Impact of Slot Discharges and Vibration Sparking on Stator Winding Life in Large Generators

Key Words: slot discharge, vibration sparking, spark erosion, stator winding

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Introduction

The stator winding insulation system in generators rated 6 kV and above is usually very reliable, with an expected life of 30 years or more. However, there are a large number of failure processes that gradually reduce the electrical and mechanical strength of the insulation to the point that insulation failure will eventually occur. Some of the failure processes are the result of various design or manufacturing issues. Most other failures that gradually age the insulation are the result of the thermal, mechanical, electrical, and environmental stresses that occur in operation [1], [2].

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 (or coil) either within the stator core slot, or just outside of the slot. (The term "bar" will be used generically to include coils in this article.) In fact, there are 3 general sources of PD that can occur as slot discharge:

- **Loose bars** allow vibration of the bar in the slot to abrade and destroy the slot conductive coating.
- **Poorly manufactured slot conductive coating** occurs when the slot conductive coating is not fulfilling its function because of 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 because of the presence of an insulating film or insulating sidepacking between the slot conductive coating and the stator core.

These will be described in more detail below. In some cases it may be difficult to determine which of these three processes initiated the slot discharges, because one process may cause another to occur eventually. In all cases, the energy for the discharge comes from the capacitive energy stored in the electric field, and thus these processes tend to occur only on the bars at the high voltage end of each phase. In air-cooled machines, the slot discharges create ozone, which in turn produces nitric acid that can accelerate the failure process.

Slot discharge has long been known to be a common failure mechanism of stator winding insulation. Less well known is the fact that vibration sparking can result in very rapid failure, and has many of the characteristics of slot discharge.

There is a similar but actually completely different deterioration process referred to variously as "spark erosion" or "vibration sparking" (VS). As described later, this failure process is sometimes confused with one of the above types of slot discharge, because bar vibration is involved and sparking occurs on the surface of the bars in the slot. The root cause of VS is faulty design and manufacturing, and machine manufacturers have been able to avoid it on most designs. The mechanism is driven by the magnetic field in the stator core, and thus it can occur at any point of the winding, including at the neutral. Although this process is uncommon, it does occasionally appear on both air-cooled and hydrogen-cooled machines.

This article reviews the mechanisms for each of these four failure processes, i.e., three types of slot discharge and the VS mechanism, and gives examples of each. We also attempt to indicate how each process can be detected and distinguished before actual stator winding failure has occurred. Guidance on possible repair options (short of a rewind) is also presented.

Slot Discharge Mechanisms

A. Slot Discharge Caused by Loose Bars

The fundamental cause of the loose bar slot discharge mechanism is the 100 or 120 Hz electromagnetic force acting on bars in the slot, together with some looseness of the bar in the slot. Bars may be loose in the slot initially when manufactured because of a design or workmanship deficiency. Initial radial looseness can be prevented by several methods, e.g., the use of top ripple springs, 2-part wedges which can create a positive force down into the slot, incorporation of compressible materials such as conductive silicon rubbers into the slot contents, or bonding with a global vacuum pressure impregnation (GVPI) [1], [3], [4]. Figure 1 shows a photograph of a bar removed from an air-cooled generator that was loose in the slot because of poor design and installation. It shows abrasion of the insulation on the side of the bar caused by being loose in the slot.

Loose bars in the slot can also exist as a result of shrinkage of the insulation over the years caused by material creep and thermal aging. In addition, radial ripple springs (if present) may gradually lose their ability to hold the bars tightly, especially in the presence of oil [1].

If a bar is not tightly held, and starts to vibrate, the bar insulation system moves relative to the stator core, primarily in the radial (i.e., up and down in the slot) direction. The bar movement abrades first the slot conductive coating, and then the groundwall insulation (Figure 1).

