass-backed mica paper than they do to polyester-backed mica paper. Glass backing may have a slight advantage for use in the larger machines. The polyester backing can be damaged due to hydrolysis if water enters the insulation, if there was high humidity during production, or if excessively wet rags were used during the brazing operation. Epoxy resins are also adversely affected by water within the insulation. Several Reclamation coils and windings have been damaged due to water ingress that occurred during winding installation.

**Groundwall to Turn Insulation Interface**

In many dissections of moderately aged multiturn windings where the turn insulation is not severely deteriorated, the bond between turn and ground wall insulation quite often has little to no bond strength. It is difficult to determine the quality or even the existence of the bond of an aged winding during dissection as the dissection process can damage the bond. Tapping the coil surface and the resulting hollow sound (prior to dissection) provides some indication of
delamination either at the turn insulation surface, between layers of groundwall insulation, or significant deterioration at the copper strand insulation boundary.

A shear test of a coil cross section is the best way to determine bond strength. Loss of ground wall to turn interface bonding does not imply damage will occur in this area as a void is required for PD-related damage to occur. Further, the voltage stress in this area is lower than at the copper (unless the turn insulation is severely damaged). Loss of bonding in insulation layers adjacent to the subject interface rarely occurs prior to the loss of the interface bonding. This implies an inherent interface weakness. Some windings by design actually incorporate a shear plane in each coil (internal or external to the groundwall insulation).

It is suspected that it may be quite difficult to obtain or, over time, to maintain quality bonding between the turn and groundwall insulation due to the following:

- Turn surface contamination in storage and when handling and forming the coil (dust, moisture, and fork lift carbon dioxide exposure, oily or dirty hands and tools [10]).
- The smooth turn surface associated with mica flake turn insulation.
- Initial relaxation, shrinkage, and settling of the insulation. (Once in service, insulation thickness can shrink between 0.02–0.25 %.)
- The radial mechanical forces due to conductor current pounding the conductors into the thermally aged insulation. The loss of binder at the interface by weight and volume can result in weakening the interface bond.
- Lower adhesion of polyester-backed mica paper and/or intentional tape reversal at the interface.

Loss of resin due to thermal aging is sometimes mis-identified as LTA impregnation. LTA impregnation usually results in very early failures. A special test is required to accurately make this determination on significantly aged insulation.

**Coil Aging**

It has been the author’s experience that the front leg of a multiturn coil operating at or near rated voltage will age much faster than the back leg of the same coil. Dissection results of coils having high PD readings or of coils that have failed in service almost always reveals the deterioration to be greatest in the front turn of the front coil leg.

As discussed in the paper, multiple stressors must work in synergy to create the condition necessary for the subject failure mode to occur. The front leg is the typical failure location due to the radial mechanical forces being three times higher in the front half of the coil and to some degree, due to the greater tangential forces on the front turn of the front coil leg and the higher

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3. B stage turn to turn tapes (pre-impregnated): Amine-cured epoxies can absorb moisture and carbon dioxide (CO₂), which can result in chemical reactions that produce an oily or waxy feeling film, thereby affecting bonding to the groundwall tapes. The film appears milky to amber in color.

4. Reclamation rejected a winding due to LTA impregnation. The winding failed the acceptance tests.
eddy current losses in the conductors closest to the air gap. Thermal aging over time weakens the insulation bonds and reduces binder volume. This allows voids to form but by itself does not lead to this failure mode as dissections of lower voltage coils in machines reveal the thermal aging (discoloration) to be about the same in both coil legs.

Voltage stress also contributes to the failure once large enough voids are formed but by itself is not primarily responsible for this failure as the voltage stress is about the same in each leg of the subject coil. PD related damage is greatest in the front coil of higher voltage coils and, thus, is a major stressor but only in conjunction with the thermal deterioration and the follow-on mechanical-related deterioration. The forces due to differential coefficients of expansion on startup and at load can be ruled out as a major stressor as these forces also are the same in both legs of the subject coil. Furthermore, windings that are frequently cycled appear to last as long as windings that are not subjected to frequent cycling. Thus, the observations from dissections, in general, tend to indicate that thermal aging must be significant before radial forces and PD can become dominate aging stressors. Corona probe test results support this, because it takes many years of thermal aging before corona probe readings begin to detect increases in PD signals.

A recent example that illustrates this coil aging process is Flatiron Unit 1 generator. The details of the generator are: 13.8 kV, 47.8 MVA, 514 revolutions per minute (rpm), epoxy mica paper insulation, mica flake turn insulation, three turns per coil, and 1,000 amps per parallel circuit. RTD temperature at rated load is about 90 °C. This machine had 3,809 starts in the 23-year service history. It usually ran at full load for equivalent months at a time, passing water to fill a reservoir and providing power for a motor to fill an irrigation lake (summer operation 24/7: 50% load at night and 100% during the day; winter operation 24/7: 100% load for 50% of the time). It generated 2,591,204 megawatthours (MWh) over a total running time of 103,064 hours. The I-squared coil forces are two to three times higher than in most all Reclamation multturn, lower speed, larger diameter machines. Coil samples taken after the machine failed in service after 23 years showed extensive thermal aging in line and neutral end coils. The front leg of the coil that failed in service had extensive mechanical- and PD-related damage (see figure 1).

