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DETERIORATION MECHANISMS

IN

RECENT AIR COOLED TURBINE GENERATORS

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ABSTRACT

Several designs of recently installed air cooled turbine generators have developed serious deterioration and failures within the first few years of service. This paper discusses case histories of generator stator and rotor problems that have resulted in service interruption and major repairs.

INTRODUCTION

Since 1996, more than a thousand combustion turbine generators were purchased and installed due to a flood of venture capital that poured into the increasingly unregulated electric power market, and the low cost of natural gas leading up to 2002. By 2004, according to Federal Government data collected by the Energy Information Administration, 17.9 percent of the net domestic generation was attributed to natural gas.[i] The same source also showed that natural gas electric generation was accomplished by just over 3,000 natural gas turbine generators[ii] and forecast that over 94,000 Megawatts of new natural gas fired capacity will be added from 2005 thru 2009.[iii] Because of a number of different market, technical, and, certainly, cost factors, air-cooled generators were the primary technology utilized with most of the natural gas units. While not all of the natural gas fired turbine generators are air cooled, the overwhelming majority are. Arguably, technical compromises were made by some manufacturers to meet market demands, and this has resulted in numerous operational problems and a short service life for some generators. Failures within the first five years of service are not unknown.

PARTIAL DISCHARGES

Air-cooled generators are considered, by some, to be ancient technology. Newer air cooled generator designs face a number of difficult technical challenges not faced by older designs. These include elevated output ratings, higher operating voltages, and smaller physical foot prints. In providing cost-

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competitive generators for combustion turbine applications, the manufacturers seemingly overcame these challenges. However, in operation, it appears, several factors have offset the competitive generator pricing, such as higher operating temperatures, greater windage losses, and increased maintenance costs associated with air-cooling. Additionally, there are partial discharges (PD) that are inherent to high voltage air-cooled generator stators.

Older designs for air-cooled generators, which operated at very low ground wall insulation voltage stress levels, used asphalt-based mica flake stator insulation. These materials were selected due to their natural resistance to partial discharges and the resulting chemical attack of ozone. They were somewhat soft and tended to swell in the slot, helping to dampen vibration and hold the stator bars tightly within the core slots.

Newer air-cooled generator designs have not improved the partial discharge outlook. Instead they have further compounded problems with insulation systems that are subjected to higher ground wall insulation voltage stress levels and higher temperatures, resulting in increased partial discharge activity. In addition, some of the synthetic resins now used, are not resistant to ozone bleaching. These insulation systems are very rigid and on their own are not very effective in holding the stator bar tight within the core slots. As a consequence, in some instances, vibration can open new sites for corona activity.

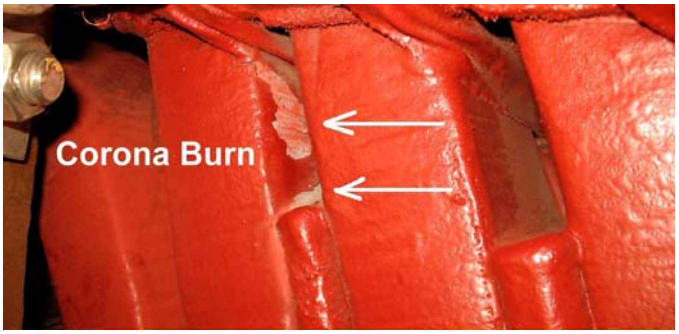

Figure 1: Corona and gap discharges on the stator endwinding after three years of service.

STATOR EXAMPLE #1

Figures 1 through 6 show the various effects of advanced PD on a group of three similar 3600 rpm, 13.8 kV generators with a nominal rating of 150 MW each. The design was identical for all three, and they were all manufactured by the same company. The machines all failed after experiencing similar operating hour durations; 43,500 hrs, 45,550 hrs and 52,401 hrs. Figure 2 gives a summary of operational data for the three units. Coils from failed machines were dissected and it was determined that the designed volt per mill stress level of the ground wall insulation was approximately 72 volts per mil.

