Deterioration of Stator Winding Insulation by Vibration Sparking

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***Abstract*: Since the introduction of epoxy mica stator windings, 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. This paper describes the vibration sparking failure process, which seems to require that the partly conductive slot coating must be much more conductive than normal; and that the coil or bar must be loose in the slot and vibrating under the 100/120 Hz magnetic forces.**

I. Introduction

The stator windings on large generators are usually very reliable, with an expected life of 20 years or more. However, there are failure processes that can occur as a result of electrical and mechanical stresses [1,2,3]. This paper discusses two mechanisms in particular – slot discharge and vibration sparking (also known as spark erosion). These failure mechanisms are closely related in physical appearance, but fundamentally different in root cause and corrective actions.

II. Slot 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 [1, 4-6]:

- 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].

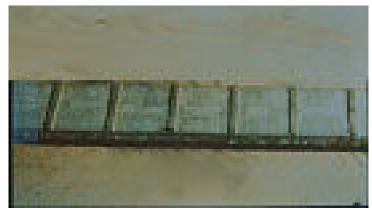


Fig. 1 Photo of a stator bar where the ground insulation was abraded since the bar was loose in the slot.

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 1-2 show photos of bars experiencing slot discharge considered as fairly serious and corrective action would be considered necessary.

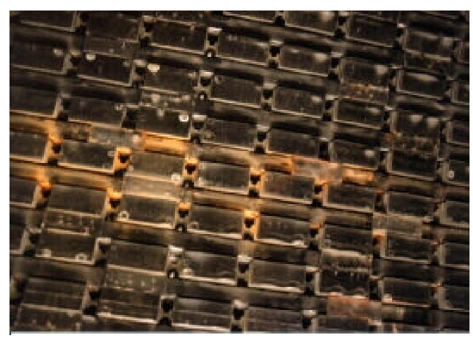


Fig. 2. Wedges destroyed by slot PD.

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, or defective bar insulation. In air-cooled machines, the slot discharges create ozone. If produced in sufficiently high concentration, ozone can cause numerous other problems, including health hazards, and may require a rewind.

II VIBRATION SPARKING

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

The first instance of vibration sparking first occurred during the late 1950s in hydrogen-cooled turbine generators, when hard (polyester and epoxy) insulation systems were first introduced. It seems to occur rarely, but the author is aware of instances since the 1960s on both motors and generators. The vibration is driven by the magnetic forces, and is primarily vertical in the slot. The use of improved wedging systems can largely eliminate the vertical bar movement. In more recent times, side vibration has occurred on large air-cooled turbo generators with deep, narrow slots.

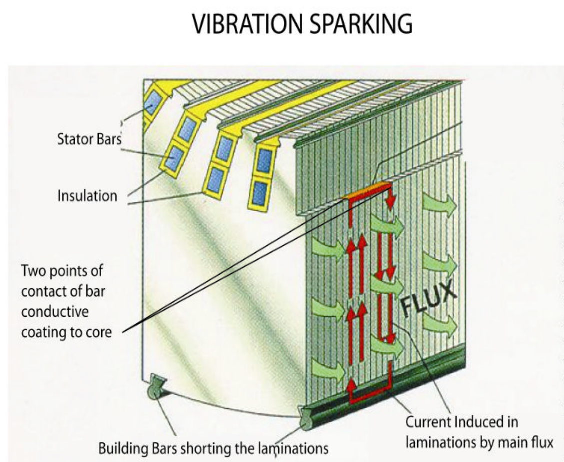
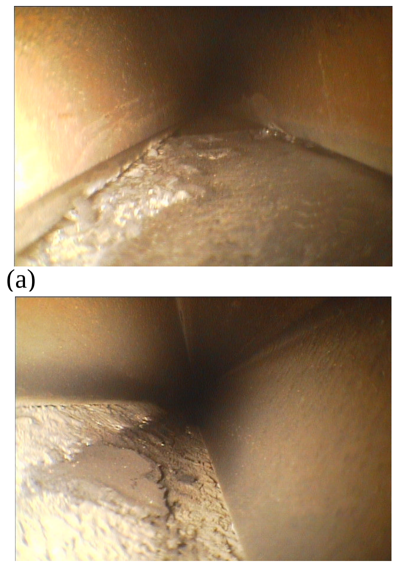


Figure 3: Mechanism of VS

The root cause of VS is too low a resistance of the slot conductive coating, together with vibration of the stator coil or 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 (Figure 3). If a bar is allowed to vibrate, the current in this loop will be interrupted at a contact point from the bar to the core iron. The interruption of this current will form an arc from the bar surface 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 since it is driven by the main magnetic flux in the stator core. 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.

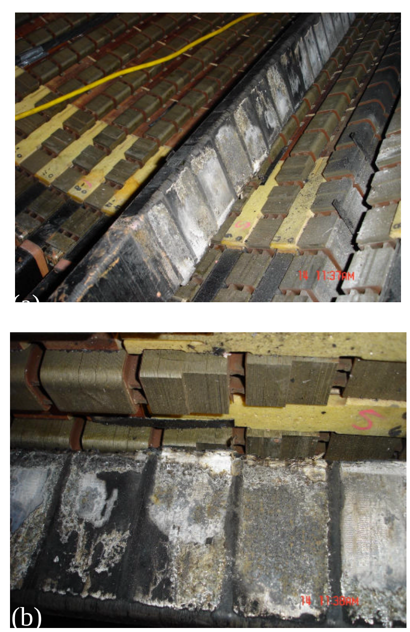
Vibration sparking is a relatively fast deterioration mechanism and has caused service failure in a relatively short time. Figure 4 shows borescope pictures of damage to a modern epoxy-mica groundwall insulation caused by vibration sparking. The stator winding of a generator of similar design failed in service after about 4 years of operation.



