Root Cause Analysis
Of
Machine Stator Failures

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ABSTRACT

This paper discusses the basic methods for root cause analysis of large rotating electrical machine stator failures. Several in service and test failure examples are presented.

BACKGROUND

The first question asked by asset managers after a machine stator failure is when will it be returned to service. This information is critical for them to maximize plant operation. However operation and maintenance engineers need to know why the motor or generator failed and what can be done to prevent a reoccurrence in that machine or similar units. A failure root cause analysis of specific circumstances leading up to each failure is essential to understand the deterioration mechanism. With this knowledge successful remedial action can be developed. If the machine is very large and critical to the economics of the site then a visual inspection of the failure by a seasoned expert with that type machine is required for the best results. There are very few experts in the industry that understand and can identify the variety of deterioration mechanisms that result in stator failures. If time of casts do not permit input of a specialist then the failure should be examined by someone with some understanding of rotating machine insulation systems. There are formal "root cause" training programs available but these are often just a method to list all possible conditions that can result in deterioration and not those specific to the machine in question. An understanding of machine design, operation conditions, maintenance history and the experience of similar designs are all critical to arriving to a correct conclusion. You can not take too many digital photographs as the investigation unfolds.

OPERATION INFORMATION

Records of machine operation immediately before a failure can provide information on why a stator failed even before an inspection is conducted. Was there a storm in the area? Was there a temperature, speed, vibration or load excursion? Past operation information must also be studied. Has there been a trend of increasing temperatures or increasing partial discharge activity. Has the winding been in service for several decades or is it new? Large rotating electrical machines are complex devices and failure mechanisms can be equally complex. Often there are several types of deterioration occurring simultaneously. Determining the real root cause of a failure requires careful analysis of data collected before the event. No prior indications of developing problems are also important.

DETERIORATION MECHANISMS

Stator deterioration mechanisms can be classified into a few general categories.

1. **Thermal deterioration due to operation at temperatures higher than the insulation system can safely withstand.**
2. **Electrical stress (short term or long term) higher than the insulation system was safely withstand.**
3. **Mechanical stress from movement or vibration of the winding.**
4. **Contamination of the winding with dirt or moisture.**
5. **Inadequate design, manufacturing QA processes or material application.**

DISSECTION

Dissection of the failed stator bar or coil is essential. Dissection of adjacent bars and coils that did not fail is also essential. Usually the deterioration that resulted in a failure is also present throughout the winding. This deterioration is often at various stages of development at other parts of the stator winding. Do not scrap the removed winding until it is clear no additional understanding of the deterioration can be gleaned from the pieces.

Failure of a New Winding

After the completion of a small hydro-generator stator rewind a coil failed before the final 2E+1 voltage was obtained. The defective coil was removed and replaced with a spare. The coil supplier and the generator owner needed to know why the coil failed and if the rest of the winding was at risk.

The failure exit point was quickly located just inside the core near the top. There appeared to be a crack in the conductive armor tape near the failure. There were no other abnormalities present on the surface of the specimen. The remaining stator coils were able to withstand the desired overpotential test.

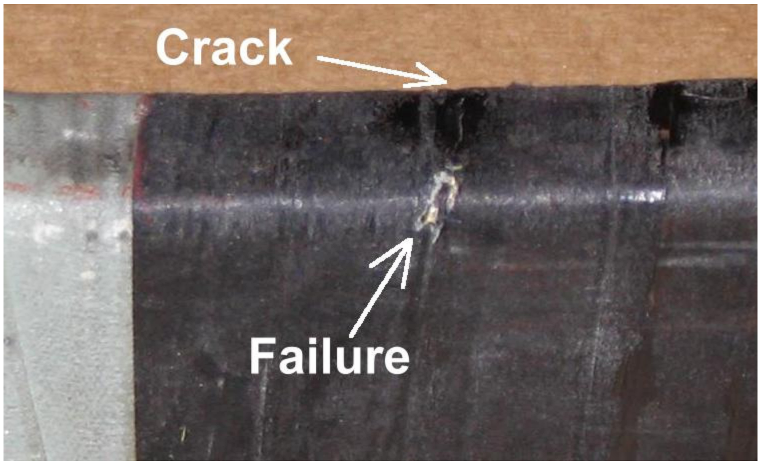

FIGURE 1: A stator coil failed during the final acceptance overpotential test.

