SALIENT POLE GENERATOR FAILURES

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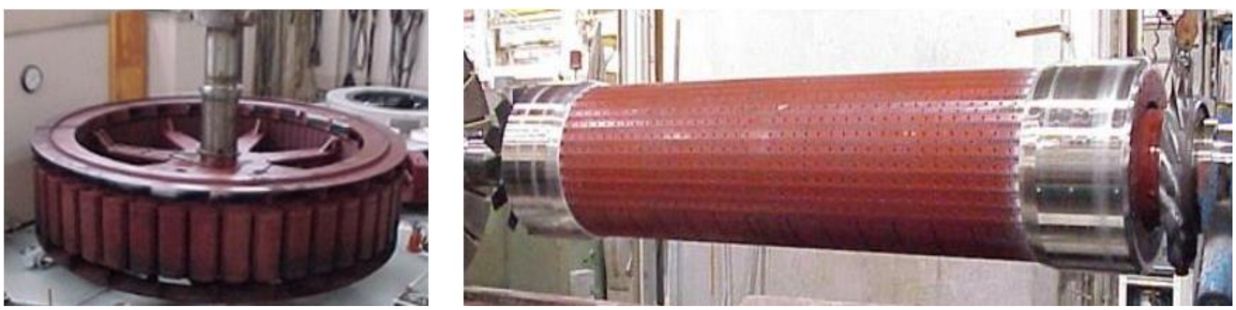
ABSTRACT

This paper focuses on failures of a family of salient pole generators from multiple manufacturers ranging from about 15 MVA to about 65 MVA, with nominal operational speeds of 1200 and 1800 RPM. The damage from these failures was considerable, requiring stator core restacking or replacement, stator rewind, and other rotor repairs and/or upgrades. The presentation reviews the basic construction elements of salient pole generators and identifies failure mechanisms and engineered solutions. Long-term maintenance and operational considerations are also discussed.

INTRODUCTION

Synchronous generators have been utilized for electrical power generation since their inception in the late 1800s. They have two primary rotor design types, salient pole and cylindrical. Examples of these two types can be seen in Figure 1. The outward protruding poles of the hydro generator salient pole rotor are easily distinguishable from the cylindrical rotor's smooth cylinder body shape.



Hydro Generator Salient Pole Rotor (Left)
Cylindrical Rotor (Right)
Figure 1

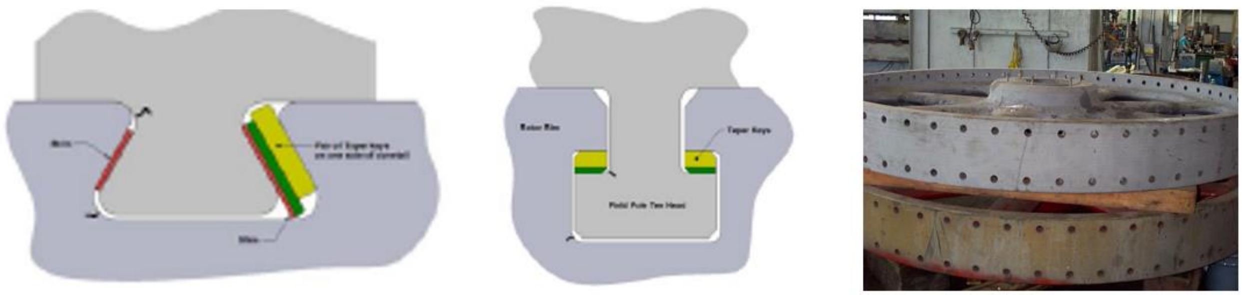
There are several other noteworthy characteristics of salient pole rotors relative to cylindrical rotors. The electrical output or rating of salient pole designs is lower than cylindrical designs. In addition, salient pole designs have larger body diameters and shorter axial lengths than cylindrical ones. In fact, the protruding poles of salient pole designs result in an irregular air gap and relatively less mechanical strength. Also, the operational speed range of salient pole designs is typically slower, lower RPM.

