Stator Winding Failure Due to Spark Erosion

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Abstract

This paper describes a 2007 generator failure attributable to spark erosion deterioration of a high voltage stator winding. The unit is a large air-cooled generator, rated at 213 MVA and 19 kV. The unit began commercial service in 2000, and operated 51,636 hours before failing in 2007. Initial repair work included removing a total of 12 bars damaged from spark erosion. These bars were re-insulated by NEC and then the bars were re-installed. This was done quickly to return the unit to reliable service as fast as possible. Subsequently, NEC manufactured a new, replacement stator winding and installed it into the same machine later that same year.

Key aspects of NEC's investigation into the root cause of the failure are described below. Contributing factors to the spark erosion related failure are discussed. Findings from another unit that also failed from spark erosion are included. Specific methods to prevent spark erosion on large, air-cooled generators are discussed.

Background

A large air-cooled generator failed in service due to a stator winding fault. The unit had been in operation for about 7 years prior to the failure. The unit is an air-cooled generator, rated at 213 MVA and 19 kV. Failure occurred on a top phase bar in slot 31. This bar and the top bar from the adjacent slot 32 were initially removed from the stator core after the failure. After further inspection and evaluation, 10 more top bars were removed from slots 21 to 30. In total, 12 top bars were removed and visually observed to have suffered spark erosion damage. In other published sources, spark erosion has also been referred to as slot discharge[i] and vibration sparking[ii]. It is a fast acting, stator bar failure mechanism, that causes damage to the bar's ground insulation. The primary contributor is loose bars in the stator slots. These 12 bars were reinsulated by NEC in the summer of 2007 and installed back in the winding. The purpose of the reinsulation was to allow the unit to be put back on line as quickly as possible. In October of 2007, the unit was taken off-line for a stator rewind with all new stator bars manufactured by NEC. The original stator winding was sent to NEC at their Brownsville, Texas facility for evaluation.

Figure 1. Stator bar with spark erosion damage being removed from slot.

Findings

Visual Inspection

A visual inspection was performed on the stator winding which included 60 top bars and 60 bottom bars. As was mentioned previously, 12 top bars were re-insulated by NEC and re-installed leaving 48 top and 60 bottom bars with the original OEM insulation. The unit had never been previously rewound, so this was the original insulation since the first day of service.

When the unit was rewound in late 2007, all of the original bars were brought back to NEC's facility for study and evaluation. The bars were laid out on the factory floor in proper sequence to evaluate the degree of spark erosion damage as it relates to each individual bar's voltage. A photo showing the bars is seen below.

Figure 2. Removed stator bars laid out in sequence for evaluation and inspection.

It was found that 36 of the 60 original OEM top bars had specific marks of spark erosion on the cell semi - conductive coating surface. The other 24 top bars had no evidence of spark erosion at all. The newly reinsulated 12 top bars, when removed at the time of the rewind, had no traces of spark erosion. Not a single one of the 60 originally installed bottom bars had any evidence of spark erosion. The graph below shows the distribution of damaged bars compared to the individual voltage of that bar.

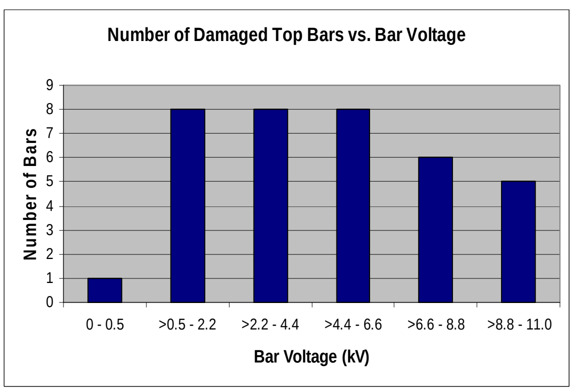

Figure 3. Graph showing number of damaged bars versus individual bar voltage.

This distribution is typical of spark erosion in that bar damage by this failure mode does not just occur on the bars having the highest voltage, but is typically distributed across bars of all voltages.

The degree of spark erosion damage, visually observed on the surface of the bars, was rated as to falling into one of three stages. This rating is approximate and there is no exact margin to define the boundary conditions for each stage. The photo immediately below shows an undamaged bar surface.

Figure 4. Photo of undamaged bottom bars removed from the original winding.