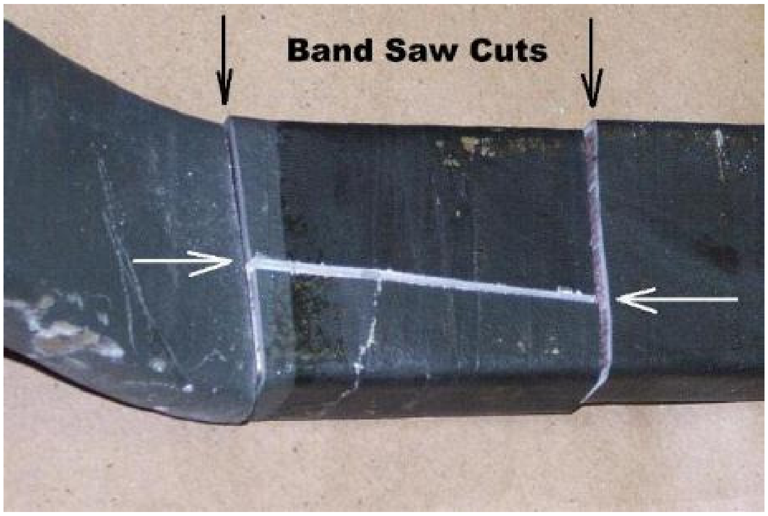

FIGURE 2: Black arrows show cuts made to isolate the failure site. White arrows show the cut that permits insulation removal from the sample.

One of the first decisions was to determine how to isolate the failure area. Failures often do not progress straight through insulation but follow weaknesses between tape layers. Isolation cuts should be made no closer than 2-3 cm from the failure site. Once removed two additional cuts must be carefully made to permit lifting the groundwall insulation from the conductor stack.

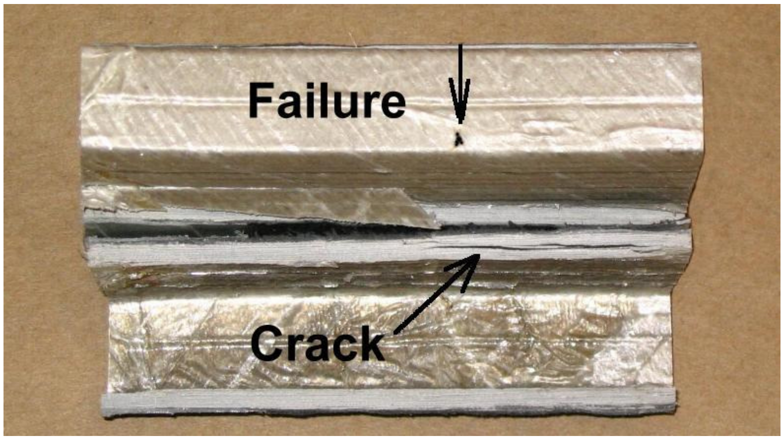

FIGURE 3: **Groundwall insulation was easily folded away from the conductor stack.**

A telltale black puncture spot indicated this failure started at the conductor stack edge. This is a high voltage stress area and many failures start at a corner. It was also apparent the surface crack penetrated through all tape layers at this location and was the cause of the dielectric failure. Another problem was also uncovered. Groundwall insulation tape layers were well bonded together but not bonded to the conductor turn tape.

FIGURE 4: **In this view we can see the fracture completely circled the coil insulation.**

With an insulation fracture across as well as along the groundwall insulation it is apparent the coil endarm was twisted during installation. A weak resin bond between conductor stack and groundwall insulation was not adequate to prevent mechanical then electrical failure of groundwall insulation.

ROOT CAUSE: **Fracture of groundwall insulation during coil installation. Lack of bonding between tape layers was a major contributing factor.**

In Service Failure of a Mature Winding

A 1912 vintage generator that was operating with epoxy-mica stator coils installed in 1986 fail during a thunderstorm. This machine does not have a step-up transformer and the generator leads are 3 miles long following the river to the next site and a tie to the local 138kV system. There is a history of lightning induced stator failures.