These characteristics are why hydro generators have utilized salient pole designs for well over a century. The typical operational speed range of salient pole hydro generators is about 90 RPM to about 500 RPM. Diesel and other internal combustion engine prime mover applications can vary, but 8-pole or 900 RPM machines are common.

Despite their differences, the stator configuration and electrical design of both salient pole and cylindrical rotor generators are similar. For this reason, stator content discussion of this paper will primarily focus on damage incurred and repair/replacement options and challenges.

ROTOR SALIENT POLE ASSEMBLY ATTACHMENT CONFIGURATIONS

Most salient pole units with 10 poles or more fall into one of three primary configurations for affixing pole assemblies to the rotor body/rim, as shown in Figure 2.



Dovetail Root (Left), "T" Root (Center) and Bolted Rim to Pole Body (Right)
Figure 2

Both the dovetail root and the "T" root configurations utilize shims and opposing taper wedges to secure the assemblies to the rotor rim. Both configurations have also been applied with a double configuration on larger and heavier rotor applications. A photo example of a double dovetail, large 10-pole unit can be seen in Figure 3. Bolted rim to pole body configurations are most common on older vintage, smaller, slower speed machines.

Double Dovetail Root Pole Being Mounted to the Rim of a 10 Pole Rotor
Figure 3

Several original equipment manufacturers (OEMs) have provided salient 4- and 6-pole, 1800 RPM and 1200 RPM respectively at 60 Hz. The higher speed of these units significantly increases the mechanical forces and stress acting on rotor components. Industrial plant applications for these units include power, petrochemical, pulp and paper, and food processing, to name a few. These units range from about 15 MVA to about 65 MVA. OEMs typically offer several models to cover the range of ratings.

One configuration applied by some OEMs consolidated the shaft, hub, pole body, and pole head into one solid rotor component. This configuration was manufactured from one steel billet and machined to required dimensions. A large turntable was used to rotate the entire solid steel rotor component, enabling insulation materials and the electrical winding installation, one pole at a time. The steel rotor component was indexed on top of the turntable to allow the next pole to be wound. Most units applied with this configuration have been applied to smaller rating units, some also having lower voltages. Despite reasonable operational performance, it does not appear this configuration was manufactured in great numbers. Repair, and rewinding of this configuration, was challenging due to the requirement for the large turntable and other special tooling to facilitate the repair or rewind.

Another configuration more widely manufactured by at least four different OEMs has a configuration that consolidates the shaft, hub, and pole body into one solid steel component, with a separate pole cap. The separately manufactured pole head is secured to the pole body with large bolts. Between the poles, V-block assemblies aid in securing and stabilizing the pole assemblies. This configuration has been used across both 4-pole (1800 RPM) and 6-pole (1200 RPM) units.

4-Pole Salient Pole Rotor with Removable Pole Top Caps
Figure 4

The V-block bolts and pole head bolts can be seen on a 4-pole unit in Figure 4 above. The white arrow points to a broken (missing head) V-block bolt. Note that similar V-block bolt failures have occurred on multiple units across different manufacturers, models, and ranges of generator ratings having this configuration. Similarities in failure and damages incurred will be easily recognized as we explore two failure case discussions: one a 6-pole machine, the other a 4-pole machine.

Six-Pole - Salient Pole Generator Failure Case Discussion

The generator in this case discussion is rated 38,750 KVA; 13,800 VAC; 1200 RPM. Figure 5 (upper left) shows a photo of the rotor, exciter and stator as received for incoming inspection. One of the V-block bolt heads fractured, became liberated from the V-block assembly. The rotor sustained numerous gouges and dings, see Figure 5 upper right. The exciter was undamaged from the event. The stator damage was catastrophic as seen in Figure 5 lower left and right.