For Stage I Degradation, shown in Figure 5 below, the outer spiral double layer of semi - conductive tape is partially damaged with areas open to the bar's semi-conductive coating.

Figure 5. Photo of Stage I Degradation.

Stage II Degradation is characterized by portions of the bar's semi-conductive tape completely open. There is no spiral outer layer of semi-conductive tape left over the cell semi - conductive tape. The cell tape underneath is partially eroded and there are "slag–like" looking deposits on the this surface.

Figure 6. Photo of Stage II Degradation.

Stage III Degradation includes complete destruction of the outer spiral double layer of semi-conductive tape. The cell semi-conductive layer is also badly eroded everywhere. Instead of the smooth semi-conductive tape surface, a slag-like surface is now present. The outside layer of the insulation becomes carbonized. Conductive tracks appear in the outside and inside insulation layers. These layers are conductive with surface resistivity ranging from 10^5-10^7 ohm s.

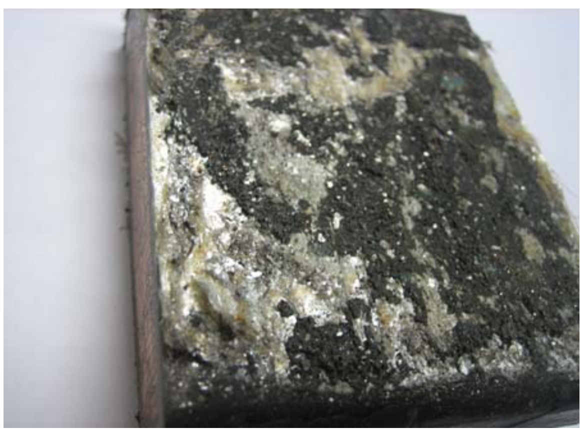

Figure 7. Photo of Stage III Degradation.

As part of the failure investigation, surface resistivity measurements were made on all the bars. For undamaged bars, the surface resistance of the outer most semi-conductive tape portion was measured to be between 300 and 400 ohms/square. However, in the heavily damaged areas, surface resistance was measured to be much greater and more non-uniform. Values ranged from 100,000 ohms per square up to 10,000,000 ohms per square in these heavily damaged area.

It should be mentioned, that there was no evidence of spark erosion on the narrow sides of the bars and in the middle of the vent channels on the wide sides of the bars. These parts of the bars had no direct contact with the stator core iron. Stator bar width measurements were made on a total of 19 undamaged top and bottom bars. This was then compared to an average slot width. The average maximum gap or clearance in the slot came out to be 0.009 inches.

Failure Analysis

The presence of spark erosion on these large air-cooled generators is attributable, first and foremost to loose bars in the stator slot. Also important, but to a lesser degree, is the surface resistivity of the semi-conductive coating on the bar. Spark erosion occurs when electrical arcing occurs between the stator bar in the slot and the stator core iron.

The arcing is in the form of sparks that jump across a small air gap between the stator bar and the core iron. These gaps form when the stator bars are loose in the slots. Due to magnetic forces, loose bars will vibrate in the slots, interrupting currents and creating repeated electrical sparks. Sparking at high current levels cause erosion of the stator bar ground insulation.

Spark erosion is different from conventional Partial Discharge (PD) in that it occurs on stator bars of any voltage, and is not predominant on the higher voltage bars like PD. Also, while PD is a relatively slow deteriorating mechanism, spark erosion can deteriorate a winding quite rapidly. NEC has gathered data from several different generators of this particular style, and found good correlation between stator winding degradation and eventual failure. The graph in Figure 8. illustrates the correlation between unit service hours and the deteriorated condition of the winding due to spark erosion.

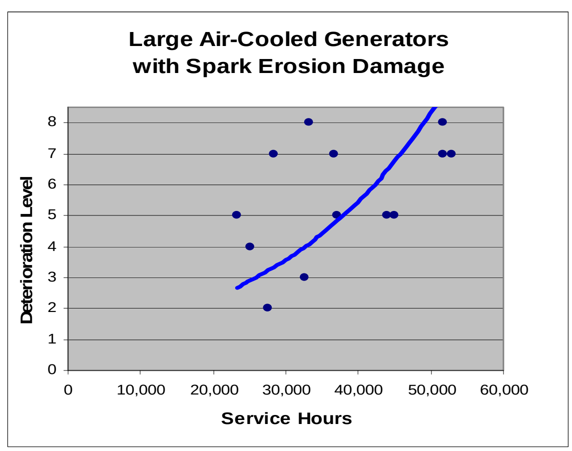

Figure 8. Stator bar deterioration level due to spark erosion versus actual service hours.

