



THE EFFECTS OF CYCLING ON HYDROGENERATORS

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ABSTRACT

This paper will discuss the effects of cycling on hydrogenerators. Each major component of the hydrogenerator, and how it reacts to cycling operation, will be covered. The effects on the rotating parts, especially on higher speed turbogenerators, are quite obvious. Fatigue cracking in rotor shafts, tooth tops, blower hubs, pole crossovers and copper field winding effects due to cyclic operation are well documented for high speed turbogenerators.¹ The effects on slower rotating hydrogenerator rotors are less obvious, but are still present. Particular areas of concern include the field pole dovetails and pole to pole connectors. Case histories of failed parts in these areas due to cyclic operation will be presented and discussed. In the stator winding and core components, the effects of cycling are more obscure. Since these parts are stationary and don't see rotational forces, fatigue is less of an issue. Other effects from cycling, do come in to play. These include primarily temperature differentials, between the coil insulation, coil copper and the stator core iron. Each of these components has different rates of thermal coefficients of expansion and cycling and the associated temperature changes can have an effect. These issues will also be discussed.

INTRODUCTION

Cycling effects on high speed turbogenerators are well documented. Fatigue cracking and failure analysis of rotor shafts, tooth tops, fans, blower hubs, pole crossovers and copper field windings have been discussed at numerous conferences. Fatigue cracking of these components on the higher speed turbine generators can be easily envisioned. These components see very high cyclic stresses with each start and stop of the turbogenerator, from 0 rpm to 3600 rpm and then back to 0 rpm again. The effects on slower rotating hydrogenerator rotors are less obvious but are still present.² Particular areas of concern include the field pole dovetails and pole to pole connectors. Even though many hydrogenerators have significantly lower rotational speeds, the larger diameter causes the resulting stress to still be high, especially if there is an additional stress concentration factor. The basic equation³ for rotation force illustrates this fact:

$$F = m \times r \times \omega^2$$

where F = unbalance force,
 m = mass of object,
 ω = angular velocity

In the stator winding and core components, the effects of cycling are more obscure. Since these parts are stationary and don't see rotational forces, fatigue is less of an issue. Other effects from cycling, do come in to play, however. These include primarily, temperature differentials between the coil insulation, coil copper and the stator core iron. Each of these components has different rates of thermal coefficients of expansion and cycling and the associated temperature changes can have an effect. The paper below discusses first, the effects of cycling on hydrogenerator rotating components, then secondly, a discussion on the stationary components.

EFFECTS OF CYCLING ON HYDROGENERATOR ROTATING COMPONENTS

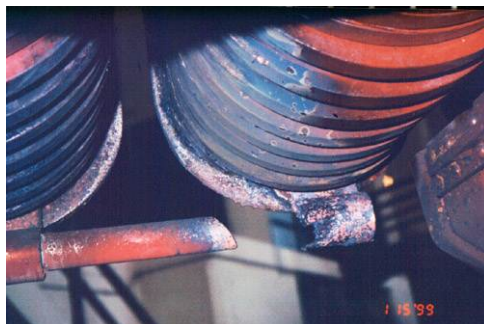
There are several components that are affected the most by this cyclic stress with each start and stop of the generator. The impact on the major components for the rotor is described below.

Rotor Pole to Pole Field Winding Connectors

Rotor pole to pole connections provides the means to complete the field winding circuit from one pole to the next. Copper conductor connections are typically part of each poles field winding, allowing each pole to be independently installed on the rotor rim. Connections are then either bolted, soldered or brazed together to complete the field winding circuit. Many different connection designs are used in the industry today. Service conditions can impose complex movements and stresses and when solid connections are used and cyclic expansion and movement and vibration can cause connection distress. Connection failure is obviously unacceptable as this results in an open circuit condition and a forced outage. The list below identifies dimensional change and movement that can occur during operation. These all can affect the life of the pole to pole connections.