Rotor, Exciter and Stator
Figure 5

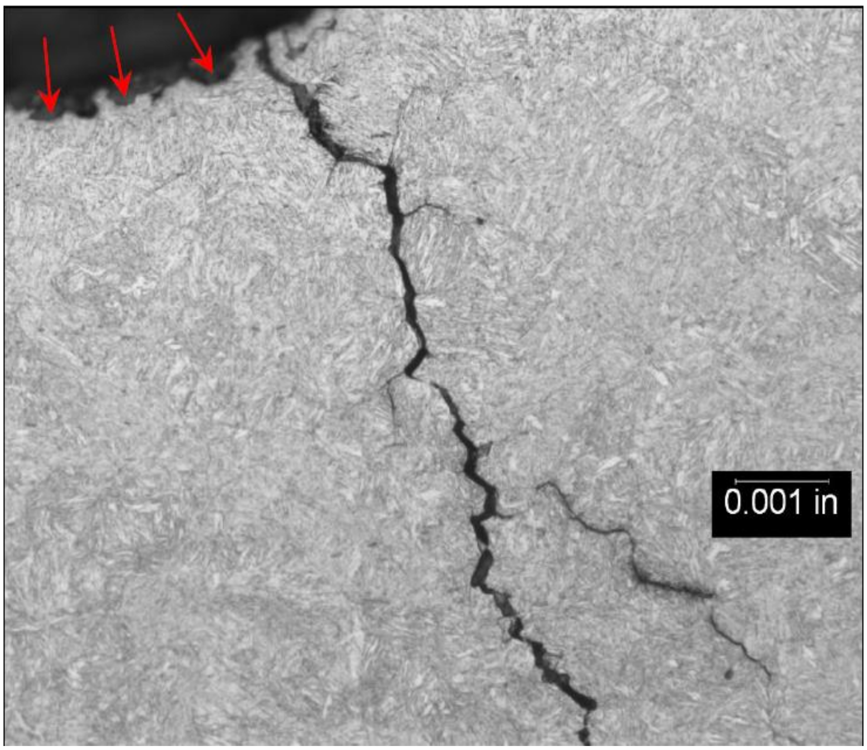
Figure 6 shows the V-block assembly missing a bolt head (left), and the bolt stem end at the fracture (center). The failed bolt can be seen under the other non-failed bolt of the assembly, Figure 6 (right). As reference, the undamaged bolt length is slightly over 10 inches. Two V-block bolts, washers, and the plate weigh approximately 3 ½ lbs. A visual observation was made regarding the minimal radius at the head to stem juncture of the V-block bolts.

V-Block Assembly
Figure 6

Analysis of the V-block bolts identified they were likely manufactured to ASTM F568M-07, Class 12.9 alloy steel specification. This material is commonly referred to as AISI 4140 alloy steel. The high hardness of the material makes it susceptible to environmentally influenced cracking such as hydrogen embrittlement and stress corrosion cracking. Corrosion can clearly be seen in the right photo of Figure 6. Although, hydrogen embrittlement was the primary failure suspect given:

- High hardness low alloy steels, such as this bolt material are susceptible to hydrogen embrittlement
- Inter granular cracking was in one plane
- Cracking location was at an area of stress concentration – juncture of the bolt head and stem
- The approximate 6-year life is indicative of the delay, which results from constant load, such as this applications bolt preload.

A metallographic cross-section through the non-failed V-block bolt head to shank radius was performed. The cross section was polished, Nital etched, and magnified. Intergranular cracking can be seen in Figure 7. Pitting can also be seen on the bolt surface at the red arrows in the upper left.