A limited shear test was performed on four 8-inch-long samples from the front and back legs of a neutral and line end coil. The samples were measured (length) at 23 °C, heated in an environmental chamber to 94.5 °C and measured again. The change in length between copper and insulation was 0.0040 inch for both legs of the line end coil and 0.0055 inch for the front leg of the neutral end coil. (For this particular winding, the thermal coefficient of copper is slightly greater than that of the insulation.) The neutral coil bottom leg differential was zero; that is, the insulation, even though grossly aged thermally, was still bonded to the copper bundles or, if partially delaminated, still expanded the same as the copper.

**Single Turn Windings and Rewinds**

It has been the author’s experience that single turn windings generally last longer than multiturn windings because turn insulation is exposed to higher temperatures and deteriorates faster than ground wall insulation. Turn-to-turn failures occur well before the lower temperature groundwall insulation approaches failure. The more robust single turn coil strand package and, in some cases, the poor multiturn coil interface bonding may further contribute to the aging differences. Roebel transposed single turn coils usually fail due to thermal (charring) aging of the insulation. In Roebel coils, the aging stressors result in the creation of strand shorts. Shorted
strands result in relatively large circulating currents that initiate the charring. These currents can be rather unbalanced about the point of heating. Current to ground increases until thermal runaway occurs and results in a failure to ground. When design allows, at Reclamation and elsewhere, many multiturn machines are rewound with the more robust single turn coils.

When rewinding a machine, several additional factors may be introduced that may reduce the life of the new winding. Many older machines, when rewound, are up-rated in part by taking advantage of the thinner thermoset insulation systems. The thinner insulation can adversely affect the voltage distribution in the end winding regions and result in PD, paint erosion, corona, and even in serious surface tracking.

In addition, older machines originally designed with a weak grid in mind operated at lower core flux densities to enhance stability. Some of these machines received rather large up-rates by means of changing the air gap, increasing the flux density, and installing modern excitation systems. The higher flux density and up-rated current result in higher stator tooth tip saturation, which, in conjunction with the conductors sitting closer to the air gap, result in higher tangential conductor forces.

CONCLUSIONS

Laboratory tests, inservice performance, cited technical papers, dissection results, general insulation basics and operational records and histories strongly support the following conclusions:

1. The information presented strongly supports the argument that, once thermal aging significantly weakens the bonding strength, the mechanical conductor forces become a significant aging factor, further damaging and displacing the insulation about the conductors. About the same time, voltage related aging (PD) accelerates considerably due to the voids generated from loss of weight (thermal decomposition of the binder) and the mechanical damage and insulation displacement as seen in figure 1. These forces working in synergy lead to the winding failure in a majority of machines.

2. In the majority of windings, the strong mechanical bonding and the plastic nature of the resin prevents delamination from occurring until thermal aging significantly reduces the bonding strength. This is supported via ramp dc testing, corona probe tests, and the detailed dissections on fairly well aged neutral and line coil legs previously presented in this paper. Numerous accelerated life tests and operational experience further supports this conclusion. It follows, and per the GE paper [6], that start/stop cycling is a minor, if not negligible loss of life factor.

3. The Glen Canyon, Flatiron, and Mt. Elbert winding case studies are just three examples strongly supporting the contention that thermal aging is a major life determining factor; and that thermal cycling is not as significant an aging factor as once thought.

4. The relatively early failure of the Glen Canyon (16) and Flatiron (23) machines at first glance appears alarming; however, several factors contributed to these failures. Both units operated close to or at full load for over 100,000 hours. Thus, the winding strength due to thermal aging alone was significantly reduced based on an insulation system that
would lose half the strength and 3% weight after 300,000 hours at a hot spot temperature of 125 °C. Add in PD, loss of resin volume, and mechanical related-aging, and a 100,000- to 150,000-hour life span for these multi-turn windings seems very reasonable (a few utilities replace windings at this interval).

5. Turn insulation thermally ages considerably faster than the ground wall insulation. When the turn insulation has thermally aged 25 years, the groundwall insulation on average has aged thermally only 18 years (based on the thermal gradient across the insulation thickness). Other aging factors at the copper will further accelerate the aging rate of the turn insulation.

6. Due to all the variables and unknowns, there is not enough information available to predict winding insulation system life with any reasonable degree of accuracy. The same holds true regarding remaining life. However, the corona probe and some other tests, to a lesser degree, do provide substantial information on when end of life is approaching.

7. The subject of start/stop being a major aging factor has been studied for quite some time. Over the years, there has been a growing body of knowledge associated with aging processes, test methods, databases, refined investigations and analysis methods, etc. During this period, no evidence of start/stop-related aging has come to light, which supports the conclusion that start/stop stress is not a significant aging factor.

REFERENCES


Additional Technical Resources


AUTHOR BIOGRAPHY

Bert Milano received a Bachelor of Science degree in electrical engineering (1971) and a Master of Science degree in electrical engineering with emphasis in power engineering (1973) from Worcester Polytechnic Institute, Worcester, Massachusetts. He joined the Bureau of Reclamation in January 1972. He was a technical expert in the Electric Power Field Test Section, and became the section supervisor in 1977. In 1986, he became Branch Chief of the Hydroelectric Research and Technical Services Group, where he was responsible for electric power-related technical, electrical, and mechanical operation and maintenance programs; special projects; and electric power research for Reclamation. In the early 1970s, he developed the Reclamation Ramp Direct Current test and established the associated test program. He has been involved in numerous technical advisory roles regarding Reclamation and non-Reclamation generator insulation, rewinds, core assessments/repairs, rehabilitation, testing, assessment, and analysis throughout his career. He retired from Reclamation in September 2007 and is currently a contractor/consultant in hydroelectric power with emphasis on generators and generator insulation evaluation and assessment. He is a registered engineer in the State of Colorado and a senior member of IEEE.