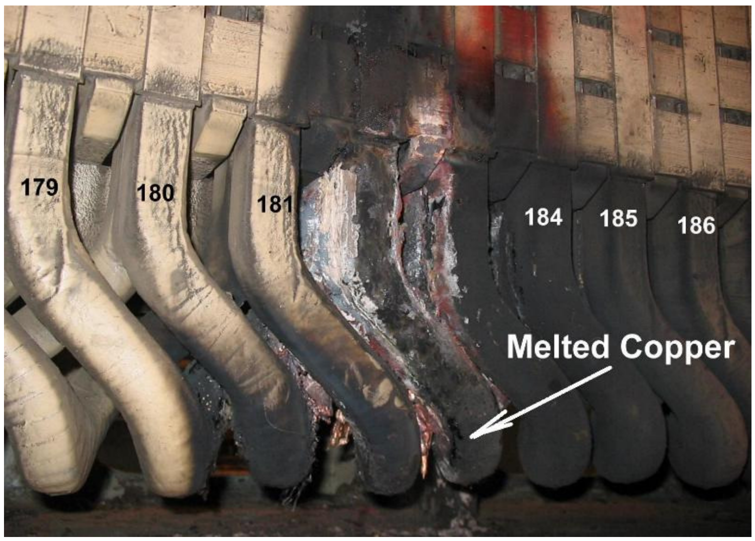

FIGURE 5: With the rotor removed stator winding damage was found to be extensive.

The failure burned for a period of several minutes and melted a great deal of copper out of slot 182. Coils against rotor rotation from the failure were not damaged. There was no damage to coils before coil 178. Coils after 182 suffered fire damage. The failed coil and adjacent damaged coils were removed and replaced with half coil splices.

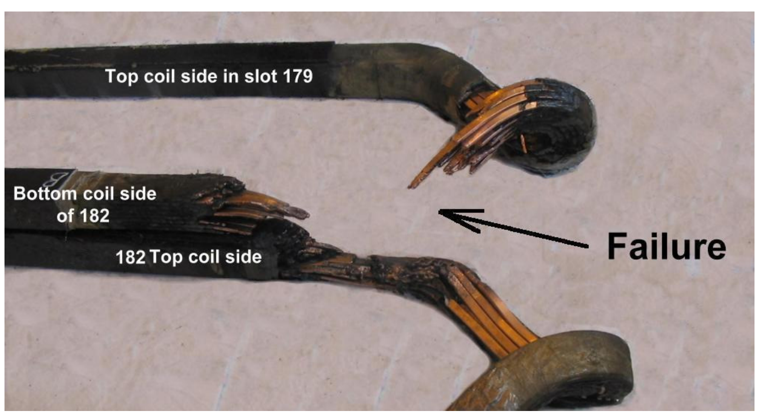

FIGURE 6: **This failure created a sphere of missing copper. The center of this ball indicates where the failure originated in the bottom coil in slot 182.**

The two coil sides involved in this failure were placed on a table and positioned as they were in slot 182. In Figure 6 we are looking from the back towards the machine bore. The failure appeard to have started on the first inside turns at the lower end arm of top coil 179 just below the core edge of slot 182. Circulating currents become very high and the melted copper shorts adjacent turns. The fault is maintained within the thick mica insulation until the pressure and heat burns into the top coil in slot 182. Phase 3 is now open. No ground fault developed. The generator is removed from service due to imbalance phase currents.