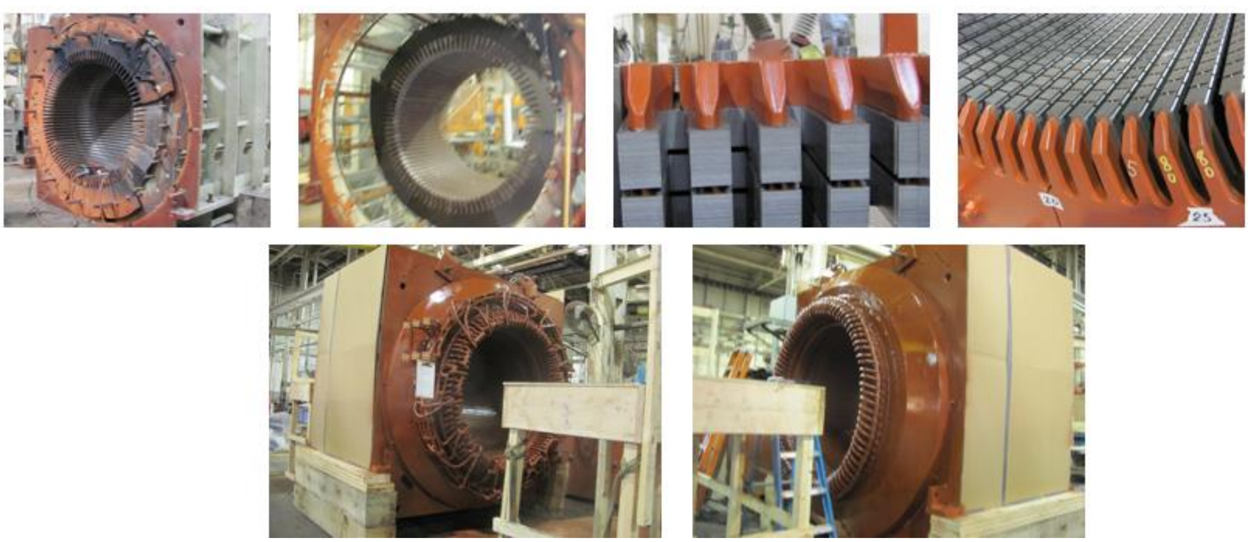


Intergranular Cracking and Pitting
Non-Failed V-Block Bolt at the Head to Shank Radius
Figure 7

As part of the repair, the owner chose to employ an improved alloy more resistant to hydrogen embrittlement and stress corrosion cracking. The geometry of the bolt and fasteners was upgraded, including improved bolt geometry, and increased radius at the juncture of the bolt head and stem. Rotor damage was primarily superficial, requiring dressing and blending of the gouges and dings. As per NEC’s recommendations, the owner chose to remove the pole coils to address all impact damage and reinsulate the poles as seen in the top row of Figure 8. This also allowed a thorough cleaning of the shaft, hub and pole body assembly prior to painting and preparation for reassembly, center row Figure 8. The bottom two pictures of Figure 8 show the rotor being built into the high-speed balance facility.

Rotor Repair Process – Pictorial Overview
Figure 8

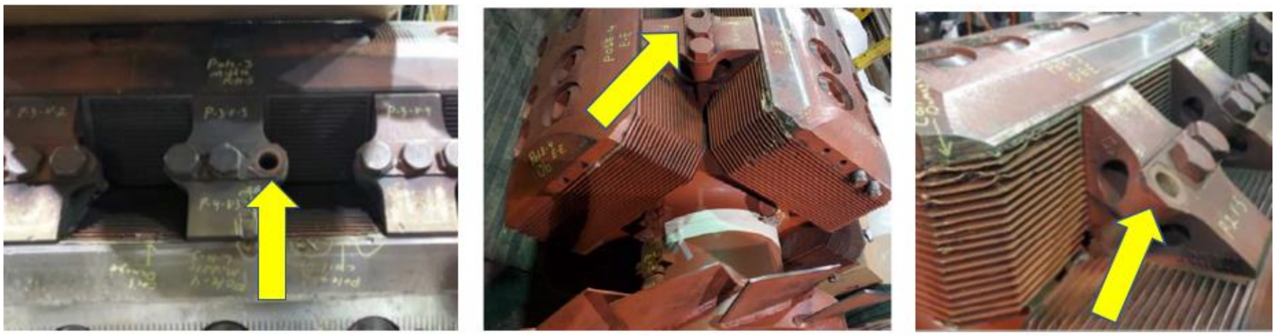
The catastrophic stator damage required the core to be stripped, frame requalified, and the core restacked with new iron, see top row Figure 9. The stator was originally an autoclave processed Global Vacuum Pressure Impregnated (GVPI) winding and a qualified GVPI winding system was applied as part of the repair. The bottom row of Figure 9 shows the completed stator, exciter end and turbine end, respectively.