- Thermal expansion of field coil end turns in tangential directions which shorten connection span.
- Rim growth from centrifugal force during cyclic operation increases span between connections.
- Axial thermal expansion of the field coil is typically downwards, but not always. In some cases frictional restraint may allow some field coils to expand downward and others to be restrained. Consequently, the top of one field coil may move downwards and its neighbor may not. This imposes an axial shear force between connections which can tear and twist the connection in the axial direction.
- Should poor geometric location of the connections exist on the coils, field personnel may end up forcing the connections into alignment. This puts the connection in a high state of initial stress before any external loading is applied.
- The field poles move radially away from the rim surface due to centrifugal loading on the pole attachments during cyclic operation. With a single attachment, the mass of the pole and coil may be visualized as being pin connected at the attachment. Under this condition, particularly if the pin connected mass happens to be resonant, negative sequence currents in the armature and flux harmonics can cause the pole to vibrate at 2X line frequency and slot frequency, in the tangential direction. This condition termed “pole rocking” can quickly lead to fatigue cracking of the connections.
- Inter-connected damper windings can experience the same fatigue mechanism under cyclic operation when they are directly connected, pole tip to pole tip.

If the above considerations are not taken into account, and significant dimensional changes occur or if significant stresses are imposed during cyclic operation, failure of the rotor pole to pole connectors will likely occur. Photos of failed field winding pole to pole connectors on hydrogenerators are shown below in Figures 1 and 2.



**Cracked and failed pole to pole connector. Round tie rod configuration.
Figure 1.**



**Cracked and failed pole to pole connector. Bolted and soldered solid cross section.
Figure 2.**

In many cases, pole to pole connectors with multiple copper “leaves” do better than solid cross section connectors, especially if the leaves have a built-in flexibility loop to accommodate relative displacements due to rotation, temperature change and misalignment.

Rotor Field Pole Dovetails

The constructional features of hydro electric generators vary considerably, depending much on the operating speed, runaway speed and output. The poles are typically manufactured as independent components and require a method of attachment to the rotor rim. The vast number of units in service will either have “dovetail” attachments, or “tee head” attachments. Both the dovetail and the tee head attachments can crack due to low cycle fatigue, based on start – stop operation as shown below in Figures 3 and 4 show tee head attachments cracked and failed on a pump storage generator with many start stop cycles.



**Crack in Tee head field pole attachment on pumped storage generator with many starts.
Figure 3.**



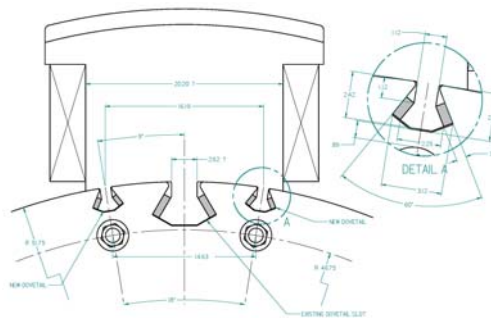
**Failure of Tee head attachment in field pole of pumped storage generator.
Figure 4.**

When evaluating the stresses that can cause this type of fatigue failure, rotational force is by far the most predominant. Although the loads are at the highest during a runaway condition, stresses imposed during cycling operation are significant. Pumped storage units undergoing thousands of starts over their lifetime, are most susceptible to cracking in the field pole attachments. Although it is common to design for runaway speeds with significantly higher rotational loading, stress concentrations in the fillet areas of the “Tee” can produce significantly higher stress.. In comparison, the magnetic forces may only be about 2% to 3 % of the inertia loading at rated speed and zero at runaway. Consequently, the magnetic forces are typically excluded from the design process, other than being given consideration for pole stability.

There are many variations on the dovetail and tee head pole attachment basic principle. In most cases, the design intent is to pull the pole seat down against the outer surface of the rim. In some instances, however, the pull down force cannot be made equal to the normal operating centrifugal force and the pole will lift elastically off the rim. The small resulting gap allows the pole to oscillate, or, as sometimes described, ‘to rock’ under the influence of magnetic forcing frequencies. This mechanism has been concluded by some to be the source of cracked field connections. Quite often, especially on high speed machines, twin attachments are deployed. Twin attachments have three major benefits:

- Reduction in the size of the individual attachment, thereby increasing resistance to buckling of both the pole and rim laminations,
- Increased stability against magnetic ‘rocking’ forces,
- Reduction in the radial depth of penetration into the rim.

