Problems with Modern Air-Cooled Generator Stator Winding Insulation

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A very large percentage of the new generation of generators brought into service in the past decade has been driven by gas turbines, or based on smaller steam turbines, often in a combined cycle arrangement. The generators needed for such turbines are usually in the range of 25 MVA to 300 MVA, rather than the 600 MVA and greater generators that were common a decade ago in conventional fossil and nuclear plants. The market for supplying these smaller turbine generators has become extremely competitive and there is tremendous pressure on the generator manufacturers to reduce production costs.

The generator manufacturers have developed several approaches to make their generators more cost effective. One of the most widely adopted approaches is to make the turbine generator air cooled. That is, rather than using the traditional hydrogen cooling that in the past predominated in high-speed machines rated more than about 100 MVA, air is used to directly or indirectly cool the rotor and stator windings [1-3]. The benefit is that all the equipment for the hydrogen handling is no longer needed, reducing costs. The impact of using air cooling is that the stator windings are much more likely to suffer from partial discharges (PD), since the breakdown voltage of air is much lower than the breakdown voltage of high-pressure hydrogen. In addition, PD in air creates ozone, which can accelerate deterioration as a result of chemical reactions.

Another approach with the new turbo machines is to increase some of the design stresses. For example, by increasing the design electrical stress of the groundwall insulation, the groundwall thickness decreases. This enables the stator slots to be smaller, and the whole machine to be smaller, reducing material costs (copper, steel, insulation) by as much as 20% [4]. Another benefit is that the thinner groundwall insulation can conduct the heat from the copper I^2R losses in the stator coils to the stator core (heat sink) much more effectively, reducing stator temperature. In addition to increasing the electric stress, some generator manufacturers have also been taking better advantage of the thermal capabilities of modern epoxy-mica groundwall insulation. This allows the copper cross-section to be reduced (increasing the copper I^2R losses) and/or the endwinding length to be reduced (reducing the effectiveness of the endwinding as a heat sink). The consequence is higher operating temperatures. However, one should recall that the common Class F materials are specified to have an average life of 20,000 hours (about three years) at 155° C [5]. Using the Arrhenius relationship, where the thermal life of a material increases about two times for every 10° C drop in operating temperature, users can obtain an indication of the life of a winding if it operates close to the "rated" temperature of 155° C.

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A third approach to reduce the manufacturing cost of modern stator windings has been to simplify the system used to support the bars or coils in the stator slot. Large turbine generators used elaborate multipart wedges, ripple springs, and/or conformable packing materials in an effort to eliminate coil vibration in the slot due to 100/120 Hz magnetic forces. Such systems are expensive and time consuming to install. Since the modern machines have lower ratings, the

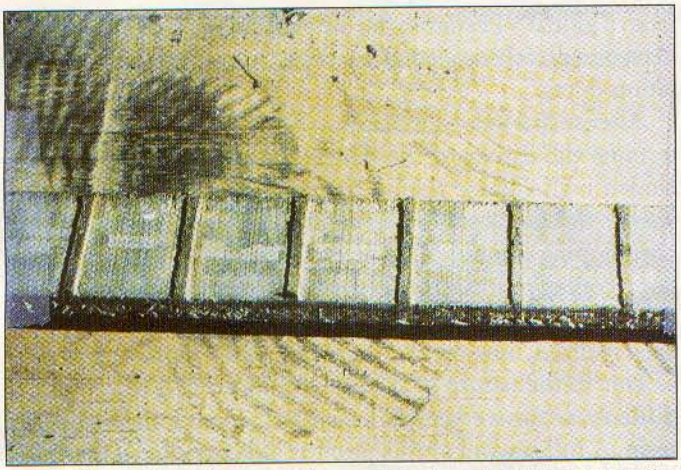

Fig. 1 Photo of a coil removed from a stator bar that failed due to slot discharge. The original winding was not installed in the winding tightly, and no ripple springs were used. This was a conventionally made stator, where the coil insulation was cured outside of the slot.

bar/coil currents are lower and, consequently, there may be less need for elaborate slot support systems.