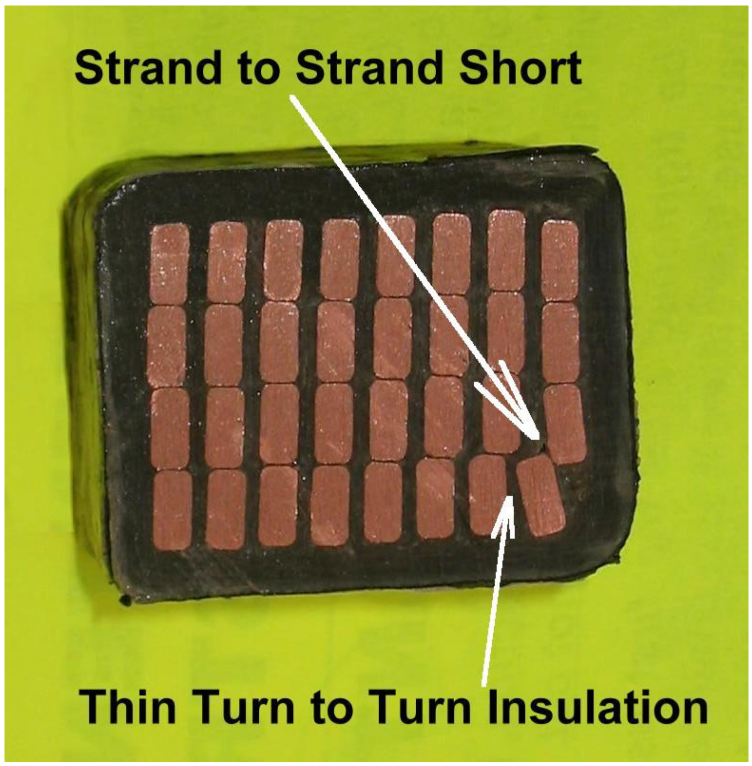

FIGURE 7: **Dissection of adjacent removed half coils found strand defects and voids in the insulation.**

Dissection of several removed half coils found two strands on the first turn crushed together and shorted. Note there is misalignment in the second turn strands as well. Voids are present at the interface between turn insulation and main groundwall insulation. There was also slightly thinner turn insulation between the first and second turns due to the twisted strand.

There were numerous voids and tape folds in the endarms but this is a low operating dielectric stress area where voids have little effect. This is not the case during a voltage surge when endarm turn-to-turn voltages can be very high.

ROOT CAUSE: A twisted conductor strand in the original construction may have resulted in a strand-to-strand short resulting in localized heating. Thinner turn-to-turn insulation may have also been present at this location. A lightning surge failed the coil due to the original defects and time related deterioration of turn-to- turn insulation in this one coil. Winding replacement was recommended.

Mature Winding Test Failure

During the 120% overpotential maintenance test of a 1955 vintage steam turbine generator one stator circuit failed. These machines had been exceptionally trouble free with a history of only minor stator maintenance. The bar was removed and breakdown site dissected.

FIGURE 8: Dissection of the failed stator bar found no bonding between tape layers.

This generator was constructed with the first synthetic resin polyester bonded groundwall insulation. None of the original polyester resin remained to bond layers of mica flake insulation after 50+ years of service. The resin had returned to the original constituent oils.

ROOT CAUSE: Time related deterioration of the base resin. Rewinding all eight similar generators was recommended.

Mature Winding Test Failure Case two

During a 130% maintenance overpotential stator test prior to rewedging, one phase of a 20 year old pump-generator winding failed. The coil was removed and bypassed. The other two phases were not tested and the stator rewedging project was cancelled. This was a severe duty machine with several starts each day. These stator coils had indications minor corona activity and surface corona burns had been repaired several times.

FIGURE 9: This test failure started at a corner of the top turn conductor stack.

FIGURE 10: Additional cuts along the failed coil found internal corona had destroyed most strand insulation on the first turn near the machine bore.

The top most stator winding conductors operate at the highest temperatures and ozone deterioration is accelerated by the increased temperature. There was some minor damage to the middle turn and no strand insulation to the bottom turn. Loss of strand insulation will create circulating currents and the increased losses add additional heating. Eventually a turn-to-turn failure develops and the coil fails.

ROOT CAUSE: Age related internal corona activity destroyed the strand insulation and weakened adjacent groundwall insulation. Rewinding both similar pump-generators was recommended.

Vibration Sparking Failures

FIGURE 11: These motor coils appeared to have rodent damage in the slots.

A series of new 7000 hp, 4 kV motors experienced multiple stator coil failures after three years service. The filler strips and side packing were of a material not able to withstand the operating temperatures. The coils became loose and there was minor vibration in the slots. Pitting and erosion of the bottom of the bottom stator coils resulted from vibration sparking.

VIBRATION SPARKING CASE TWO

Several half coils removed from a failed 3,000 hp, 4 kV motor were dissected for an analysis of the test failure. These are very unique coils made only a few years by one OEM. A red silicone rubber tape was applied as the only groundwall insulation. There is no mica in this insulation system.

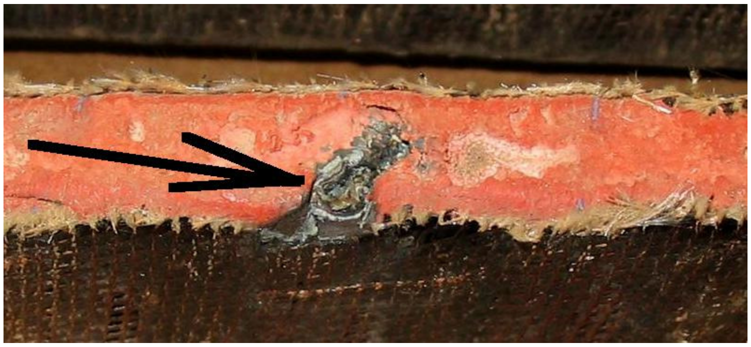

FIGURE 12: The motor coil failure location was apparent. Note all varnished glass armor tape is gone on the bottom of this coil.