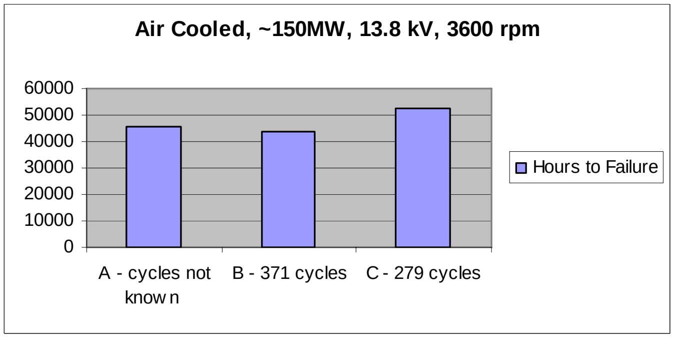

Figure 2: Average lifetime operational data for three identical generator units.

Within approximately three years, the generators developed minor end winding corona and gap discharges on the stator end windings. Figure 1 shows how ozone from the partial discharges eroded away the surface stress grading paints and the red protective coating. Figure 3 shows a burnt tie between stator bars and severe damage to the surface paints.

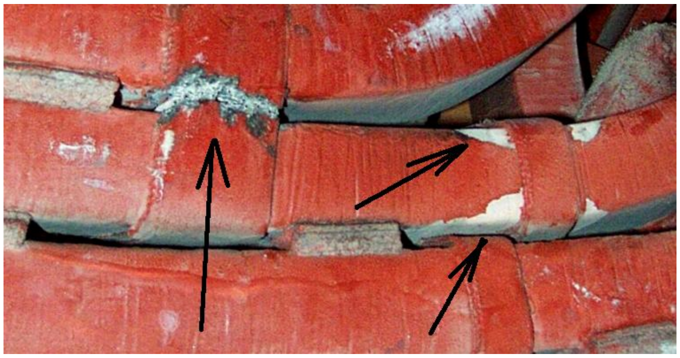

Figure 3: PD activity resulted in severe damage to surface paints and the burning of ties between stator bars.

Figure 4: With binding resins eroded by ozone, only the glass armor tape remains.

In Figure 4, although the stator bars were tight in the slots, partial discharge activity on the high voltage top stator bars destroyed all the black conductive surface paints. Ozone had bleached away all the paints and binding resins leaving only the bare glass armor tape.

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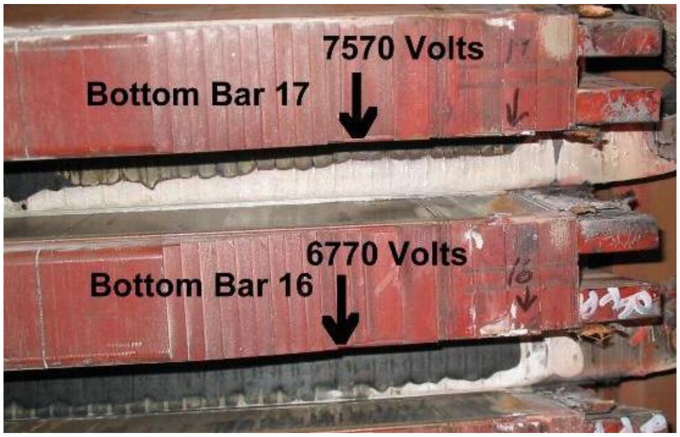

Figure 5: Bottom bars that experienced severe damage with operating voltages to ground indicated.

In addition to the top bar damage discussed earlier, which resulted in the unit's failure, the bottom bars also had severe damage. All of the bars operating at higher voltages experienced extensive erosion of the conductive coating after five years of service. Stator bars in the top of the core slots, which operate at higher temperatures, had the most damage. There was similar deterioration of bottom bars that operated at high voltages. In Figure 5 the operating voltages to ground are indicated next to the deterioration.