The author’s company was involved in one refurbishment project involving redesign of a single dovetail attachment on a high speed machine. The poles were noted to be loose at speed. The addition of twin smaller dovetails on each side of the main dovetail stabilized the pole, resulting in a safe, reliable design.



**Field pole attachment refurbishment to correct pole looseness.
Twin outboard “rigger” dovetails added to stabilize pole during operation.
Figure 5.**

There does not seem to be any universal agreement on which design, dovetail or tee head, is better. The adaptation of one or the other is based on the established practice over many years of deployment by the supplier. The benefits and detractions of both are often points of discussion. The fact is that both work. There is a tradeoff here, between the extra rim depth to allow for the deeper tee head against the extra rim depth to allow for the greater imposed force using dovetails. As the number of poles decrease, the unit speed increases and the likelihood of using twin fixings also increases. Mating the sloping contact flanks of twin dovetails requires precision fitting. In order to introduce lateral compliance under this circumstance, one supplier introduces a slit in the pole body. Since the contact faces of tee heads is already 'lateral', this would not be a concern.

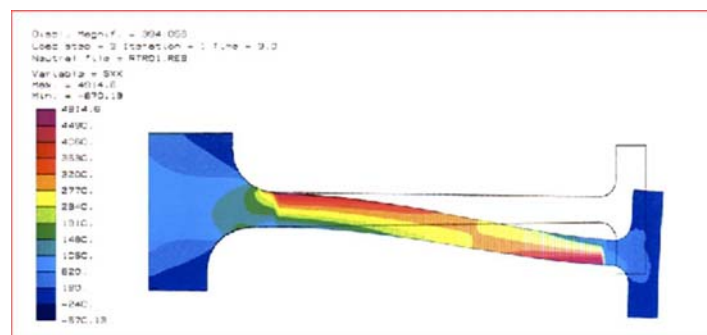
The radial flexibility of a dovetail attachment is likely to be greater than an equivalent tee head. Additional flexibility would be introduced into the dovetail by the lateral elastic extension of the slot due to rim stress. It would be expected that greater radial flexibility in the attachment would have the effect of transmitting the field coil end turn loading further along the pole length and thereby reducing the magnitude of load concentration at the pole end.

Rotor Spider and Rim

Typical rotor rim designs include segmented laminations linked together in layered circles to form a concatenated yoke to which the field poles and coils are attached. Many earlier and smaller machines have solid rotor rims, typically made from cast steel, or sometimes, from steel forgings. On some of the very old units, the rims are integrally cast with the spider, and sometimes, even include the pole bodies. On more modern designs, rims typically are shrunk on to the spiders and sometimes they 'float'. In one particular refurbishment project completed by the author's company, an integral, cast steel, rotor spider and rim was found with extensive cracking as shown in Figure 6.



**Large cracks found in spider of hydrogenerator.
Figure 6.**



**Deflection (magnified) and stress plot of spider arm.
Figure 7.**

The centrifugal force of the rim and poles can be very high and imposes a similarly high hoop tensile force on the rim structure. Typically the hoop tension attains several million pounds force. Although the rim studs are sized to transmit the hoop tension from lamination to lamination, there will always be some clearance between the holes in the laminations and the stud diameter. Initially, the clamping force on the overlaps will provide sufficient friction to transmit the tension.

As the speed increases, the imposed hoop tension increases and the clamping force tends to relax slightly due to Poisson effect in the stressed laminations. At some speed, the imposed hoop force overtakes the clamping friction and slippage occurs on the overlap faces until equilibrium is again restored by the rim studs acting as shear pins.

Rim slip is therefore caused by the hoop tension in the rim and not by machine torque and is essentially a single occurrence. The magnitude of slip can increase whenever the machine reaches a higher speed threshold but this would be due to additional crushing of the contact edges of the laminations and the studs. When a rim has 'slipped', physical circumferential displacement has taken place and the rim will increase slightly in diameter. It can only be corrected by restacking.