Stator Repair Process – Pictorial Overview
Figure 9

Four Pole - Salient Pole Generator Failure Case Discussion

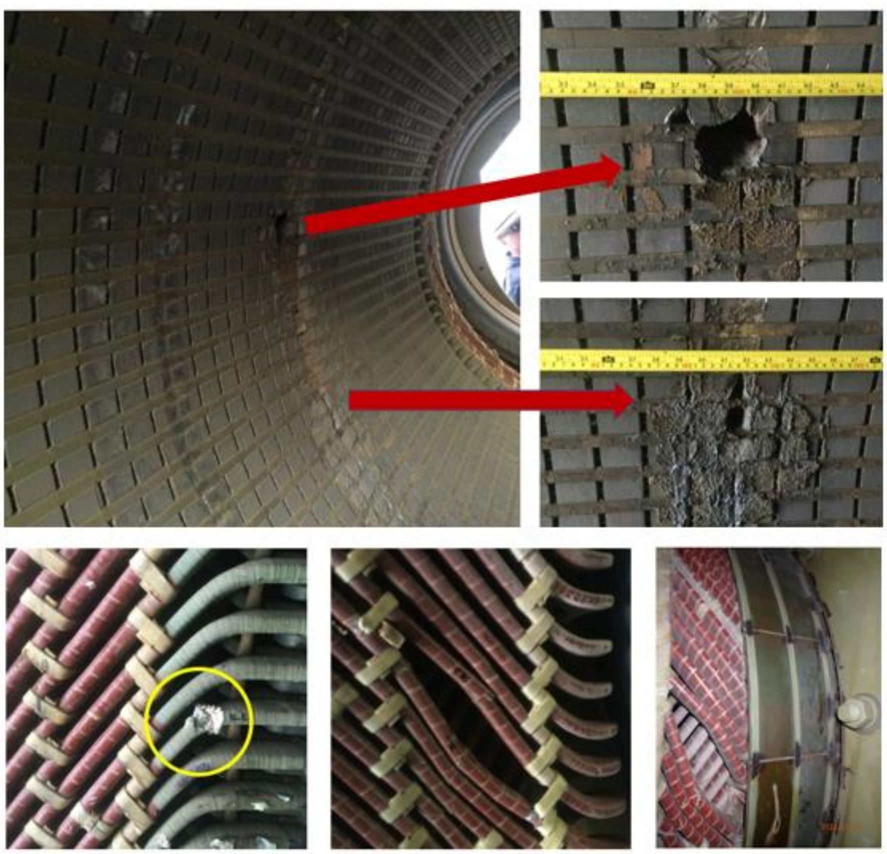
The generator in this case discussion is rated 52MVA; 13,800 VAC; 1800 RPM and was manufactured in 2008. At the OEM recommendation, the owner replaced the V-block bolts using OEM replacement bolts during a 2015 outage. Seven years after the replacement bolts were installed, this failure of 3 V-block bolts occurred in 2022. Figure 10 shows the location of the three failed V-block bolts.



Pole 3-4 Center   Pole 1-4 EE   Pole 2-3 OEE

Three Failed V-Block Bolts
Figure 10

The rotor sustained numerous gouges and impact dings. The exciter was undamaged from the event. The stator damage was catastrophic, see Figure 11 below.



Stator Damage from Three Failed V-Block Bolts
Figure 11

There were several unknowns regarding the 2015 V-block bolt replacement. Supposedly, the original OEM V-block bolts were an “exotic alloy,” but this was not confirmed, and no further collaborative information was available. No documentation accompanied the OEM replacement bolts, however, it was reported that the radius between the bolt head and bolt stem was increased along with an increased chamfer of the thick washer/spacer plate, immediately below the bolt head, to accommodate the increased bolt radius. Supposedly, a coating was also applied to the V-block replacement bolts, but this could not be confirmed. The process of bolt replacement was not well documented or recorded.

Observations and analysis of the V-block bolts, after the 2022 failure, were comparable to the prior case discussion, but the bolts and assembly are considerably larger to make up for the higher unit rating and increased mechanical stresses. Each V-block assembly, which in this case includes the V-block, 3 bolts, and heavy washer/spacer plate, weighs 98 lbs. The V-block itself is a large majority of the weight. Breakaway torque of the replacement V-block bolts was inconsistent. Sixteen of the sixty total V-block bolts per unit (total including three failed) had a breakaway torque ranging from about 500 lbf-ft to 1100 lbf-ft. The remainder of the unit V-block bolts breakaway torque ranged from only about 25 lbf-ft to 150 lbf-ft.