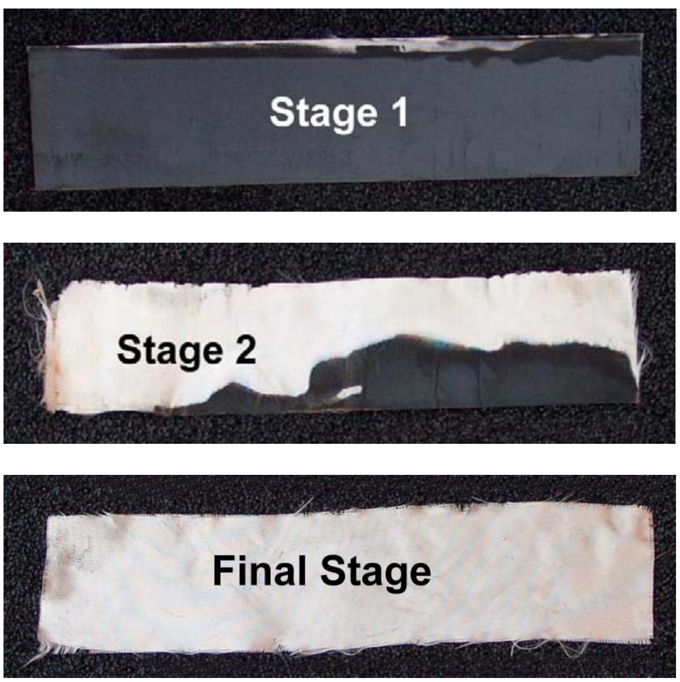

Figure 6: Progressive deterioration of slot side packing material.

Deterioration of slot side packing is likewise dependent on the operating voltage of the adjacent stator bar. Over time, as shown in Figure 6, severe slot discharges in this generator destroyed the side packing meant to hold the stator bars tight in the core slots. In the final stage, all conductive material and binder disappeared and only a bleached glass cloth remained adjacent to the high-voltage bars. With no side packing, PD levels increase greatly and, eventually, the stator bars vibrate and fail.

EXAMPLE #2

Figure 7: Stator slot with wedges burned along almost the length of the entire slot.

During a scheduled outage of the unit pictured in Figure 7, an inspection found one slot with wedges that were burned along nearly the entire length of the slot. At least one wedge appeared to be dangling out of the slot. The generator was disassembled and the rotor removed. Further inspection and disassembly found severe PD damage in the slot with the burned wedges. Signs of significant PD were also noted in other slots and areas of the stator.

Figure 8: A wedge from the affected slot.

Some generator designs do not utilize side packing in the slot area, as was the case with this unit. Despite the intent to essentially glue the coils into the slot, side vibration leads to mechanical abrasion of the coil insulation. The inability to establish a solid ground plane along the sides with the core iron, causes increased levels of PD activity. Together, the mechanical abrasion and PD activity eroded the coil insulation, fillers and even the slot wedges

Initially, the owner of the machine pictured in Figures 7 and 8, performed an epoxy injection procedure in the stator

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slots, along with other efforts to “tighten up” the machine. Following completion of this work, the owner started the unit and began slowly applying load. Before reaching full load, less than 24 hours after starting the unit, it failed to ground in a different slot and phase than the previous one with the burned wedges. Following the second outage, the unit was successfully rewound with an optimized coil slot configuration.

Figure 9: Bars removed from the unit by the non-OEM rewind contractor.

Figure 9 shows the condition of the bars removed during the rewind process. A difference can be noted in the degradation between the various bars. As mentioned with Example #1, corona damage was most predominant in the coils at the beginning of the coil groups that experience higher voltage levels.

SOLUTIONS

The original design of a generator stator may severely limit options for maintenance to extend service life. In some cases, recoating the damaged area shown in Figure 1 may be a way to lengthen service life. This is normally done with a process known as epoxy injection. However, repair of stator bar damage in the slots is difficult and in some designs impossible.

Some original equipment manufacturers have tried a “global” VPI (vacuum pressure impregnation), which immerses the fully-wound stator into resin, in an attempt to lower production costs and keep the stator bars tight. However, instead of solving problems this technique has introduced a new series of failure mechanisms. Stator bar repairs and even compete winding replacements can be challenging, if not impractical with globally VPI’ed machines.

In many cases, a new stator winding design, or at least slot configuration, with improved materials may be the most prudent path to reduce future partial discharge activity. If so, a root cause analysis of deterioration or failure analysis should be performed and modifications implemented in the replacement stator winding to prevent a reoccurrence. Materials that suppress slot discharges, which are more tolerant of high operating temperatures, should be included in the new winding. Recalculating the coils losses may indicate opportunities to further decrease coil losses, allowing the unit to run cooler. It may be possible to reconfigure the coil cross section geometry to allow for extra space that can be filled with additional ground wall insulation to reduce the voltage stress and/or increase the copper content. Making a change to the coil cross section may also allow space for improved side packing, such as semi-conductive ripple springs.

Traditionally, the original manufacturers of the equipment have been considered the only ones technically competent to access and make appropriate changes. This is not necessarily factual in today’s market. A non-OEM company rewound the unit shown in Example #2, utilizing an optimized coil design and slot configuration along with up-to-date coil manufacturing techniques and materials, which were engineered in-house by the company and installed by their own field service team.