Slot discharge occurs when the slot conductive coating is abraded away and the surface of the bar (at least at the abraded spot) is not well grounded. Partial discharge will then occur in bars operating at the higher voltages, because thousands of volts can build up across the air gap between the core iron and the exposed groundwall insulation surface [1], [4], [5]. Such a high voltage across an air gap leads to electrical breakdown of the air or hydrogen, i.e., PD. The PD is just a symptom of the fact that the bars are loose enough to vibrate in the slot.

Figure 1. Photo of the side of a bar that has been abraded by movement caused by looseness in the slot.

This process can occur in all types of air-cooled and hydrogen-cooled machines. The speed of deterioration depends on the magnitude of the electromagnetic bar forces and how loose the bar is in the slot. Failures have occurred in service in both hydrogenerators and turbo generators in as little as 3 years.

B. Slot Discharge Caused by Poor Slot Conductive Coatings

A slot conductive coating is almost always placed on the surface of stator bars rated 6 kV or more, and in some machines rated as low as 3.3 kV, to prevent surface PD in the slot [1], [5], [6]. Without the coating, PD will occur in the small gaps that would inevitably be present between the surface of the bar and the core iron, as described above. Researchers have calculated that the surface resistance of the coating needed to suppress PD between the bar surface and the core should be less than 15 to 25 kΩ per square [5], [6].

With poorly made slot conductive coatings, the coating essentially is or becomes non-conductive in a localized area, perhaps only a few centimeters in diameter. In the bars that are operating at high voltage, PD will occur between the bar and the core, because in this region, a capacitive voltage will develop on the surface of the bar that exceeds the breakdown strength of the air between the surface and the core. In an air-cooled machine, the slot discharge generates ozone which in turn bleaches the surfaces white (Figure 2). This PD and ozone will attack the groundwall insulation. In principle, the PD may eventually erode a hole through the groundwall. However, because mica-based groundwall insulation is *very* PD resistant, it can take many decades for this process to progress to the point where a rewind is necessary. Even then it is usually the high ozone concentration that necessitates the rewind, rather than groundwall puncture. Note that this process occurs even if the bars are held tightly in the slot. The process is sometimes called "electrical slot discharge," to differentiate it from slot discharge caused by loose bars described in the previous section.

Invariably, the root cause of the slot conductive coating failure is poor manufacturing: the coating is not properly applied, followed by inadequate testing practices to ensure the resistance is in the correct range. There are three causes of manufacturing problems that seem to lead to this process:

- The coating surface resistance is too high, possibly because the graphite or carbon fiber particle density is too low in this area. High resistance regions of only a few centimeters in diameter have led to surface PD.
- In some types of manufacturing processes, small air pockets or bubbles may occur just below the slot conductive coating, between the groundwall and the coating. In bars located in the higher voltage portions of the winding, small PDs can occur in these voids. This PD and ozone attack the

Figure 2. Slot discharge primarily due to poor slot conductive coatings.

conductive coating, increasing its resistance. Eventually the problem progresses into the stages described above.
- The design may incorporate a non-conducting layer between the grounding surface and the mica groundwall insulation that includes voids.

Essentially, the coating gradually becomes non-conductive in a process that tends to aggressively spread laterally over the surface as a result of PD and nitric acid attack. As the excessively high resistance area spreads, the PD becomes more widespread, very slowly destroying the underlying groundwall.

C. Slot Discharge Caused by Isolated Slot Conductive Coatings

Large sections of the slot conductive coating can sometimes be insulated from the stator core, or at least have a very high resistance contact to the core at only a few points, even in the absence of bar vibration. This may occur as a consequence of the global vacuum pressure impregnation (GVPI) manufacturing process, where a thin epoxy or polyester film isolates the bar surface from the core. In principle, it also could occur on older stator designs where insulating side and/or depth packing is used and bar vibration dynamically isolates the slot conductive coating from the grounded stator core for portions of the AC cycle. Examples are given in references [4] and [5].