This was a dielectric failure starting at an edge of the conductor stack then progressing straight through the insulation. There was no obvious deterioration of the rubber insulation other than on bottom edge of some samples. There appeared to have been in service coil movement and the resulting vibration sparking removed small pieces of insulation. There was severe time/temperature related mechanical strength deterioration of the glass armor tape and black varnish coating. There were numerous voids between the conductor stack and the groundwall insulation. The bond between the red silicone rubber and the conductor stack was gone in many locations. This permitted copper vibration within the insulation, the resulting vibration sparking on the higher voltage coils reduced insulation thickness.

Materials other than the red rubber had the typical thermal deterioration associated with 30+ years of service. Deterioration of the silicone rubber insulation thickness resulted from movement between the top and bottom coils in the slot. This resulted in abraded armor tape and vibration sparking of the insulation causing the test failure.

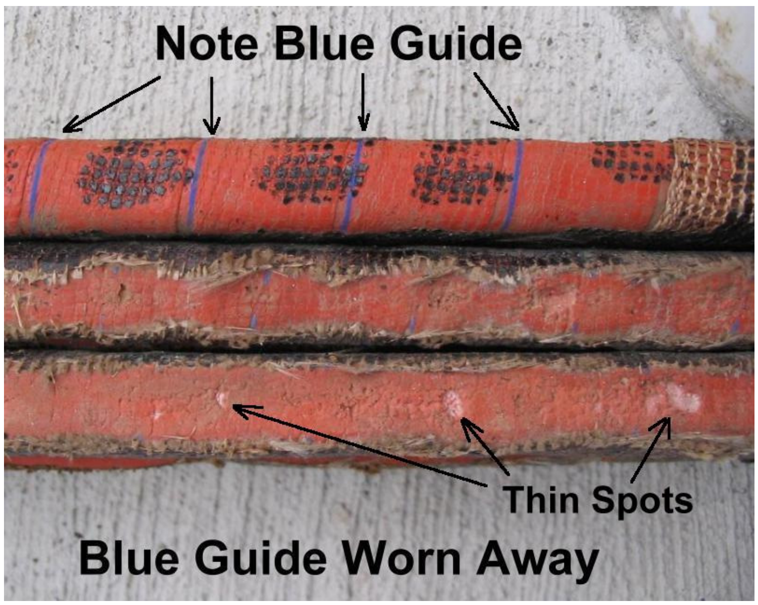

FIGURE 13 Three coils placed side-by-side show the progression of vibration damage on the bottom coil sides.

When glass armor tape was removed from one coil the blue tape overlap guide was apparent (first coil). With the second coil the in-service coil vibration has removed the armor tape and some of the red rubber tape. In the third coil thin spots in the rubber are present but a failure had not yet developed.

ROOT CAUSE: These two failures occurred 30 years apart but in both cases slot filler materials had deteriorated and permitted coil movement. Vibration sparking deterioration was faster than the usual mechanical abrasion of groundwall insulation,. Rewind all similar motors was recommended.

SUMMARY

Performing the root cause analysis of stator failures is a necessary step in preventing additional incidents. Anyone with a basic knowledge of insulation systems and a curious nature can gain some understanding of why the system deteriorated and failed through a few simple dissection techniques. You can never take too many digital photographs! Seasoned engineers familiar with the type of machine in question may also to improve the confidence level and offer additional insight in failure mechanisms.

BIOGRAPHY

James E. Timperley (BSEE, 1968 Oklahoma State University) is a member of the Doble Engineered Strategies expert consulting division. He previously held the position of staff engineer at American Electric Power in Columbus Ohio. Jim has published over 65 technical papers on operating, maintaining, testing and repairing rotating electrical machinery. Other experience includes maintaining high current isolated phase bus, equipment root cause failure analysis, the development and application of EMI Diagnostics and R&D projects dealing with insulation materials. He is an IEEE Fellow, a past chairman of the Doble Rotating Machinery Committee, active in several standards groups and a registered professional engineer in the state of Ohio.