A variation of this has been the trend to global VPI stators, i.e., stators that are completely wound with flexible "green" coils or bars, and then the entire stator is impregnated with an epoxy in a large tank [2,6]. This greatly reduces the labor costs and production time as well as usually ensuring the coils are rigidly held within the slot.

All of these innovations have reduced the cost of the generators. However, as occurs when any innovations are introduced, some stator winding problems have become apparent in the operation of recently installed air-cooled machines. The following are some of the problems the authors have encountered to date, together with some of the options to be considered for repair.

Loose Coils in Conventional Stators

Coil vibration in the stator slot has long been a problem in all nonglobal VPI stators made with thermoset insulation systems such as epoxy mica. The first instances were reported with thermosetting polyester mica 50 years ago [7]. The root cause of the problem is that if the coils are not tightly held in the slot, at or near full load, the double power frequency magnetic forces will vibrate the coil. Consequently, the groundwall insulation rubs against the laminated steel core—a very abrasive surface. First, the semiconductive layer of the bar or coil is abraded away, and then the groundwall insulation. The mechanism is sometimes referred to as slot discharge because once the semiconductive coating is abraded, PDs occur between the coil surface and the core, further increasing the rate of deterioration. First in hydrogen-cooled turbos, and then in hydrogenerators, generator manufacturers have developed techniques outlined above to keep the windings tight, even as the insulation and other slot components shrink with normal ageing.

There has been a tendency in the modern turbo generators to reduce the cost and complexity of the slot support system. Unfortunately, cases have occurred where the windings were able to move in the slot when new, or gradually become loose in operation, especially if oil is present. The result has been some premature failures caused by the slot discharge process. Figure 1 shows the side of a coil for a 40 MVA generator where about 30% of the groundwall insulation thickness has been abraded away by the vibration, prior to failure. It is believed that the coils were not originally installed tightly enough during manufacture. The ridges where no abrasion occurs at the stator core ventilation ducts are clearly visible. The larger the machine, in general, the larger the magnetic forces acting on the coils/bars, and thus the faster the failure process.

Arresting this failure process is fairly straightforward, if somewhat expensive. During a suitable opportunity with the rotor removed, re-side packing and rewedging are needed, preferably with ripple springs and/or two part wedges. If the repair can be done before the semiconductive coating is abraded away, then the winding can often be restored to as-new condition. Unfortunately, if the semiconductive layer is worn away and the epoxy-mica insulation is exposed, then PD will continue to occur, gradually (but at a much slower rate) destroying the groundwall. Injecting into the slots carbon loaded varnishes, silicone rubber or epoxy can somewhat restore the semiconductive coating, but PD will still occur in areas where the injection was incomplete.

Loose Coils in Global VPI Machines

In global VPI windings, the "green" coils or bars are often manufactured slightly oversized to ensure a tight fit within the slot. The green coils are then pressed into the slots and a simple wedging system is utilized that mainly serves to hold the bars in place prior to impregnation. Once assembled, the stator is moved into a large tank that is then put under vacuum. A low-viscosity epoxy resin is then injected into the tank in order to impregnate the whole of the main wall insulation system of the stator bars. It is also intended to fill all the voids in the slot between the bar and the core and to lock the bars in place since baking to cure the resin follows the resin impregnation. Since the stator is manufactured with a nominal interference fit (subject to tolerances of both bar size and core pack variations) the thin layer of resin is relied on to hold the bars in place.