Included in the data are two units from two different OEM's that had actual stator winding failures. These are identified as deterioration level 8. One unit failed after 33,183 hours, and the other unit failed after 51,636 hours of operation. The other data points are from units currently in operation that have some level of spark erosion degradation.

Spark erosion and damage of the semi-conducting coating occurs due to high levels of current. The current comes from a small electric arc (spark), occurring when contact between the core and the bar semi-conductive coating is interrupted. This current can come from two sources and both are believed to be active at the beginning of the deterioration process. The first source is based on the inductive model, and the second is based on a capacitive discharge mode. The diagonal line in Figure 9 represents the inductive model. The horizontal lines represent the capacitive mode.

In the inductive model, the magnitude of the interrupted current depends on the surface resistance coating and the contact point transition. In the capacitive model, the current is determined by the capacity of the bar insulation area around the point of interrupted contact and the bar voltage.

The graph in Figure 9 identifies sparking current levels (horizontal lines) as a function of stator bar surface resistances, according to the capacitive discharge model. The sparking current for the capacitive discharge model can be calculated according to the formula I = ∏ x U (bar voltage) x f (frequency) x C (capacitance) x l (length between contacts). These curves are only applicable if the bars are loose in the slot, and, due to bar vibration, the bar is making intermittent contact with the core. Destructive current levels are noted at the 0.5 milliamps level and above, with safe currents identified at the 0.1 milliamps level and below.

A "grey" area exists between 0.1 and 0.5. Based on a standard capacitive discharge approach, contact of the bar to the core at a length of 20 inches will result in a very high and damaging current above 1 milliamp. On the other hand, having the bar contact the core at intervals in the range of 0.4 inches, will result in a safe level of current that will not be damaging to the stator bar surface.

The green diagonal line represents the inductive levels of current according to the model I = (generated voltage/inch x bar circumference (inches))/bar resistivity (ohms/square). It states that at lower levels of surface resistivity, higher sparking currents can occur if the bars are making and breaking contact (loose). At 300 ohms / square, for instance, sparking current values are at 0.4 milliamps. This is a level at which damage occurs. At 1,000 ohms/square, for instance, the induced current level is about 0.12 milliamps, and considered a safe value.

It is also known that the surface resistivity can decrease with age, so levels sufficient enough to anticipate this reduction should be incorporated at the initial bar manufacture. If the surface resistance of the bar gets too low, there is danger of shorting the core laminations and inducing additional core losses.

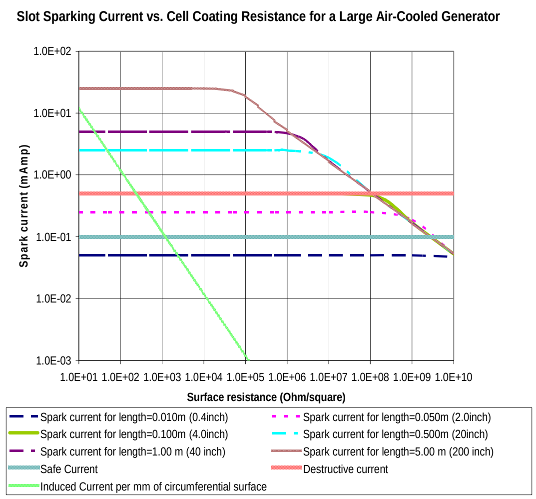

Figure 9. Slot sparking current as a function of the bar surface resistivity.

Loose Stator Bars

Loose stator bars in the slot are the primary contributor to spark erosion. If gaps in the slot exist, bars can vibrate, causing repeated opening and closing of the gaps between the bar and the core. The intermittent contact, combined with the voltage presence on the surface of the bar, creates sparking. The diagram below illustrates the effect of this intermittent loss of contact between the bar and the core.

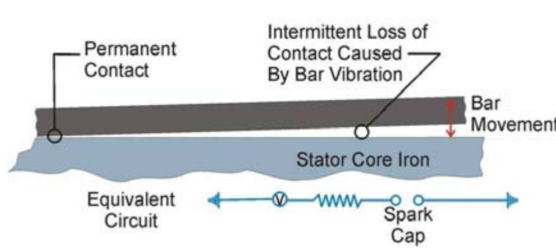

Figure 10. Mechanism of spark erosion caused by intermittent contact between bar and core.

