Vibration Sparking and Other Electrical Failure Mechanisms on Large Generator Stator Windings

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Abstract. There are several significant maintenance issues on generator stator windings that are directly related to electrical deterioration. A few are rather aggressive; most will not result in winding failure for many years if at all. These failure mechanisms often are closely related in physical appearance, but fundamentally different in root cause. As a result, winding deterioration is easily misdiagnosed, and resulting corrective actions are often less than optimum.

This paper discusses the various electrical duties that may result in stator winding deterioration, describes available diagnostic tools and methods of detection, offers cautions relating to the potentially high costs of misdiagnosis, and gives suggestions for optimum repair.

1. INTRODUCTION

The stator windings on large generators are usually very reliable, with an expected life of 30 years or more. However, there are numerous deterioration mechanisms what can shorten generator life. Some of these mechanisms are primarily related to design/manufacturing of the stator winding; some are related to operation/maintenance issues. Interestingly, while generators are correctly regarded as an electrical machine, the root cause of failure is usually related to mechanical deterioration mechanisms, e.g., vibration due to electromagnetic forces, static and cyclic loads due to centrifugal and differential expansion forces, foreign object damage.

However, there are significant maintenance issues on generator stator windings that are directly related to electrical deterioration. [1,2,3]. These electrical failure mechanisms on generator stator windings often are closely related in physical manifestation (appearance), but fundamentally different in root cause and corrective actions. As a result, stator winding failure due primarily to the electrical duties is often misdiagnosed, and corrective action is often less than optimum.

This paper will discuss the various electrical duties that may result in winding deterioration, and will provide guidance on optimum maintenance paths. These mechanisms will be categorized as:

- Slot vibration sparking
- Slot partial discharge, sometimes referred to as "slot discharge"
- Endwinding partial discharge
- Miscellaneous electrical failures

2. ELECTRICAL DETERIORATION MECHANISMS IN STATOR WINDINGS

2. 1 Vibration Sparking

Vibration sparking (sometimes called "spark erosion") is a similar but actually completely different deterioration process from partial discharge. The mechanism is driven by the excitation flux in the core and whereas partial discharge can only occur on higher voltage bars, vibration sparking (VS) can occur at any point of the winding, including at the neutral.

The first instances of vibration sparking occurred during the late 1950s, when hard (polyester and epoxy) insulation systems were first introduced. The vibration was vertical in the slot and was corrected by use of improved wedging systems which eliminated vertical bar movement. In more recent time, side vibration has occurred on large air-cooled generators with deep, narrow slots.

The root causes of vibration sparking are too low a resistance of the slot conductive coating, together with vibration of the stator bar. The current loop is axially along bar, radially through the core laminations, axially along the keybars at the back of the stator core, and radially back to the bar. If a bar is allowed to vibrate, the current in this loop will be interrupted at a contact point to the core iron, and the interruption of this current will form an arc to the core. If the conductive coating of a bar is low, this current will be of significant magnitude and the resulting arc can damage the groundwall insulation by an erosion process.

The energy available to drive the vibration sparking mechanism is substantial, in that there is up to about 160 V per meter along the length of a bar in a high flux turbine generator. A comprehensive description of the physics involved has been made by Liese [4]. Liese has estimated that the resistance of the slot conductive coating should be no lower than 300 to 2000 ohms per square to prevent the mechanism.
Vibration sparking is a relative fast deterioration mechanism and has caused service failure in a relatively short time. Photos 1 & 2 are borescope pictures of damage to a modern epoxy-mica groundwall insulation caused by vibration sparking. The stator winding of a generator of similar design failed in service after about 4 years of operation.

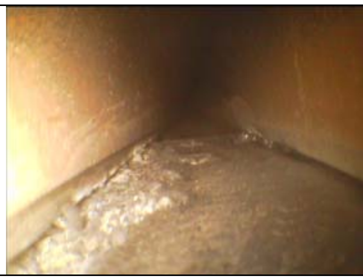

Photo 1. Vibration sparking damage.