DETECTION OF PARTIAL DISCHARGES

For those owners of air-cooled machines who want to track the effects of partial discharge and avert a forced outage, there are several types of devices on the market to measure PD activity. During an outage PD couplers can be added to the three generator line terminals to allow the collection of trending data by the various measuring devices on the market. The trended data will provide information on deterioration rates.

However, the off line installation of additional PD couplers is not always necessary. One method, EMI (electromagnetic interference), is a very useful tool in determining generator condition, even when there is serious external “noise.” Instead of PD couplers, data is collected with the in-service installation of a split core radio frequency current probe.

EXAMPLE #3

A generator had severe slot-related and endwinding-related PD. However, the windings were tight. There was no increase in PD activity with increased load. There is also very high PD activity in the generator bus and unit breaker.

SOLUTION

It is known that when stator bars are loose, the PD levels increase with machine load. The higher stator currents increase bar forces and vibration increase. With more stator bar vibration there is an increase in slot PD activity. The EMI signatures in Figure 10 show the slot related PD activity remains the same at two different loads.

The EMI mean and standard deviations change only slightly with load changes. There is a slight change in the exciter pattern around 0.01 MHz, due to the higher exciter currents. The part of the EMI spectrum that describes the generator from 0.1 MHz to 10 MHz did not change. The graph shows the machine had severe slot discharges, but the stator bars were tight in the core slots, as well as in the end-windings. This site has very high PD activity in the associated

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generator breaker and isolated phase bus. There was a slight increase in bus/breaker related PD with a load change. This high noise level is shown on the curve from 20 MHz to 120 MHZ.

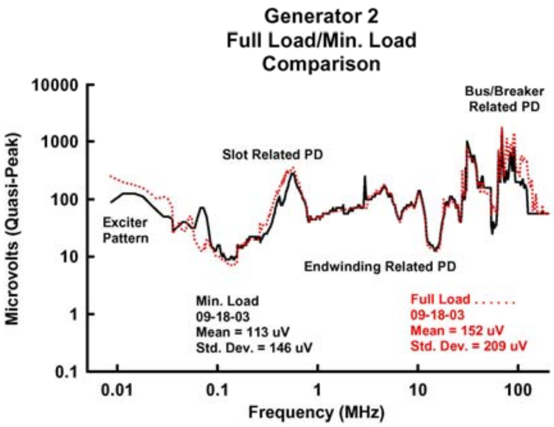

Figure 10: Plot of slot-related PD and endwinding-related PD shows no increase in PD activity despite changes in load.

The stator bar shown in Figure 4 is the same as found in this generator before it was rewound. EMI Diagnostics made it possible to predict the remaining service life, and a stator winding replacement was scheduled before a failure occurred.

ROTOR-RELATED PROBLEMS WITH AIR-COOLED GENERATORS

Several air cooled generators have experienced premature problems or failures of the rotor. The concerns have been primarily noted in the end winding areas of the rotor. For the purpose of this discussion, the symptoms exhibited have been separated into two groups, one being conductor issues and the other being turn insulation issues.

When considering actions to correct problems with rotors, it is important to realize that addressing the symptoms alone will not prevent them from reappearing. The root cause of the symptoms must be understood and addressed in order to realize a long-term solution.

EXAMPLE #4

Figure 11 shows rotor conductor cracking of several top turns near the rotor body that caused a grounded rotor condition. Within the air cooled generator fleet, it is common for the units to be frequently cycled to follow demand. Cyclic operation can introduce low cycle fatigue stresses to the copper conductor, leading to cracking of the conductor.

Figure 11: Cracking of top turns near rotor body caused this rotor to go to ground.

EXAMPLE #5

After removal from the rotor, this coil, shown in Figure 12, was cleaned by bead blasting. The cracked top turn is easily recognizable. The crack pictured was one of many found throughout the rotor winding. In all, more than ten percent of the total number of turns had cracks or indications of excessive conductor stress, requiring the replacement of the complete rotor winding.

Figure 12: Cleaning exposed the full extent of this rotor coil cracking.