However, when the machine enters operation and undergoes load cycling as well as other mechanical and electrical stresses, the bars will tend to move in the slot. The three main components—core steel, copper, and insulation—all have different coefficients of expansion, and often, a high number of thermal cycles during the commissioning of a unit will lead to the shearing of the resin bond between the bar and core. This now leaves the interference fit and the wedges alone to hold the stator bars in place. From here the failure mechanism is much the same as for a conventionally wound stator. The wedges may not help to overcome impact of the changes in

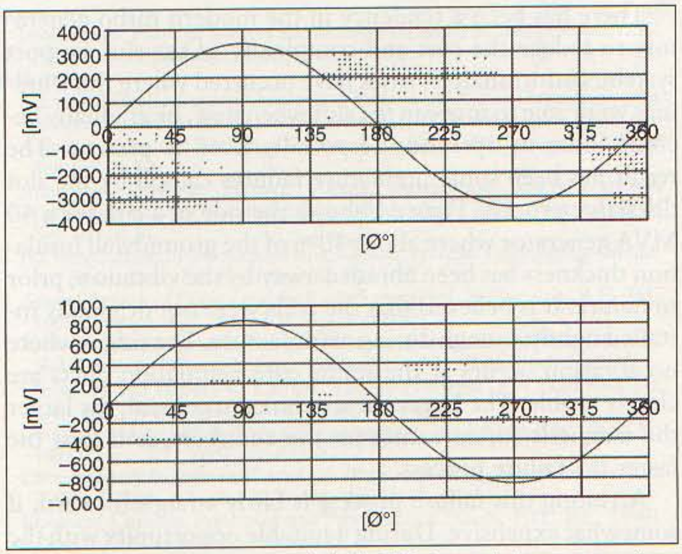

Fig. 2 Examples of PD on two globally VPI air-cooled generators from different manufacturers (note different PD magnitude in y-axis scale). The horizontal scale shows the phase angle of the ac cycle.

Fig. 3 Example of bar removed from a global VPI stator that failed due to slot discharges. The photo shows the edge of the bar where abrasion and PD damaged the insulation.

magnetic forces as the machine operates, and so over time movement of the bars may become possible. Once this movement is allowed to occur, voids will appear between the bar and core. This allows PD to begin, which accelerates the failure mechanism by increasing the size of the voids.

Figure 2 shows levels of PD between two different OEM air-cooled generators. The difference in levels is of an order in magnitude. Both have similar slot packing systems and are subjected to the same global vacuum impregnation technique.

As movement increases and PDs become stronger, the main wall insulation is gradually abraded away, just as described above for conventionally made stator windings. If there is a weak spot at any point in the insulation, perhaps where the resin did not fully penetrate during manufacture, insulation may fail completely with all the attendant alarms and excursions. Figure 3 shows an example of such a failure from a global VPI stator; the outer semiconducting layer has been completely eroded along the bar except for at the ventilation ducts.

After such a failure, extensive testing was carried out to determine the extent of the damage in the machine. This included high-voltage testing the winding, checks on the slot wedge tightness, stator bar-to-core contact resistance, and boroscoping around 50% of the stator vent slots. Until the boroscoping results were seen the full extent of the damage to the remaining winding, other than the one failed bar, had not been realized, thus altering the extent of the repair necessary.

Due to the nature of the global VPI process rewedging is difficult, as the wedge will have been glued to the bar by the resin. A full rewind at this point is uneconomic, despite extensive damage. This leaves injection of a semiconducting material as a palliative attempt to restore the integrity of the insulation system.

Thermal Cycling in Conventional Stators

Rapid load cycles are possible in gas turbine generators—where the load can change from zero to full load in one or two minutes. If an unloaded generator suddenly increases to full load, the temperature of the copper conductors can reach maximum operating temperature in a few minutes, due to the copper I^2R losses. The increase in copper temperature causes the copper to expand as governed by the coefficient of thermal expansion. The coil may grow as much as 1 or 2 mm in the axial direction [8]. Unfortunately, the epoxy mica insulation on the coil does not expand as much as the copper—primarily because the epoxy mica insulation is considerably cooler than the copper in the first 10 to 15 minutes after a rapid load change. The result is a shear stress on the bond between the copper and the insulation after each rapid load change. Experience shows that with a sufficient number of rapid load changes, and a high enough winding temperature (possibly greater than 120° C), the bond between the copper and the insulation, or between insulation layers, will fatigue crack. The delamination created will enable PD to occur, hastening the failure process. Figure 4 shows the delamination in a 13.8 kV coil in a stator that saw thousands of rapid load cycles.