Listed below are several potentials of the V-block bolt failure contributors that were considered:

- The geographic location of the unit, and 3 sister units, is susceptible to tropical storms and hurricanes, presenting significant potential exposure to saltwater mist, a strong source of corrosive chlorides. This and other factors make stress corrosion cracking (SCC) a primary failure contributor.
- It is suspected that the failed V-block bolts had been over torqued, making them more susceptible to SCC failure.
- Hydrogen embrittlement remains a strong potential contributor despite the owner claim of no hydrogen presence in their processes. However, the owner was told the V-block replacement bolts had a coating treatment applied to help inhibit corrosion. While not confirmed, there is reason to believe that as the coating deteriorated over time, hydrogen was let off.

Four Pole - Pole Head Bolts Evaluations

While there is no doubt the V-block bolts caused the failure, reports and evaluation discoveries regarding the pole head bolts became a large concern. Photos of the bolt can be seen in Figure 12 below.

Four Pole – Pole Head Bolt
Figure 12

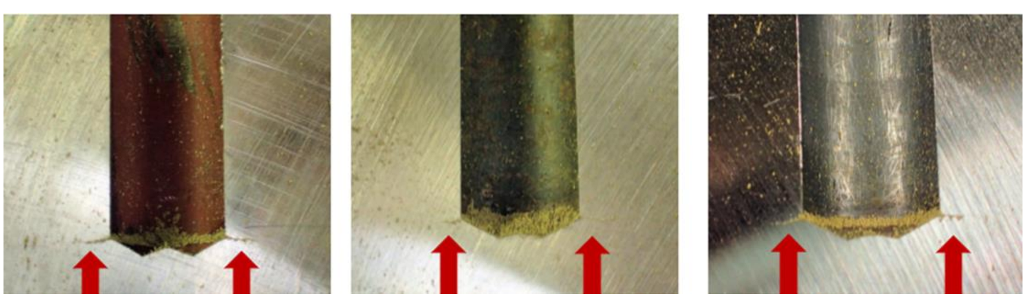
The OEM supposedly expressed to the owner that a similar generator had experienced a pole head bolt failure about 10 years earlier. The bolt reportedly failed during commissioning following a 1½ year period at standstill. The bolt separated at the head to shank area of the bolt, liberating the bolt head. Intergranular cracking was reportedly present at the fracture origin. OEM consultants supposedly attributed the failure to temper embrittlement (TE). The OEM reportedly expressed that there was no evidence of stress corrosion cracking (SCC), or hydrogen embrittlement found in the failed bolt. TE, SCC and hydrogen embrittlement can all be manifested by intergranular corrosion.

Three representative samples of the pole head bolts were processed through an extensive metallurgical protocol, including destructive sectioning, to best evaluate the subject bolts. Results of the chemical pole head bolt samples were found to have an analysis of the base metal composition of the bolts aligned with the composition requirements for a grade 12.9 bolt, as specified in ASTM F568M. This is the highest strength class of steel fastener commonly available. The chemical composition of the bolt base metal was also used to calculate the material's Watanabe Factor. This factor indicates the likelihood that the material is susceptible to TE based upon the content of silicon, phosphorus, and tin in the material. A Watanabe Factor less than 180 is considered good for having less susceptibility to TE. The pole head bolts of this study discussion had a Watanabe Factor of 156. The OEM reported the Watanabe Factor on the pole head bolt failure 10 years prior was high, supporting the OEM consultant's conclusion that the bolt failed because of TE. A reconciliation of the Watanabe Factor reading differences from this case and the 10-year prior failure was not possible, but the difference is noteworthy.

