Vibration Sparking and Slot Discharge in Stator Windings

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***Abstract*: In the late 1980s and again in the past few years, some turbine generator stator windings have apparently failed due to a mechanism variously referred to as spark erosion or vibration sparking. The mechanism can produce relatively intense sparking between the surface of the stator bar and the core. The intensity of the sparking is such that it may erode the groundwall insulation much more quickly than slot discharges. Unlike the normal loose coil/slot discharge failure process, spark erosion can happen anywhere in the winding, and not just in stator bars that are operating at high voltage. For this mechanism to occur, apparently (a) the partly conductive slot coating much be much more conductive than normal; and (b) the bar must be loose in the slot and vibrating under the magnetic forces.**

I. 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 that 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 often 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. The paper will concentrate on the slot partial discharge, sometimes referred to as "slot discharge" and slot vibration sparking mechanisms.

II. DETERIORATION MECHANISMS IN STATOR SLOTS

A. 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 and ground-wall insulation.
- 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 ground-wall [1].
- 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 [4].-

Fig. 1 Photo of a stator bar where the ground insulation was abraded since the bar was loose in the slot.

Fig. 2 Stator bar where the slot conductive coating degraded, as a result of poor manufacturing.

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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.

Figures 1-4 show photos of bars experiencing slot discharge considered as fairly serious, and corrective action would be considered necessary.

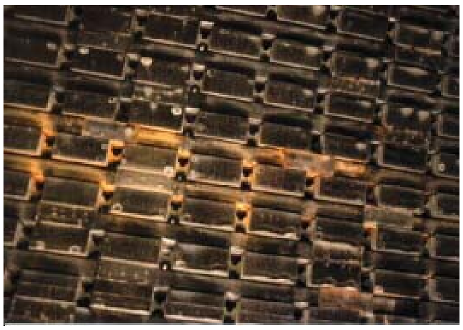

Fig. 3. Wedges destroyed by slot PD.

Fig. 4. Major slot PD due to inadequate slot conductive coating system.

In general, PD 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 a 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 [1,4-6].

B. Vibration Sparking

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

The first instance of vibration sparking occurred during the late 1950s in hydrogen-cooled turbine generators, 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 cause of VS is too low a resistance of the slot conductive coating, together with vibration of the stator bar. A current loop may exist axially along bar, radially through the core laminations, axial 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 resistance 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 to drive the VS 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 [7]. 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 relatively fast deterioration mechanism and has caused service failure in a relatively short time. Figure 5 shows 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.

(a)

(b)

Fig. 5a. and b. Borescope vibration sparking damage to stator bar insulation.

As previously stated, it may be difficult to distinguish the evidence of VS and slot discharge PD. 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 VS. Figure 6 show bars that appear to have both VS and PD damage.

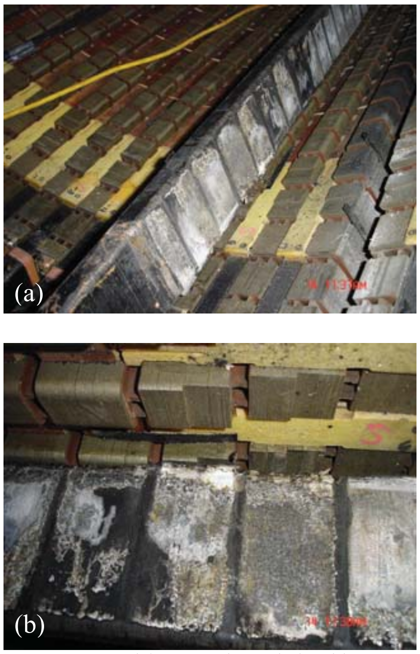

Fig. 6 a. and b. Bars removed from an air-cooled turbine generator suffering from both VS and the loose-coil form of slot discharge.

III. Characteristics

A. 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 PD 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 PD, without any extraneous influences, seem not to penetrate the mica tapes even after 20 or 30 years of service. 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. In air-cooled machines, rewind due to high levels of PD-created ozone rather than insulation puncture 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.

B. Most Likely Winding Location

Partial discharge due to slot discharge 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.

The slot portion can be difficult to inspect. If there are radial ventilation ducts, a good inspection can be made via Borescope (Fig. 5). If there are no radial ducts, some indication may be observable at the ends of the slots.

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.

C. Root Causes

Inadequate design and/or manufacturing are the principal root causes of slot discharge and VS problems, e.g., slot conductive coating resistance too high (PD), slot grounding coating resistance too low (VS), together with an inadequate wedging system. Occasionally, poor maintenance may be a factor, primarily due to failure to rewedge a winding that is developing looseness.

IV. Methods Of Detection

A. 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 [8]. Most on-line PD monitors detect the PD with capacitive sensors at the phase terminals [1]. Alternatively, PD can also be detected as electromagnetic interference using a sensor located at the generator neutral [1,8,9]. At this time, it is not known with certainty whether PD and EMI instrumentation will detect VS. On-line PD instrumentation would only detect VS if the problem were occurring near the phase end of the winding. EMI test will probably detect VS near the neutral, where the sensor is usually located.

In air-cooled machines, high PD caused by slot discharge can be easily detected by ozone monitoring. Experience shows 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 VS, especially if the vibration sparking is occurring in a few isolated areas and on lower voltage bars. Since VS 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.

B. Off-line Detection

Off-line detection is primarily by visual inspection, usually with a boroscope looking down the slot ventilation ducts (if present). Wedge tapping is an indirect method of assessing conditions that may lead to VS 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 VS.

In principle, the conventional off-line PD test may indicate that either VS or slot discharge is occurring – especially if there is major deterioration of the slot conductive coating. However, in the off-line test the stator bars are not moving, and experience indicates that the slot discharge may be lower than would occur on-line. VS itself cannot occur in an off-line test since the bars are not moving, and there is no magnetic flux in the core to cause circulating current to flow in the slot conductive coating. But since VS often leads to erosion of the slot conductive coating, when the bar is energized to operating voltage, PD may occur as a symptom of VS. This symptomatic PD could be localized with a TVA or corona probe [7].

V. REPAIR OPTIONS

A. Slot Partial 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. The first priority of corrective action must be to stop the vibration. Rewedging, adding side pressure 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 PD 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 correction will probably not be possible, short of winding replacement. In-situ repair in the slot includes 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.

B. Vibration Sparking

If vibration sparking is the result of radial looseness of the bar in the slot, rewedging will stop the vibration, unless the winding was a GVPI system. In this case, restoration of the 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.

VI. CONCLUSIONS

Slot discharge and vibration sparking are two of the stator winding deterioration mechanisms acting on stator winding insulation. Slot discharge PD will be significant only in bars that are in the high voltage region of the phases. Vibration sparking can occur anywhere in the winding, high or low voltage. The manifestations of the two mechanisms can be very similar.

Vibration sparking is generally the more aggressive of the two mechanisms. Because the root cause and corrective actions are very quite 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.

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