(a)
(b)

Fig. 4a. 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 5 show bars that appear to have both VS and PD damage.



(b)

Fig. 5 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 PD, 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 PD. Significant levels of PD, without any extraneous influences, seem not to penetrate the mica tapes even after 20 or 30 years of service.

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 slot discharge.

The slot portion can be difficult to inspect. If there are radial ventilation ducts, a good inspection can be made via borescope (Fig. 4). 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.

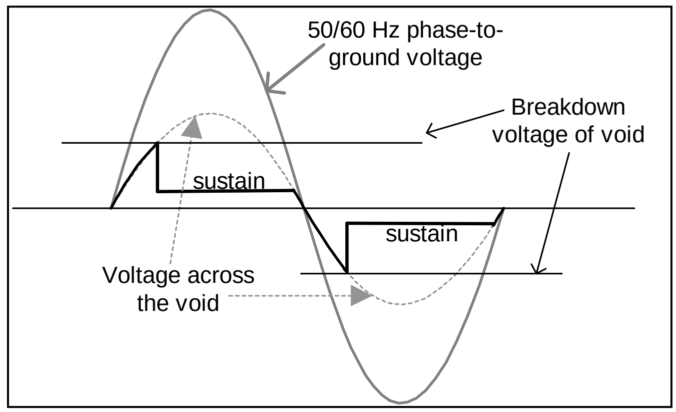
C. Root Causes

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.

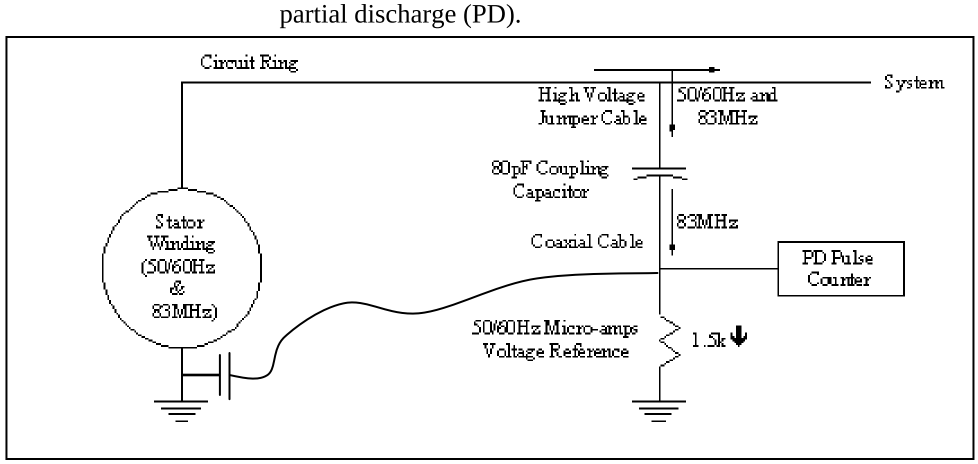
IV. METHODS OF DETECTION

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]. At this time, it is not known with certainty whether PD will detect VS. On-line PD instrumentation would only detect VS if the problem were occurring near the phase end of the winding.



When the applied 50/60Hz increases sinusoidally, the apparent electric stress across the void increases until it reaches 3,V/mm or the equivalent breakdown voltage in the void. Over voltage is the state at which the voltage across a void exceeds the breakdown voltage required for the void size and gas. The larger the over voltage achieved, the more intense the space charge effects in the void. Although a void may be in an over voltage state, breakdown will not occur until a free electron due to cosmic or natural radiation appears within the gap and starts an avalanche of the electrons. The avalanche is a flow of electrons across the gap which gives rise to a very fast rise-time (a few nanoseconds) current pulse [1], called a partial discharge (PD).



The first step of PD detection is the placement of a sensor somewhere near the source of the PD and VS, that is at the line and neutral ends of a winding. Iris uses capacitive couplers, Epoxy Mica Capacitors (EMC) - for motors, hydros, and small turbos. The capacitive couplers used are 80pF +/- 3pF. These couplers block the 50/60Hz signal and pass the high frequency PD signal. This is obvious by comparing the impedance of an 80pF capacitor at a typical power frequency (60Hz) to a typical partial discharge frequency (83MHz).

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 are electronic sensors and sorbent tube sensors available for ozone monitoring. 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 borescope 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.

- Measure effectiveness of wedging system
- Calibrated hammer with instrument
- Robotic inspection without rotor pull
  - No two adjacent wedges in the same slot
  - No end slot wedges
  - No more than 25% of the wedges
  - No wedges should be cracked

In addition, if the DC 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.

- 1000 to 2500 ohms (typical)
- < 300 ohms sensitive to VS
- > 5000 ohms sensitive to slot discharge

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 (Tennessee Valley Authority) or corona probe [7] or dual-frequency off-line PD sensor.
The dual frequency test has both low frequency and high frequency output as described in IEEE 1434 and IEC 60034-27; and therefore is more sensitive to pulses originating away from the sensors. It is possible this will more thoroughly evaluate the damage done due to vibration sparking.

V. 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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