One of the three representative samples was found to have a crack about 1/3 the way down the threaded portion of the bolt. The bolt was cut above the threads and again through the cracked area in the threads as can be seen in the left photo of Figure 13 below. The blue arrows show the crack location. The cut segment was then cut through the bolt centerline, splitting the 10 mm bolt elongation measurement hole. The segment halves were flipped over for evaluation and comparison, as can be seen in the right photo of Figure 13. The red arrows point to the bolt elongation measurement hole.

Segmented Pole Head Bolt
Figure 13

Magnetic particle testing of the segments through the pole head bolt elongation measurement hole found cracks in all segments emanating from the radius at the bottom of the hole, see Figure 14. Crack lengths varied from 0.10 to 0.16 inches. No cracks were revealed in areas other than the bottom radius of the elongation measurement hole. Only one bolt was found to have a coating inside the bolt elongation measurement hole. This can be observed in the left photo in Figure 14, which shows a reddish color cast to the hole wall. Coating coverage was not complete on the hole ID where the coating was missing. But no corrosion was observed under the coating indicating the coating was at least somewhat effective. The other two uncoated bolts did have observable corrosion.



Crack Propagation from Elongation Hole Bottom Radius
Figure 14

Four-Pole Salient Rotor Repairs

Following analysis and investigative efforts, the scope of work for the repair included new V-block and pole head bolts. The V-block bolts employed an improved alloy more resistant to hydrogen embrittlement and stress corrosion cracking. The V-block bolt geometry was optimized, increasing the radius at the bolt head to the stem. Given the as-found pole head bolt was already the highest strength class of steel fastener commonly available for the given size, a nonstandard specialty manufactured pole head bolt was used to at least gain a minimal amount of design margin. The rotor pole windings were refurbished and then proceeded much the same as the 6-pole case discussion with the impact gouges and dings dressed and blended prior to reassembly. Rotor reassembly was performed following strict procedures and QA/QC checks to ensure proper placement as well as necessary assembly process sequencing and critical to quality factors including bolt torque application and final torque values applied. The catastrophic stator damage was addressed with essentially the same scope as the prior 6-pole case discussion stator scope.

CONCLUSIONS

The case discussions show a configuration of salient pole generators that have been exhibiting reliability concerns with the V-block and pole head bolts. Failures can result in catastrophic high cost long duration repairs or replacement of the unit. Owners should be prudent to carefully review their operational circumstances and reevaluate their maintenance program, taking into consideration the insight from these case study discussions. V-block bolt upgrade should be considered to gain extra design margin to better withstand operational stresses and potential cracking, which may initiate from stress corrosion cracking and hydrogen embrittlement. It should be noted that the design margin gain by upgrading the pole head bolts is much less. Even though some margin is gained by utilizing well designed nonstandard specialty manufactured pole head bolts, the narrow margin to resist normal operational stress as well as potential environmental deterioration factors is very concerning.

Environmental unknowns remain a significant concern for both bolt types. The presence of elements leading to hydrogen embrittlement and stress corrosion cracking are evidenced by their contribution to failures as expressed in the case discussions. A better understanding of time duration until crack propagation would be most beneficial. Some owners with multiple units are embarking upon proactive bolt replacement. This is being done at finite durations, with the replaced bolts being metallurgically inspected, dissected, and evaluated to establish a better understanding of the time duration to the emergence of crack propagation.

Detailed, well-engineered work procedures should be developed and deployed for reassembly operations, with close attention to detail by experienced personnel. Proper placement and seating of components is critical. Bolt assembly progression, including preliminary and final torquing, is of paramount importance. These should be carefully monitored by an effective QA/QC program.

Both units featured in the case discussions are base loaded. It should be clearly noted that cyclic operations significantly increase operational stresses acting on rotor components, including the V-block and pole head bolts.

ACKNOWLEDGEMENTS

Special thanks to National Electric Coil – Columbus Service Center and specifically Bill Harris, Plant Manager, for insight and content contribution.

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BIOGRAPHY

W. Howard Moudy received his B.S degree from Western Kentucky University. He has been with National Electric Coil for over 22 years and is currently Managing Director. His career spans 44 years focusing on repair and upgrading large high-voltage rotating electric machines with an emphasis on coil manufacturing.

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