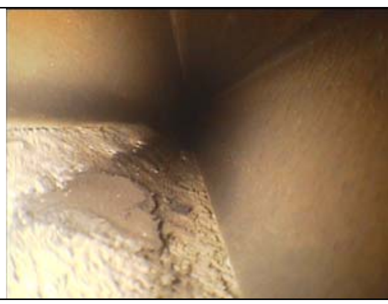

Photo 2. Vibration sparking damage.

As previously stated, it may be difficult to distinguish the evidence of vibration sparking and partial discharge. If a bar is a high voltage bar, there may be no way to be certain, but if a deteriorated bar is from a low-voltage portion of the winding, it is certain to be vibration sparking. Photos 3 & 4 are of bars from an air-cooled turbine generator that appear to have both vibration sparking and partial discharge damage.

Photo 3. Damage from vibration sparking and the loose-coil form of slot discharge.

Photo 4. Damage from vibration sparking and the loose-coil form of slot discharge.

2.2 Slot Partial Discharge

With the introduction of the epoxy mica insulation system in the 1950s, an important class of failure mechanisms sometimes referred to as "slot discharge" became more likely. Slot discharge refers to the observation that partial discharges (PD) may occur on the surface of the bar (half-coil), either within the stator core slot, or just outside of the slot. There are three general sources of this slot discharge:

- Loose bars – where vibration of the bar in the slot abrades and destroys the slot conductive coating.
- Poorly manufactured slot conductive coating - occurs when the slot conductive coating is not fulfilling its function due to excessively high initial resistance or poor application of the coating to the groundwall.
- Poor connection of the conductive coating to ground, i.e., where the bar is not properly grounded due to the presence of an insulating film or insulating side-packing between the slot conductive coating and the stator core.-

Photos 5 & 6 show examples of slot damage resulting from severe PD due to abraded insulation and due to poor conductive coating to ground.

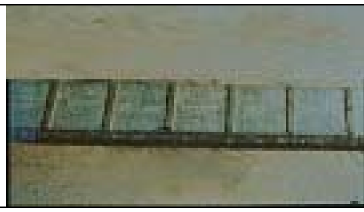

Photo 5. Bar that has been abraded due to looseness in the slot.

Photo 6. Slot discharge primarily due to poor slot conductive coatings.

Often it may be difficult to determine which of these three processes initiated the slot discharges, since the appearances may be similar and one process may cause another to eventually occur. In all cases, the energy for the discharge comes from the capacitive energy of the electric field, and thus these processes occur *only* on the bars at the higher voltage end of each phase.

Two other forms of slot PD are shown in Photos 7 & 8. Both would be considered as serious, and corrective action would be considered necessary.

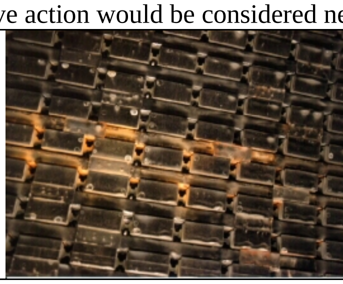

Photo 7. Wedges destroyed by slot PD.

Photo 8. Major slot PD due to inadequate slot grounding paint system.

In general, partial discharge in the slot is a very slow-acting deterioration mechanism on mica insulation systems. Failure would not be expected for many decades without extraneous influences, e.g., vibration, bar insulation defect. In air-cooled machines, the slot discharges create ozone. If sufficiently high, ozone can cause numerous other problems, including health hazards, and may require rewind.

These deterioration mechanisms will not be covered in detail in the paper as the topic has been discussed in numerous previous papers. In particular, see Reference 1.

2.3 Endwinding Partial Discharge

Partial discharge in endwindings takes a different form than in the slots. In addition, the endwinding has no equivalent to slot vibration sparking. The predominate endwinding partial discharge is at the phase breaks. Many large 2-pole generators are designed Y-connected, 2-circuit; these winding will commonly have 3 locations at 120^{o} around the circumference where there is a line-to-line phase break. Midway between these 3 locations are the neutral-to-neutral phase breaks; partial discharge will concentrate at these high-voltage phase breaks. Photos 9 & 10.