One of the findings of the failure investigation described previously, is that the average gap between the stator bar and the core iron was 9 mils. This was based on the average of measurements taken of undamaged bar widths, versus the core iron slot width. A gap of 0.009 inches in the slot between the bar and the core is considered excessive, and correlates well with the root cause of this failure. A gap of 0.009 inches with no followup side pressure from a ripple spring will allow the bars to be loose in the slots and vibrate.

Side Packing Designs

The semi-conductive coating and side packing system installed in this machine consisted of layers of tape and RTV. The flexible RTV can be applied just before insertion of the bar into the slot, and can provide, at best, a “zero clearance” condition at the start of the generator’s life.

However, with repeated start / stop cycles and long operating hours, shrinkage of coil insulation, tapes and RTV can occur, allowing gaps to open up between the bar and the core. These gaps get progressively worse as bars become loose and are allowed to vibrate.

Other original OEM designs for these large air-cooled machines have used a flat semi-conductive side packing material. Proper fitting of the flat side packing during initial bar installation can result in relatively small gaps between the bar and the core. But again, as the unit goes through its repeated thermal cycles during operation, the existing insulation will shrink, move and wear, opening up larger gaps and allowing the bars to vibrate.

NEC, along with one other OEM, has recommended and used semi-conductive side ripple springs for many years. Side ripple springs, as shown Fig. 11, allow the bar to be fitted tight against the core iron, down the entire length of the slot.

More importantly, the side ripple springs keep the stator bar tight against the slot for many years, due to the spring action loading of the ripple, maintaining a constant force pushing the bar tight against the core. Although side ripple springs are more costly, the resulting improved performance[iii] justify their installation.

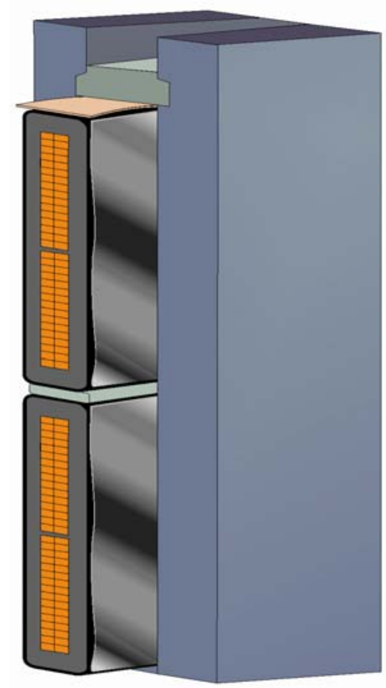

Figure 11. Illustration of top ripple and semi-conductive side ripple springs in the stator slot.

One unanswered question in this failure investigation is why 24 of the stator top bars did not see any damage. It could be presumed that these bars were somehow wedged more tightly, were not subject to vibration, and did not undergo spark erosion. Measurement of the undamaged bar widths, however, did show excessive clearances.

All bottom bars were undamaged. This can be rationalized more readily. Vibration of top bars is more likely since the radial forces affecting the top bar are three times higher than the bottom bar. The bottom bar also has more rigid constraints with the core at the bottom and the hard top bar at the top. Vibration of bottom bars is less likely, and therefore the probability of spark erosion on the bottom bars is less likely.

Surface Resistivity

The surface resistivity on the outer semi-conductive layer measured between 300 to 400 ohms/square. These values generally are considered too low for new installations, although no industry standard is in place. Lower values of surface resistivity will create higher levels of sparking current (inductive model), more rapidly damaging the bar ground insulation, if gaps and bar vibration exist.

If the bar is solidly pressed to the core, properly grounded, without vibration, the low values of surface resistivity are not detrimental. This is evidenced when looking at the situation of the bottom bars. Even with low values of surface resistivity (300 to 400 ohms/square); no spark erosion damage was found. If low surface resistivity was the primary contributor to spark erosion, damage would have been observed on these bottom bars.

