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Insulation System Reliability in Wind Generation

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***Abstract*—Wind turbine generators are subjected to unusual environments and stresses. In this paper we will discuss several types of wind generator insulation failure mechanisms as well as forensic analysis results of several different manufacturers' systems. The types of generators studied include induction, wound rotor, and permanent magnet across a number of output voltages and environmental conditions. Past studies relied upon rudementary results and stopped at the obvious. In this paper we will dig a little deeper into the failure processes observed.**

***Keywords*—wind generation; insulation system; environment; alternative energy; forensics; root cause analysis; generator**

I. Introduction

Both European and North American databases related to wind turbine reliability prior to 2006 identified gearbox bearing failure and the associated downtime as a significant factor to the availability of wind generation. In more recent years (2012-2014), the issue has shifted from gearbox bearing failure to the electrical generator system. While the exact cause of failure is not identified by owners or manufacturers of the generators; of the 13 generators reviewed for this study only two failed due to bearings. One due to poor repair practices and one due to an oddity of the machine design. Alewine and Chen[1] identified that bearings make up a majority of the generator failures, depending on the size of the machine.

One of several European databases used for tracking reliability, WMEP[2], identifies generator bearing wear-out as the primary cause of generator failure. It also identifies 0.15 failures/turbine/year with an average of 6 days/failure and unplanned outages rising significantly as the age of the turbine passes 15 years. The CREW[3] database operated by Sandia National Labs for the US Department of Energy has a smaller sampling of data. It identifies that the generator accounted for 5.2% of wind turbine unavailability in 2012 and equated the rotor blades and generator as being similar in event frequency and duration. The CREW numbers could be higher as 37.3% of the potential operating time for the generators being tracked could not be accounted for in database reporting.

Of the machines evaluated for this study, one was Permanent Magnet (PMG), seven were Doubly Fed Inverter (DFIG), and five were Induction (IG). The sizes ranged from 1.5 to 2.7 MW and encompassed four different generator manufacturers with voltage ranging from 690V to 12.4kV. All used magnetic wedges and formed coils.

A review of the more obvious causes of failure eliminated two generators from the study. The PMG failed due to bearing and mechanical fit wear and one DFIG failed due to a bent shaft that destroyed both bearings and caused the rotor to drag in the stator. For the purposes of this paper, we will focus on the data associated with the remaining eleven generators.

II. Observed Winding Failures

The initial observation identified a common symptom of the stator winding failures associated with both DFIG and IG machines and similar between the two rotor winding failures of the DFIG. The failures were all coil to ground at the top of the slot and associated magnetic wedge material was missing from the slot. There were also several conditions that went along with these machines. In some cases, only the wedge associated with the winding failure was missing, in other cases, a large number of wedges were missing, including the area where the coil failed. In all cases, the wedge material was missing where the coil failed as shown in Fig 1.

In previous work[4] it has been postulated that the primary cause of failure may be the brittleness of the wedge or the fit of the wedge in the slot. Other concepts included the VPI material used, coil fit in the slot, and even supply issues. One of the issues related to investigation in order to identify the true root cause is the method used to remove coils. In most cases

Fig. 1. Failed Stator Coil with Missing Wedge

the stator or rotor is placed in a burnout oven and the insulation material is incinerated off of the copper. The root-cause-analysis covered in this paper utilized a stator warming process which allowed the intact removal of the stator windings enabling a full investigation of the insulation system as shown in Fig. 2.

Fig. 2. Stripping Generator Vertically

For the investigation sets of coils were removed from locations where: wedges were missing and the coil failed, wedges were missing and the coils had not failed, and sample coils that still had wedges. Wedges were removed from the stator noting tightness and any wear. It was also noted that a number of the stators required no heat to remove wedges and coils and that they stripped easily either way. Data and pictures were collected for the forensic analysis to be performed.

III. Forensic Analysis

Utilizing the forensic methods outlined in [5-6] an analysis of the failure modes was performed on each generator independently using the PROACT® methodology. Following the rules of analysis, each potential issue that could cause the observed effect was analyzed. While it is possible that electrical events related to the drive may have had an impact on the failure, the scope of the information presented for this paper will remain at the generator.

The analysis starts with a simple observation that each generator failed during operation and not at startup within this group. This leaves three hypothesis that we would investigate:

- Winding failure
- Surge arrestor failure
- Rotor failure

Fig. 3. Inspection of a section of failed coil after tape removal showing surface damage on conductors only indicating ground fault

The surge arrestors were checked and found to be OK in each case, with the exception of some damage to leads related to one surge arrestor. In general, for the stator analysis, the rotors had not failed, but had suffered damage on the DFIGs requiring re-insulation. With the stator, the investigation took the next logical step of investigating whether the failures were turn to turn or coil to ground.

As shown in Fig. 3., all of the coils were found to have failed single turn to ground versus turn to turn shorts. The potential causes that were investigated on each machine included:

- Coil movement
- Dielectric stress
- Transients
- Partial discharge
- Varnish penetration
- Contamination
- Vibrating wedges
- Foreign object damage
- Thermal conditions

Based upon operational data and an inspection of the various insulation systems, it was determined that dielectric stress and transients were least likely. There were specific issues during the investigation that identified one machine design into question, however; during the warming process, the insulation systems of one particular design stator would ignite at about 210C. This called into question the selection of material by the manufacturer.