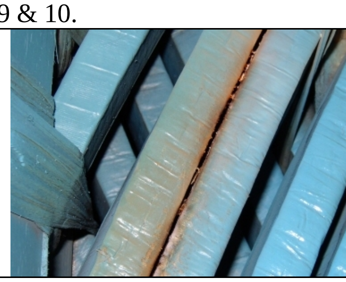

Photo 9. PD at a line-to-line phase break.

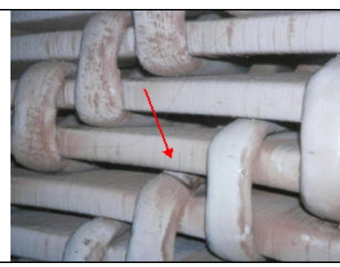

Photo 10. PD on a bar tie at a line-to-line phase break.

Also, localized partial discharge patterns may be seen on bars on windings that have been in operation for a period of time. Photos 11 & 12. The condition of Photo 12 would be of more concern than Photo 11, as Photo 12 suggests there will be significant partial discharge inside the slot.

Photo 11. Surface PD on side of bar in endwinding.

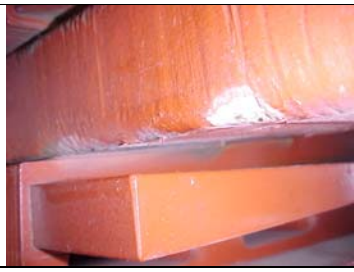

Photo 12. PD on side of bar adjacent to end of slot.

So long as the deterioration is purely partial discharge, e.g., without vibration or water contamination, the PD is unlikely to directly result in service problems. However, if the insulation is not mica-based, failure can occur in only a few months. Photos 13 & 14.

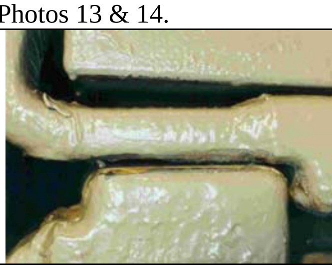

Photo 13. PD damage on non-mica insulation at a line-to-line phase breaks.

Photo 14. Failure due to PD damage to non-mica insulation.

2.4 Miscellaneous Electrical Failures

There are conditions seen in endwindings that are sometimes mis-diagnosed as PD but are not PD. Also there are conditions that are often call PD, but are probably not true partial discharge. Examples are shown below.

Mis-Diagnosed as PD

It was mentioned earlier that PD can only occur on higher voltage bars and that PD can be difficult to identify at times. These 2 simple and basic facts are sometimes overlooked by engineers performing inspection. To illustrate, the conditions shown in Photos 15 & 16 were observed on 2 duplicate air-cooled generators that had operated about 15 years. The appearance looks somewhat like partial discharge, yet these same conditions were observed randomly around the entire winding circumference on bars of high as well as low voltage. Thus the discolorations could not be indications of partial discharge.

Photo 15. Stator bar surface conditions misdiagnosed as partial discharge.

Photo 16. Stator bar surface conditions misdiagnosed as partial discharge.

Yet the condition was diagnosed as severe partial discharge by an OEM field service engineer and factory manager in insulation systems design, as well as by an engineer from an independent maintenance company; each condemned the winding in both generations in the plant, and all 3 recommended rewind (or a new stator) within a year.

In order to confirm that in fact these air-cooled generators were not experiencing partial discharge, ozone readings were taken on both units and no ozone was found. As further confirmation, another utility had a generator of similar design and age on which the stator was replaced, based on the same

OEM recommendation. The winding of the scrapped stator was over-voltage tested and held new-unit shipping hipot test value, 2E + 1.

Junction Between End-arm Grading and Slot Grounding Paints. It is not unusual to observe distress at this junction, usually about 2” outside the slot. Photos 17 & 18. An adequate temporary repair may be possible on some designs.

Photo 17. Arcing damage at end-grading junction.

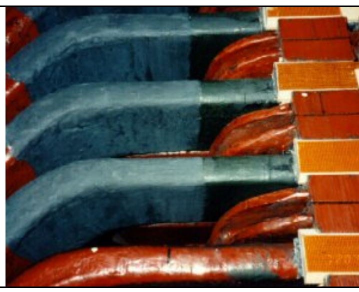

Photo 18. Repaired junction location.