If a thin film isolates the slot conductive coating, then the slot conductive coating is not effectively grounded. On phase-end bars operating at high voltage, a large voltage (determined from the capacitive voltage divider formed by the bar groundwall insulation capacitance and the film capacitance) can occur on the slot conductive coating. At a defect in the film between the slot coating and the core, or when the slot coating makes contact with the core if it is vibrating, the entire capacitive charge stored in the bar insulation is discharged [4]. The energy stored in the equivalent capacitance can be very large, and the resulting discharge has been called "high intensity," because it tends to produce discharges much larger than the PD described above. According to Mulhall, the erosion of the groundwall by the high intensity discharge can be rapid, even in epoxy mica insulation systems, and can lead to groundwall puncture in only a few months, if the entire slot conductive coating is isolated from ground [4]. The discharging (which is probably not formally PD, but rather contact sparking by two surfaces at different potential) is intense enough that it may also damage the stator core laminations.

This failure process is less likely with today's design and manufacturing processes, because manufacturers have developed ways to ensure better contact to the core during the GVPI process. In addition, side packing and depth packing tend to be partly conductive, increasing the probability that large portions of the slot conductive coating are grounded at many places along the slot.

Vibration Sparking

This process is also called "spark erosion." The root cause of this process is a too-conductive slot conductive coating, together with at least some bar vibration in the slot. It was mentioned above that the slot conductive coating needs to have a maximum resistance limit to ensure there is a negligible voltage build up across any air gap between the bar surface and the stator core. But there is also a minimum permissible resistance. If the surface coating is as conductive as (say) aluminum foil, then the stator core laminations in the slot will be shorted, causing an axial current to flow along the slot conductive coating. This current is driven by the circumferential main magnetic flux within the core (Figure 3). The current loop is along the building bars (keybars) at the back of the stator core (which are usually shorted to the steel laminations at that point), radially through the steel laminations, and then through the slot conductive coating on the stator bars in each slot. The resistance of the metallic components, the magnetic flux in the core, and the area of the loop that encloses the flux limit the current that flows. Because bars may vibrate to some degree, if the slot conductive coating at some point loses contact with the core, an arc (or spark) will form if the interrupted current is large enough [7].

For a particular machine, the interrupted current will depend on the length of the bar along the slot that has become isolated from the core (Figure 3). The longer the axial distance for which the slot conductive coating is not in contact with the core, the greater will be the area enclosed by the current loop, and thus the greater will be the induced current. This, in turn, roughly depends on how loose the bars are in the slot. Consequently, for a given slot

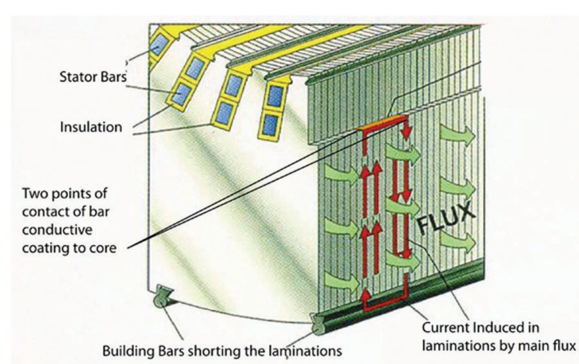


Figure 3. Sketch of the current loop formed by the flow of current through the core lamination, the building (or key) bars and the slot conductive coating on a stator bar.

coating conductivity, the looser the bar in the slot, the more likely that a spark will be formed where the slot coating loses contact with the core. Stators exhibiting this problem have shown that the spark or arc that is created can be intense enough to damage the epoxy mica insulation. A much more comprehensive description of the physics involved has been presented by Liese and Brown [7]. Liese has also estimated that the surface resistance of the slot conductive coating should be no lower than 5000 Ω per square to prevent the mechanism, although the authors are aware of many stators with loose bars and a lower surface resistance than this that apparently do not have VS. The minimum resistivity depends on the axial length of the slot conductive coating that is isolated from the core during vibration, which in turn depends on how loose the bar is in the slot [7].