SOLUTIONS

There are several potential root causes for end winding distortion. It is usually difficult, if not impossible, to scientifically narrow the root cause to just one, with complete certainty. The root cause is usually made up of several conditions or problems that contribute to the actual symptom being exhibited. The most common root cause contributors for end winding distortion are:

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- Coil configuration/geometry
- Copper conductor characteristics – alloy and hardness
- End winding blocking scheme
- Coil interface with the slot wedges and retaining ring

Figure 13 shows two examples of severe end winding distortions that have been caused by operational problems. Both square corner and edge bent configurations have been used effectively in many rotors. When coupled with the rest of the rotor components, in a well thought out and proven system, either can work well. However, instances of conductor cracking and distortion have been prevalent with the square corner coils, because of designs that provide inadequate relief of mechanical stress risers in the corner or because of manufacturing methods that result in inadequate corner braze joints.

Figure 13: End turn distortion, in square corner or picture frame type coils (left) and edge bent type coils (right).

The rotor conductor alloy most commonly used is CDA-107, an oxygen-free, silver bearing copper alloy. While other alloys may have been used in some instances, this alloy has become the standard because of the enhanced mechanical characteristics the silver content. Most would agree that the best performing coils have been those manufactured without annealing, using CDA-107 with a “Medium Hard” grade of between 75 and 85 Rockwell F.

ANNEAL OR NOT?

Several OEM’s have issued technical notices warning of soft copper and its possible contribution to copper deformation. One common industry practice seems to be the condemnation of copper rotor conductors having a hardness of less than 50 on the Rockwell F scale. OEMs of some newer designs now exhibiting cracking and distortion symptoms have offered replacement of the top few turns with a much harder copper alloy. In at least one such instance, the new turn, made of a much harder alloy than CDA -107, was actually taken out of the electrical circuit and seemed to function more as a filler protecting the remaining portion of the coil.

Some companies use annealing in the coil manufacturing process to ease the bending and shaping of the coils. Care should be taken to restrict the annealing to specific areas and to also make certain the blocking and other functional aspects are more than adequate to insure the total system performs well as a package. To avoid creating areas of soft copper in the winding that might deform, the best replacement coils are manufactured without annealing the copper.

BLOCKING

Some concern exists regarding the effectiveness of some new rotor blocking designs. It is doubtful that inadequate blocking could be factually identified as the sole root cause of a failure, but it can clearly contribute to a failure. Adequate blocking designs must strike a delicate balance between allowing the coils to expand and contract axially, while maintaining the proper relationship and spacing between the coils and other rotor components. Simply adding additional blocking to end windings can prove quite foolish. An engineering evaluation is needed to not only determine if the additional blocking will provide the desired support and spacing, but also to insure that cooling paths and flow are maintained.

RETAINING RINGS

Of the various root causes leading to coil deformation, the coil interface between the wedges and the retaining ring, has been found to be among the greatest contributors. Letters have been issued to owners by at least one OEM, pointing out the potential for copper conductor deformation caused by friction or pinch points between the coil and the retaining rings and slot wedges. Alleviating the pinch points and friction are recommended corrective actions. When friction or pinch points exist along the coil interface, end turn distortion can emerge as a result of a ratcheting action that stretches the copper a small amount after each thermal cycle. Slip plains between the coil and the retaining rings and wedges minimize the friction and pinch points. The outer slot wedges are lightly chamfered from the outside edge to the bottom to prevent a pinch point that could grab the copper conductor as it cools and contracts axially during the cooling phase of the thermal cycle

SHORTED TURNS

Shorted turns in rotors can create significant operational issues, such as the severe vibration that follows load or swings in VAR loading. Major shorts are created if the copper conductor of a coil becomes deformed to the extent that it touches a neighboring coil as illustrated in Figure 13. Shorted turns can also arise from damaged or migrated turn insulation. Shorted turns caused by the migration of turn insulation was experienced on a number of machines of a similar design by one manufacturer. The root cause of the turn insulation migration was failure of the adhesive used to hold the strip turn insulation in the proper position, necessitating a rewind of the rotors to correct the problem.

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CONCLUSIONS

There is strong evidence that some of the recently installed air cooled generators can be expected to develop serious deterioration problems early in the service life. This deterioration may result in major repairs or failures. Modifications, which optimize the design and use improved materials, and manufacturing processes, are prudent to reduce future deterioration and extend machine service life when a new stator or rotor winding is installed. Diligent and periodic inspections and testing are key diagnostic tools, and trending data is the best safeguard against the misinterpretation of the results. When symptoms are identified and corrective actions proposed, the engineering evaluation should show how the actions will effectively address all possible root causes and deliver the desired long-term, reliable operation of the machine.

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