Electrical Arc Tracking. Two forms of this condition have been observed by the authors. One was the result of an endwinding grading system that was incapable of controlling the high voltage of factory winding high potential tests. Photo 19. Another apparently resulted from water dripping onto the endwinding. Photo 20.

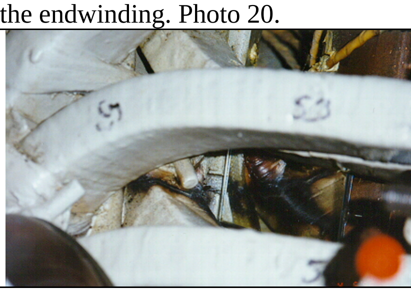

Photo 19. Endwinding arc damage during shipping hipot.

Photo 20. Arc resulting from water dripping onto endwinding. Outdoor unit.

3. DIAGNOSTICS

3.1 Rate of Deterioration

There are several somewhat unpredictable factors involved in the rate of deterioration resulting from slot discharge and from vibration sparking. Vibration sparking is normally considerably more aggressive than pure partial discharge, and partial discharge apparently can take several forms. As a result it is not possible to define clear rules for predicting deterioration rates.

Well-made mica insulation systems have proven to be highly resistant to partial discharge. Significant levels of partial discharge, without any extraneous influences, seem not to penetrate the mica tapes even after 20 or 30 years of service. But there are anecdotal reports of winding failure purely due to PD, for example when accompanied by a vibrating instrument wire or rain water dripping onto an endwinding. Photo 20. Whether these conditions of failure can be considered as true partial discharge is perhaps subject to discussion. On the other hand, there have been cases of PD failure of non-mica phase joint insulation in a very short time, e.g., 18 months. Photos 13 & 14. In air-cooled machines, rewind due to high levels of PD-created ozone is somewhat common.

Vibration sparking and slot discharge due to loose coils, however, can be very aggressive. If there is sufficient clearance in a slot to allow significant movement, e.g., 0.1 mm, failure may occur in less than 2 years of operation. If clearance is small, e.g., 0.01 mm, failure may not occur for several years.

3.2 Most Likely Winding Locations

Partial discharge can occur in the endwindings as well as in the slots. It will focus on the highest voltages in each phase of the winding, and *can only occur* on the higher voltage portion of the winding, i.e., typically the top one-third of the winding. If questionable conditions are observed in the low-voltage portion of the winding, the condition of concern *cannot be* partial discharge.

Partial discharge can occur in the slots, in the endwindings and on the connection rings. The slot portion can be difficult to inspect. If there are radial ventilation ducts, a good inspection can be made via borescope. Photos 5 & 6. If there are no radial ducts, some indication may be observable at the ends of the slots. Photo 12.

Vibration sparking can only occur in the slot portion of the winding, but as previously indicated, can occur throughout the entire phase of the windings irrespective of bar voltage.

3.3 Root Causes

Inadequate design and/or manufacturing are the principal root causes of partial discharge and vibration sparking problems, e.g., grounding paint resistance too high, grounding paint resistance too low, inadequate slot support systems. Occasionally, poor maintenance may be a factor, primarily due to failure to inspect and rewedge a winding that is developing looseness.

4. METHODS OF DETECTION

4.1 On-Line Detection

The most common on-line method for detecting slot discharge is PD monitoring, and in fact the earliest on-line PD monitors were called slot discharge detectors. At this time, it is not known with certainty whether partial discharge and EMI instrumentation will detect vibration sparking. On-line PD instrumentation would only detect vibration sparking if the problem were occurring near the high-voltage end of the winding. EMI test may possibly detect VS throughout the winding, but most likely occurring near the sensor at the neutral.

In air-cooled machines, high partial discharge can be easily detected by ozone monitoring. Experience has shown that if the ozone concentration exceeds about 0.1 ppm, severe PD is probably occurring. There is insufficient experience to know if ozone monitoring can reliably detect vibration sparking, especially if the vibration sparking is occurring in a few isolated areas and on lower voltage bars. Since vibration sparking also often leads to the loose bar form of slot discharge, PD monitoring and ozone monitoring may eventually be useful.