The speed at which slip takes place is called 'slip speed'. The slippage takes place on the planes of least frictional resistance. These preferential slip planes will be the overlap planes. More serious is the situation when a flexible floating rim is on a laterally flexible spider. The rim can be pulled over - unidirectionally - until the float clearance has been consumed. As the machine rotates, the rim will retain the same displacement in space. The spider arms however will experience a full cyclic backwards and forwards flexure and the rim will experience a cyclic radial motion on the spider support lips for each revolution.

This mechanical fatigue mechanism imposed on the spider can initiate cracking and possible fracture of the spider arms, the rim support lips and possibly the rim punching when they rest directly on the support lips. There is no definitive rule for determining what level of rim float, rim flexibility, spider flexibility and amount of eccentricity can initiate distress. A condition of rim float or eccentricity could be perfectly acceptable on one machine and totally unacceptable on another. The most practical approach is to ensure that spiders with flexible arms always are designed to have shrink fitted rims.

EFFECTS OF CYCLING ON HYDROGENERATOR STATIONARY COMPONENTS

Stator components are also affected by cyclic operation, although the specific effects may be less obvious. Key stationary components include the stator core, the stator winding and the stator frame. The impact on each component is described below.

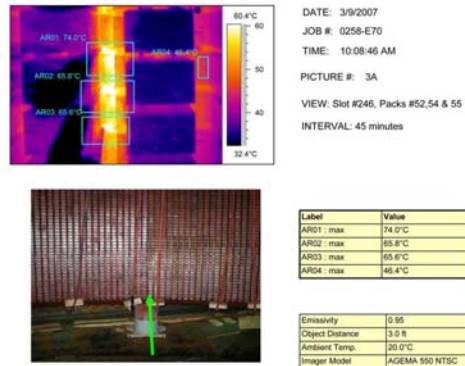
Stator Core

The stator core is primarily affected by temperature change during cyclic operation. Since the core is stationary, obviously there are no effects from rotational forces. On cores with splits, temperature changes from cold to hot with each cycle can cause shifting of the core sections. Figure 8 illustrates the displacement that can occur at the core split at the bottom of the slot, after many cycles and many years of operation. Such a change can place the stator coil in this slot under severe stress, and in many cases, coil failures occur at the stator core splits because of damage to the ground insulation as this displacement and shearing force occurs.



**Stator Core Displacement at core split and bottom of coil slot.
Figure 8.**

It is also common to find core hot spots at the core splits, as cyclic operation causes relative movement and abrasion of insulation placed in between the core splits. As this insulation wears, hot spots develop between adjacent laminations.



**Hot spot at core split on old hydrogenerator seen during core loop test.
Figure 9.**

Stator Winding

Traditionally, the stator winding of hydrogenerators is not considered to be severely affected by cyclic operation in the same way that rotational components are affected. However, there does appear to be evidence that the stator windings are also affected, albeit in different ways, with some suggesting a service life reduction of the stator winding of up to 10 hours for every new start. Again, since the stator windings are stationary, the primary detrimental effect on the stator winding is the temperature change from cold to hot with each new start. Such a change causes relative differential expansion between the ground insulation, the copper strands and the stator core, all having different coefficients of thermal expansion.

Two specific case histories were thoroughly investigated to evaluate whether a single start was equivalent to stator winding degradation equivalent to 10 service hours. NEC rewound two pumped storage units in 1995. Each unit has undergone more than 30,000 service hours since the rewind in 1995. During this time, a total of 10,500 starts were placed on each unit. This amounts to a little over 1.5 starts each day. In 2012, approximately 17 years after the rewind, two coils were removed for a life assessment. The life assessment, done by an independent third party, found no concerns for insulation failure. Additionally,

Voltage Endurance Testing per IEEE 1043 was done on the two coils. Both passed 30 kVAC for 400 hours at 100 deg. C. Based on these results, an additional 20 years or more is expected from the stator windings.

If a unit operates based loaded for 30 years, that is equivalent to 262,000 hours. If one start is equivalent to 10 service hours, a unit that operates for 30 years should accommodate 26,000 starts. The NEC windings installed in these units in 1995 have 10,500 starts and 30,000 service hours after 17 years. Based on design life in starts, the stator winding should have $10,500/26,000 = 40\%$ of its life used up. Based on design life in service hours, the stator winding should have $30,000/262,000 = 11\%$ of its life used up. In this method, the starts and the service hours must be put into one or the other and combined. So, in terms of service hours, we have 105,000 (from the starts) and 30,000 actual service hours for a combine total of 135,000 equivalent service hours. This is equivalent to 52% of service life ($135,000/262,000$).