Another way to understand the VS mechanism is to recall that along the slot in the stator bore, there is up to about 160 V per meter between the laminations in a high flux turbine generator. That is, if the stator bar slot coating is grounded at one end of the slot and if the rest of the bar surface is not grounded, then the potential difference between the surface of the bar and ground is 160 V at 1 m into the slot. If normal magnetic forces cause the bar surface to contact the core at this point, a spark will occur when the contact is broken. Note that because there is no discharge of any capacitance with this mechanism (as occurs in the three slot discharge processes described above), it would be inappropriate to refer to VS as a slot discharge or PD phenomena.

Figure 4 shows some damage to the epoxy mica groundwall insulation caused by VS. As for the slot discharge mechanism caused by a stator bar being isolated from the core slot discharge Section C, VS seems to involve a high intensity spark that has sufficient power to cause bars to fail relatively rapidly, in as little as 4 or 5 years. The sparking intensity is enough to damage both the stator bar insulation and the steel core laminations (Figure 5). The VS on the air-cooled machine shown in Figure 5 occurred on several bars throughout the stator, presumably because the slot coating was too conductive, and the bars were loose sideways in many slots because side ripple springs were not used. The appearance of the bar side abrasion in Figure 5 is similar to that seen in Figure 1 caused by slot discharge, however, unlike slot discharge, VS can occur at the neutral, winding midpoint, or phase end bars, because it is driven by the magnetic flux, and not the electric field.

The air-cooled turbine generator shown in Figures 4 and 5 was rated about 160 MW, 18 kV and was manufactured in 2001. This unit had been operating for about 30,000 hours. Such VS has been noted on several bars in the stator. This particular stator also appeared to have slot discharge caused by loose bars.

The first instance of VS probably occurred during the late 1950s, when one American manufacturer found this phenomenon in their first generation of epoxy mica insulated bars. The problem was corrected by more careful attention to the slot conductive coating resistance as well as the use of improved wedging systems and the invention of side ripple springs to reduce the probability of bar movement. The authors are also aware of occurrences in some motors made in the UK in the 1970s. In the late 1980s, a European machine manufacturer also reported the problem in some very large (>1000 MVA) hydrogen-cooled turbine generators. In the past few years, it appears that an American manufacturer has made several air-cooled turbine generators that may also have this problem. In general, however, the problem is uncommon.

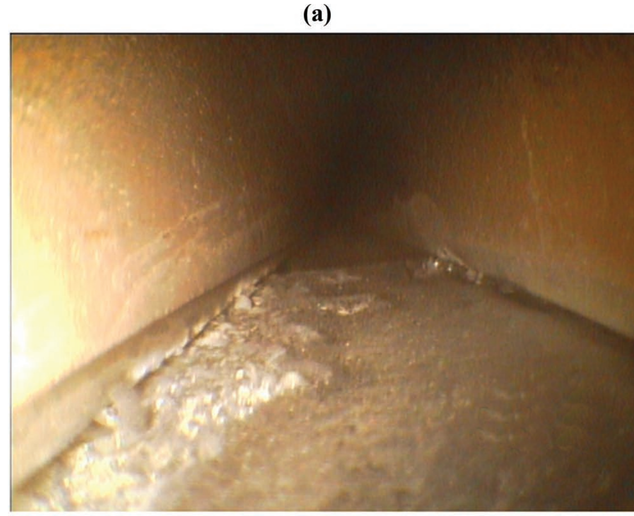
Characteristics of the Failure Processes

There are numerous somewhat unpredictable variables in the failure processes of both PD and VS, and thus it is difficult to define with precision the characteristics of these failure processes. Table 1 is included as a general guide, and each of the parameters in the Table is briefly discussed below.

A. Rate of Deterioration

There are several somewhat unpredictable factors involved in the rate of deterioration resulting from slot discharge and from VS. Furthermore, it may be difficult to distinguish between the two mechanisms with complete confidence. 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.