In severe cases, the noise of heavily vibrating bars may become audible to the ear and/or acoustic instrumentation.

4.2 Off-line Detection

Off-line detection of slot discharge and vibration sparking is primarily by visual inspection, usually with a borescope looking down the slot ventilation ducts (if present). Wedge tapping is an indirect method of assessing conditions that may lead to vibration sparking and the loose bar form of slot discharge. In addition, if the contact resistance between the slot conductive coating (just outside of the stator core) and the stator core is very low, this may be an indication of vibration sparking.

In principle, the conventional off-line partial discharge test may indicate that either vibration sparking or slot discharge is occurring – especially if there is major deterioration. Experience indicates that the slot discharge may be lower off-line than would occur on-line. In the off-line test the stator bars are not moving and there is no magnetic flux to cause circulating current in the slot conductive coating. These 2 conditions preclude direct detection of vibration sparking off-line. But since vibration sparking often leads to erosion of the slot conductive coating, when the bar is energized to operating voltage, partial discharge may occur as a symptom of vibration sparking. This symptomatic PD could be localized with a TVA or corona probe.

5. REPAIR OPTIONS

5.1 Slot Discharge

Loose Windings. Bars that are allowed to vibrate in the slots will inevitably have worn insulation. Since the slot conductive coating is applied as the last coating on the outside surface of the bars, this coating will inevitably be damaged by vibration. The first priority of corrective action must be to stop the vibration. Rewedging, adding side pressure springs to the bars, and/or bonding the bars to the core iron can accomplish this. But the damage to the slot conductive coating that has resulted in the slot discharge cannot be easily or fully repaired. Thus if bar vibration has resulted in slot discharge, there probably will not be a permanent and complete fix. After the best repair possible, the level of partial discharge may be substantially reduced but PD will remain. If the levels of PD and/or ozone remain excessively high, a stator rewind may be the only viable option.

Defective PD Suppression Coatings. When slot discharge is the result of a defective slot conductive coating, permanent and complete correction will probably not be possible, short of winding replacement. In-situ repair in the slot may include injection of conductive paints, silicon rubbers and epoxies. Defective slot grounding systems may be confined to isolated bars in the winding, and is only a problem in bars operating at

the upper end of the phase. If the ozone becomes excessive, bar replacement will probably be required. In a few situations, users have removed the worst bars from the slot, stripped off the original slot conductive coatings and replaced them before inserting the bars back into the stator.

5.2 Vibration Sparking

If vibration sparking is the result of radial looseness of the bar in the slot, rewedging can stop the vibration, unless the winding was a global vacuum pressure impregnated system. In this case, bonding may be the only option. If vibration is the result of side looseness, replacement of side packing with a side pressure springs should stop the vibration. This may not be possible, however, if the side packing is bonded to the core iron by the sparking or other bonding agent. Nor can side pressure springs be applied if the side clearance is insufficient to accept the spring.

Since vibration sparking tends to be an aggressive, relatively fast-acting phenomenon, if permitted to progress too far before being stopped, stator rewind may be the only viable option.

6. CONCLUSIONS

Vibration sparking and partial discharge are two of the stator winding deterioration mechanisms acting on stator winding insulation. Vibration sparking can occur anywhere in the slot portion of the winding, high or low voltage. Partial discharge will be significant only in bars that are in the high voltage region of the phases, slot and/or endwinding. The manifestations of the two mechanisms can be very similar; the major difference between partial discharge and vibration sparking is that vibration sparking can occur on bars located in any voltage region, high or low.

Vibration sparking is generally the much more aggressive of the two mechanisms. Because the root cause and corrective actions are very different, it is important to distinguish between the two mechanisms.

The presence of vibration sparking or partial discharge in a stator winding can have significant influence on the projected life of a stator winding. Thus it is important to detect and correctly diagnose either problem in its early stages. If the amount of activity is significant and advanced, repair may be difficult or impossible, particularly in the case of vibration sparking. Rewind or stator replacement may be required in order to achieve a reliable repair.

7. REFERENCES

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