The life assessment estimated that the stator winding had another 20 years left. If the original design life is estimated to be a 30 year design life, $10/30$ or only 33% of its life is used up. So, in this evaluation, start theory estimates that more than 50% of the winding's life is gone, but assessment indicates that only 33% of life is gone. If a start is equated to 5 service hours instead of 10, the design life based on starts converted to total service hours is 31% . This is more in line with the life assessment done on the winding. Therefore, a deterioration factor of 5 service hours per start, may be more realistic than the 10 service hours previously assumed.

Another case history includes a set of NEC Windings that have 13,000 starts after 23 years of service. The windings on this pumped storage unit have about 100,000 service hours. Based on design life in starts, the stator winding has 13,000 starts x 10 hours per start or 130,000 service hours. Adding to the winding the actual service hours of 100,000, the total service hours is equal to 230,000 service hours. Now, $230,000/262,000 = 88\%$ of its life used up.

Based on a recent CEATI hydroAMP Condition Assessment⁴, both sets of windings scored an 8.3 "Good" assessment. Based on this assessment, the owner determined that the rewind can be deferred a minimum of 5 more years. Based on a design life of 30 years, if the unit would be rewound at the end of those 5 additional years, that would put the life expended at $23/28 = 82\%$. In actuality, the winding may last much longer than an additional 5 years. If it does, the "life used up" percentage will decrease, and then the effect of starts on equivalent service life deterioration will also decrease. In conclusion, in reference to the stator winding, based on these two examples, the effect of start / stop operation on the stator winding is in the order of between 5 and 10 hours of service life expenditure for each start / stop cycle.

CONCLUSION

Cyclic operation is defined as the process of bringing a unit on line from a standstill condition, then up to full rated speed and then back down to standstill again. Each start – stop cycle has a significant effect on many components of the hydrogenerator. Components that rotate are affected most. These components include the rotor spider, rim, field pole attachments and field winding connections. Low cycle fatigue cracking due to the change in speed is a common failure mechanism on these rotating components. Stationary components are impacted also, mostly from displacements due to temperature change. Those components impacted most are the stator core and the stator winding. The stator frame can also suffer cracking, as well as other components, but these are more readily repairable. It seems that a reasonable estimate for the impact of start / stop operation is in the range of 5 to 10 service hours of life used up, when considering a base loaded unit, running continuously for 30 years.

REFERENCES [Example references to show format only]

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BIOGRAPHY



Bill Moore, P. E., is Director of Technical Services for National Electric Coil. Located in Columbus, Ohio, his department provides high level technical support in the areas of product development, proposals, advanced engineering design, research and development, machine data configuration and sales and marketing support. National Electric Coil (NEC) core business is the manufacture of High Voltage Coils for new and refurbished generators, but also performs generator, motor and exciter rewinds, core restacks and complete refurbishment projects on turbogenerator and hydrogenerator projects. Prior to joining NEC in 1997, Bill held utility power plant management positions with Florida Power & Light, working at three different power plants, over a ten year time span. A licensed professional engineer in Ohio and Florida, he started his 34 year power industry career as a generator design engineer with Westinghouse. He has been awarded several design related generator patents and has published and presented over 75 papers in the power generation field. He is a frequent short course lecturer on generator industry issues at major conferences, and for utilities and insurance companies around the world. Bill is a Fellow Member of the ASME and was past chairman of the ASME Power Division. He is a past recipient of the EPRI Innovator Award, and the "Author's Award" from Hydro Review Magazine, and a two-time winner of the Best Paper Award from the IEEE Pulp and Paper Section. He has a Master's and Bachelor's of Science degrees from the University of Pittsburgh, and Notre Dame University, respectively, along with an M.S. in Engineering Management from the Florida Institute of Technology. He is also a member of IEEE and the U.S. representative to the A1 Rotating Machinery Study Committee for CIGRE. Bill can be contacted via email at bmoore@national-electric-coil.com.