(a)



(b)

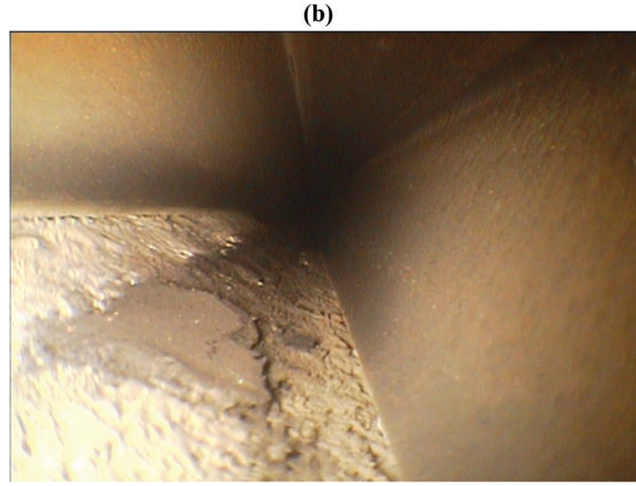


Figure 4. Borescope images of the side of a stator bar surface damaged by VS, looking from the bore down a core vent duct.

Significant levels of PD, 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 caused by PD, for example, when accompanied by a vibrating instrument wire or rain water dripping onto an endwinding. Whether these conditions of failure can be considered as true PD is perhaps subject to discussion. On the other hand, there have been cases of failure of non-mica phase joint insulation in a very short time, e.g., 18 months. In air-cooled machines, rewind caused by high levels of PD-created ozone is somewhat common.

Vibration sparking and slot discharge caused by 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.

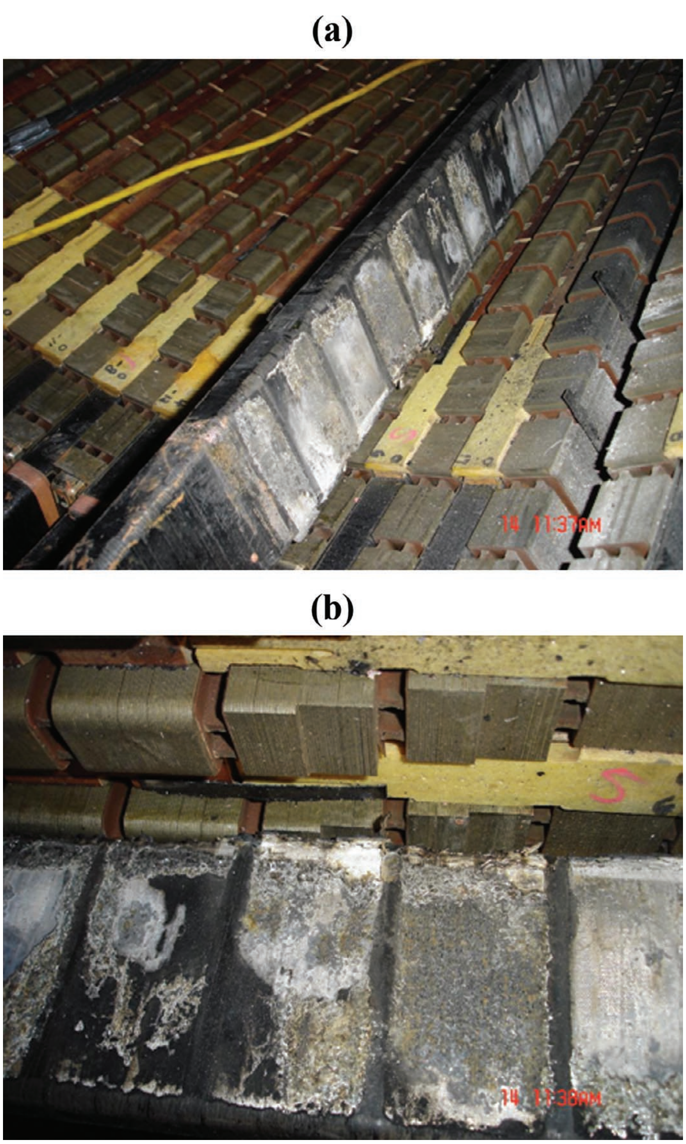


Figure 5. Bars being removed from an air-cooled turbine generator suffering from both VS and the loose coil form of slot discharge.