Once the stator is constructed no maintenance other that a rewind can fix or slow down this problem. However, operational changes—such as slowing the rate of load changes or limiting the maximum operating temperature—can slow the deterioration process.

Endwinding PD

Along with reducing groundwall thickness, manufacturers have also economized further by requiring the design engineers to place the windings into a smaller volume. Thus, in some cases the coils are much closer to one another in the endwinding. Unfortunately, one of the recent problems that has been detected on some large air-cooled machines is PD, both between coils and in the lead area. The discharges are

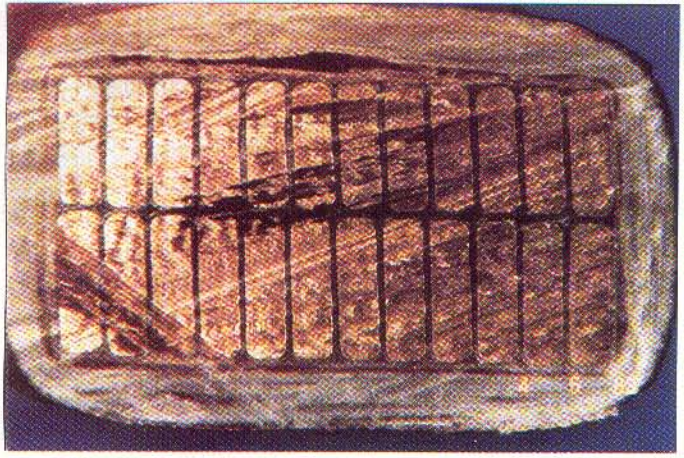

Fig. 4 Cross section of stator bar where the copper has separated from the groundwall due to thermal cycling.

Fig. 5 Small air space between blocking at two phase leads has created PD (white band).

the result of design or manufacturing deficiencies where the limits have been pushed in coil and phase lead spacing.

The close spacing has resulted in highly stressed air between coils or leads in two different phases. The resulting PD will eventually bore a hole through the insulation, triggering phase-to-phase or phase-to-ground faults. Figure 5 shows PD occurring in the air space at blocking between two-phase leads. Figure 6 shows insulating material use to fill the air spaces between leads, and indicates that not all repairs can successfully correct the problem. Figure 7 shows similar problems in the coil endwinding area. The coils are of opposing phases and have the highest potential along with the highest electrical stress.

Now that these problems have been identified, what can be done to either arrest the PD activity or completely eliminate the PD? For the lead problems, the best repair, and the one that would be permanent, is to open the clearance between the two phases, reducing the likelihood of PD. Two options are available to open the space: 1) redesign the endwinding utilizing a new connection method, or 2) modify the existing design by reducing the amount of insulation on the phase leads. The second option requires stripping the insulation from each lead and reinsulating.

Another approach, which would be quicker but not necessarily permanent, is to fill the void between the two-phase leads with a silicone rubber material. The silicone rubber has to be applied void free or PD activity can reoccur. Similar to the above approach is to install Nomex® (trademark of Dupont) sheets between the phase leads, fill all voids with an epoxy, and apply conducting paint to attempt to redistribute the electrical stress at the insulation contact point between the two phases. Again this approach may not be permanent and could require further maintenance. These two repairs will require less time and cost initially but could result in higher maintenance in the long run.

As to the repair of the endwinding PD activity between two adjacent coils of opposing phases one is left will few choices. As the spacing is set by the current design one may be only able to reduce the PD activity by inserting a solid insulating material such as silicone rubber in the affected areas.