Other Factors

There are many generators that have been running reliably for many years without the damaging effects of spark erosion. What is the difference between these machines, and this newer class of machines that is seeing deterioration and in some cases failure after less than ten years of service? One difference is that these newer, high voltage generators are operating in air, as compared to many units operating with hydrogen gas pressure. These newer air-cooled generators are operating at higher voltages and higher ratings than ever before. Operation in air, versus hydrogen gas pressure, may be a factor in the general deterioration of the winding.

Another difference may be the stator bar cross section aspect ratio. A survey of several different types of stator bars show a significant difference in the bar aspect ratio between this relatively new class of machines and many of the other machines put into service the last thirty years.

Typical bar aspect ratios, defined as the bar height, divided by the bar width, are as follows:

- Water cooled coils – around 1.5
- Large hydrogen cooled – around 1.5
- Smaller hydrogen cooled – around 2.5
- Conventional air cooled – 3.0 to 3.5
- Large, air–cooled generators – 3.5 to over 4.0

This stator bar design with a higher aspect ratio, may allow higher vibration and movement in the slot, especially when not side packed properly with semi-conductive side ripple springs.

Not OEM Specific

Many times problems occur in the industry and are confined to only one particular class or style of generator, due to the unique design associated with that particular class of machines. In this case, however, the problems are not confined to only one OEM.

NEC also had the opportunity to conduct a failure analysis on the removed stator bars from another generator OEM. This unit also failed from spark erosion[iv]. It too, was a large air – cooled generator, rated at 226,000 kVA and 18,000 volts. A photo of the damaged stator bar from this other OEM machine is shown in Figure 12. It is evident the spark erosion damage is similar in both machines.

Figure 12. Photo of spark erosion damage on a winding from another OEM. This winding failed after 33,183 hours of service and less than six years of operation[v].

CONCLUSIONS

A detailed failure investigation has been presented. The failure involves a newer, larger, air – cooled generator rated at 213,000 kVA and 19,000 volts. The stator winding failed due to spark erosion, sometimes referred to as slot discharge, slot sparking and vibration sparking. The primary contributor to this failure is loose stator bars in the stator core slots. If bars are loose, vibration can occur, creating electrical sparking across the gaps as the bar intermittently makes contact with the core and then breaks contact with the core. Original OEM methods of keeping the stator bars tight in the core slots on these machines are insufficient. The side packing method used on the evaluated stator consisted of a combination of semi-conductive tape and RTV that can have a “zero clearance” condition during initial installation. With no followup spring loading, such as provided with a side ripple springs, gaps open up, the zero clearance condition is lost, and the bars become loose in the slots. Another commonly used side packing design on these large air-cooled generators is flat semi-conductive side packing. This design also has no spring loading and over time, allows the bars to become loose in the slots and spark erosion to occur. Although these methods give initially very good results, the creation of gaps between the bar and the core rapidly occurs with start / stop cycles and operating service hours. The use of semi-conductive side ripple springs, has been recommended by and used by the author's company for many years, provides a method of keeping the bar tight in the slot, even if shrinkage of materials occur. Maintaining the bar tight in the slot is the fundamental requirement to prevent spark erosion. If gaps do occur, it is important to have a minimum value of surface resistivity on the bar semi-conductive coating to minimize the effects of damaging high levels of current. Failures due to spark erosion have been observed on machines by more than one OEM. Common denominators include large, air – cooled generators, typically rated 18,000 volts or higher. Spark erosion has, however, also been observed on similarly designed air-cooled machines rated at 13,800 volts. The root cause of this problem is loose bars in the slot, caused by a side packing system that does not maintain the bar tight to the core over time.

REFERENCES

[i] "Refurbishment of Large, Air – Cooled Generators," B. Moore, Iris Rotating Machinery Conference, Toronto, Canada, 2006.

[ii] "Electrical Failure Mechanisms on Large Generator Stator Windings," C. V. Maughn and G. C. Stone, 75th Annual Doble Client Conference, Boston, MA, 2008.

[iii] "Physical Processes in Corona Suppression Systems Under Electrical and Thermal Stresses in High Voltage Rotating Machines," B. Nindra, A. Khazanov, J. Timperley, IRMC 2005, Scottsdale, AZ.

[iv] "Air – Cooled Generators," R. Schwieger, Combined Cycle Journal, Second Quarter, 2007, page 123.

[v] "Premature Failure of a 18kV Air – Cooled Generator," R. Schultz, Iris Rotating Machinery Conference, Long Beach, California, 2008.

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