B. Most Likely Winding Location

Partial discharge is a symptom of slot discharge. It will focus on the highest voltage areas 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*** PD.

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 (Figure 4). If there are no radial ducts, 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 PD and VS problems, e.g., slot conductive coating resistance too high, slot conductive coating resistance too low, and/or inadequate wedging systems. Occasionally, poor maintenance may be a factor, primarily failure to rewedge a winding that is developing looseness.

Methods of Detection

A. On-Line Detection

The most common on-line method for detecting slot discharge is on-line PD monitoring, and in fact the earliest on-line PD monitors were called slot discharge detectors [1], [8]. On-line PD monitoring usually employs a PD sensor at each of the phase terminals [1]. A variation of on-line PD monitoring is called electromagnetic interference (EMI) monitoring, usually employing a sensor at the neutral [9]. On-line PD or EMI monitoring may only detect VS if the problem is occurring on a bar near the PD sensor, i.e., the phase end for capacitive sensors, or near the neutral for radio frequency current transformers (RFCTs) or capacitive sensors mounted at the neutral. If there are just a few isolated bars experiencing VS alone, i.e., with no accompanying slot discharge, and the bars are only near the midpoint of the stator winding, then the current pulses from the VS will be strongly attenuated as they propagate along the winding to the PD detection devices, which are invariably located near the high voltage terminals or at the neutral. Thus VS in a few localized spots far from the machine terminals may not be detected by on-line PD monitoring.

Figure 6 shows the pulse pattern obtained with an on-line PD monitor on an air-cooled machine that is known by visual examination to be experiencing both advanced VS as well as the loose bar form of slot discharge. Note the pulse pattern is shifted about 90 degrees to the left of the normal position for pulses caused by slot discharge [1]. Such a "left shift" in a pattern was observed on another machine with suspected VS. However, it is still too soon to determine if this phase shift is a normal aspect of VS. Note that because VS does involve abrasion of the insulation and slot conductive coating, VS in bars operating at high voltage will eventually produce PD as a symptom.

Table 1. Characteristics of Failure Processes				
	Slot Discharge (PD)			
	Loose Bars	Poor Coatings	Isolated Coatings	Vibration Sparking
Rate of deterioration	Moderate to fast	Slow	Fast	Fast
Most likely winding location	High-voltage end only	High-voltage end only	High-voltage end only	Throughout entire phase
Root cause	Design, manufacturing and/or poor maintenance	Manufacturing	Manufacturing	Design, manufacturing and/or poor maintenance
Methods for detection	Wedge tap, on-line PD, coating to core resistance, visual, top ripple spring deflection, radial cooling slot borescope inspection	Off or on-line PD, ozone, visual, coating resistance, radial cooling slot borescope inspection	On-line PD, coating to core resistance, radial cooling slot borescope inspection	Wedge tap, coating resistance to core, visual, on-line PD/EMI, top ripple spring deflection, radial cooling slot borescope inspection
Repair difficulty	Moderate	Difficult	Impossible (if GVPI)	Moderate (to suppress bar vibration)
Repair effectiveness	Some, if done early	Little	Little	Some, if done early

In air-cooled machines, slot discharge is also easily detected on-line using ozone monitoring. Experience shows that if the ozone concentration exceeds about 0.1 ppm, then severe slot discharge is probably occurring. There is insufficient experience to know if ozone monitoring can reliably detect VS, especially if the VS is occurring in a few isolated areas and on lower voltage bars. Because VS also often leads to the loose bar form of slot discharge, then 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 stator core 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 [1]. In addition, if the contact resistance between the slot conductive coating (just outside of the stator core) and the stator core is very low, then this may be an indication of VS. Alternatively, if the resistance is too high, some form of slot discharge may be occurring [1].