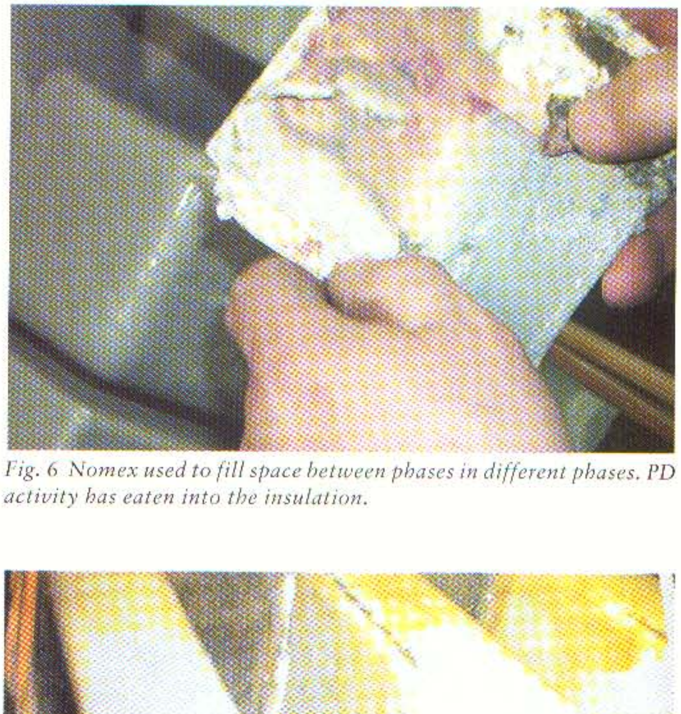

Fig. 6 Nomex used to fill space between phases in different phases. PD activity has eaten into the insulation.

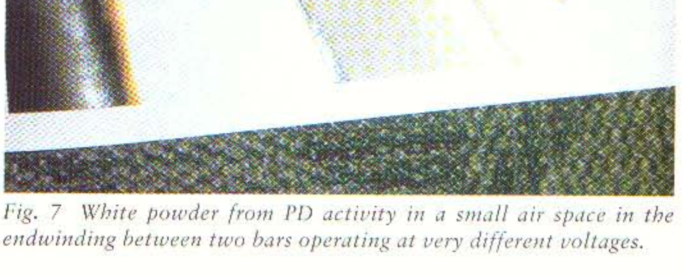

Fig. 7 White powder from PD activity in a small air space in the endwinding between two bars operating at very different voltages.

Conclusions

Modern stator winding design and manufacturing methods have been successful in reducing the costs of turbine generators.

Problems such as thermal cycling, coil abrasion in the slot and PDs in the endwinding have lead to failures after as little as five years of operation.

To avoid premature failures, users of modern air-cooled machines should ensure they have a good purchase specification, are present at the factory for critical phases of machine manufacture, operate the machine within specification, keep the windings clean, and closely inspect the stator winding after about one year of operation. The latter is much more important than it was for hydrogen-cooled machines.

Although some problems cannot be corrected, effective means are available to slow down the deterioration process, if the problems are discovered at an early enough stage.

Gary Griffith has a BS degree in electrical and electronic engineering technology from Montana State University. From 1982 to 1985 he worked for Bechtel as a field engineer constructing new power plants. From 1985 to 1988 he work for Montana Power at the Colstrip plant as the large motor specialist performing maintenance, testing and developing motor rewind and new motor specifications. From 1988 to 1994 he worked for Florida Power and Light as both a large motor and generator specialist developing both motor and generator specifications for rewinding and new. He also assisted in development of the current generator condition assessment program along with performing the generator assessment and testing. From 1994 to 1998 he worked for Mechanical Dynamics and Analysis as a generator specialist performing all aspects of generator assessment and repairs. Gary rejoined FPL in 1998 as a senior generator specialist performing generator assessment, testing, and assisting the plants in all generator trouble issues. He also has responsibility for new generator specification, surveillance and assisting with start-up of the 100 + new units FPL is installing in the next five years.

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Greg Stone has BASc and Ph.D. degrees in electrical engineering from the University of Waterloo, Canada. From 1975 until 1990 he worked at the Research Division of Ontario Hydro, where he helped to develop on-line partial discharge monitoring systems. Since 1990, he has been at Iris Power Engineering in Toronto, a manufacturer of machine monitoring systems. He is a Fellow of the IEEE, and a registered professional engineer in Ontario, Canada.

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