In principle, the conventional off-line PD test may indicate that either VS or slot discharge is occurring—especially if the failure process has advanced to the point that major areas of the slot conductive coating are missing. Note, however, that 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. Actual VS cannot occur in an off-line test because the bars are not moving, and there is no magnetic flux in the core to cause the circulating current to flow in the slot conductive coating. Because 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 [1], [7].

Repair Strategies and Value

A. Slot Discharge

Loose Windings

Bars that are allowed to vibrate in the slots will inevitably have worn insulation. Because 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 or epoxies into the slots. However, experience shows that the injected conductive material will not reach all areas where the slot conductive coating is defective, and thus some PD will still occur. Defective slot grounding systems may be confined to isolated bars in the winding, and will only be 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

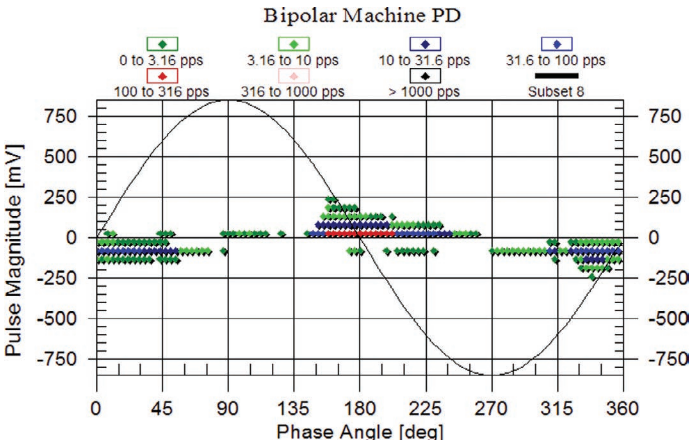


Figure 6. On-line "PD" detected by means of 80 pF capacitive couplers mounted on the turbine generator terminals.

removed the worst bars from the slots, stripped off the original slot conductive coatings and replaced them before inserting the bars back into the stator.

Isolated Bar

In the case of non-GVPI windings, this problem can be corrected, if it is caught at an early stage by replacing the insulating slot side packing with conductive sidepacking and depth packing, and then rewedging. For GVPI windings, there is probably no effective repair short of a rewind or stator replacement.

B. Vibration Sparking

If VS is the result of radial looseness of the bar in the slot, rewedging will stop the vibration, but if the resistance of the slot conductive coating is lower than the acceptable resistance, the VS will continue to short out the stator laminates creating excessive circulating currents, unless the winding was a GVPI system. In this case, bonding may be the only option.

If vibration is the result of side looseness, replacement of the side packing with a side pressure ripple spring 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 ripple springs be applied if the side clearance is insufficient to accept the spring.

Because VS tends to be an aggressive, relatively fast-acting phenomenon, stator rewind may be the only viable option.

Conclusions

Slot discharge and VS are two stator winding deterioration mechanisms acting on stator winding insulation. Slot discharge can have at least three different causes—only one of which is caused by bars vibrating in the slot. Slot discharge will be significant only in bars that are operating at or near rated voltage. Vibration sparking will only occur when two conditions are met simultaneously: a) the slot conductive coating is too conductive, and b) the bars are vibrating in the slot. This can occur throughout the stator.

The manifestations of the two mechanisms can be very similar. The major difference between slot discharge caused by loose coils and VS is that VS can occur on bars located anywhere within the winding. Vibration sparking is generally the more aggressive of the two mechanisms. Because the root cause and corrective actions are quite different, it is important to distinguish between the two mechanisms.

The presence of VS or slot 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 VS.

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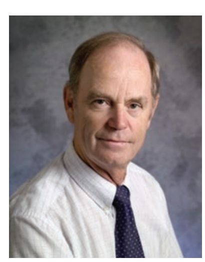

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