With all of the high voltage designs using a significant amount of mica tapes in the coils, as well as a lack of visual and microscopic evidence in all samples across both unfailed and failed sections, partial discharge was not determined to be a significant factor in the failure chain. Peeling back layers of insulating tape and sectioning the coils identified good varnish penetration through tapes on all machines inspected.

Foreign object damage and contamination was another concern as materials were present in several of the generators that were inspected. It was determined that the foreign objects did not come into contact with the winding where it had failed and contamination present within the machines was from either magnetic wedges or failed insulation. It was later identified that the metalic contamination from wedges did play a part in the failure chain.

Wedge tightness was inspected on the surviving wedges within the generator stators. It was found that the wedges were immoveable in most cases and had to be center-slit and removed. Stators ranged from one wedge coming loose and dragging on the rotor to more than half. Packing material under the wedges in almost every case was poor and spongy.

Coils were relatively loose in many of the generators regardless of manufacture. Top coils were able to be moved and lifted out of slots with crowbars at room temperature, as well as some bottom coils. The remainder had to be warmed up in order to be removed. While some coils showed signs of wear on their armor tapes, in particular the coils that had missing wedges, the remaining coils were still loose.

It was also noted as several of the generators were disassembled that plastic parts had become brittle and had crumbled. By evaluating the operating environment, it was identified that they would have been exposed to deeply cold environments, some to -50C or lower. Even with space heaters within the machine, significant temperature swings are not only possible, but probable. This would have an impact on the stability of the slot insulation system due to thermal shock.

Sections of good and bad coils were made and the material peeled back layer by layer and inspected by microscope. The small brownish objects shown in Fig. 4. are iron particles that have 'tunneled' their way into the insulation system. This symptom tended to be found along the top edge of coils where the wedges were missing and magnetic wedge iron dust had gathered.

Fig. 4. Iron filings and pathways several layers deep into mica tape along top edge of top coil.

IV. Discussion of Findings

Based upon physical findings and information from the literature based upon other populations of wind generators we postulate that the failure is initiated by loose coils and packing. When some manufacturers machines are assembled, the coils appear to have been installed with a significant gap between the coil sides and the stator slot. Spongier materials tend to be used as packing beneath the magnetic wedges, which are brittle by nature. In manufacturing it may be considered that the global VPI process will hold, or glue, the components in place and together.

During a period of time in operation as the generator cycles, in particular in times of thermal extremes, the insulation system begins to release. Forces on the coils are radial against the spongier packing materials and the material begins to compact, increasing the forces acting against the wedges. Eventually one or more wedges break loose from the slot either due to the brittleness of the wedge or the wedge acting against the wedge slot wears it open. The wedge drags on the rotor causing iron particulate to spread throughout the generator and some to gather in the open top of slot against the direction of rotation. The iron begins to drill its way into the insulation system eventually creating a path to ground or allowing electrical sparking and insulation degradation (Fig. 5.).

A key issue is that it appears that the generators tend to be developed and manufactured in a similar fashion to ground mounted and enclosed generators instead of within an enclosure with 3-dimensional movement and surrounded on all sides by the local conditions. This should result in tighter tolerances in the design, manufacture and rebuild, and higher grade materials selected specifically for the environmental extremes that the machine will see.

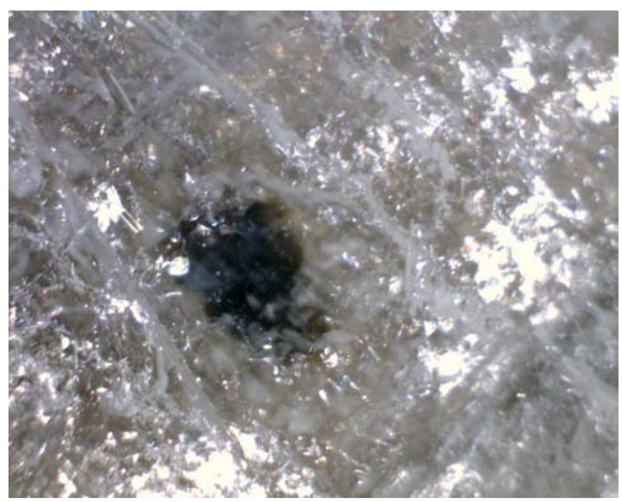

Fig. 5. Arcing point in armor tape resulting in burned mica tape.

V. Solutions

In order to break a chain of events, a link in the chain must be broken. In this case, there are two options for lengthening the life of a wind generation machine. The first one involves replacing the magnetic wedges with a different wedge material. However, the benefits of using magnetic wedges are lost.

Keeping the magnetic wedge but improving coil and packing materials may be a better solution.

The magnetic wedge is less likely to vibrate and fail if a constant tension is kept on it. This opens several solutions that can be implemented both on the new manufacture and overhaul of an electric machine:

- Larger machines may have the opportunity to use ripple springs as side and top packing. This provides the additional benefit of maintaining constant tension across significant temperature ranges. The stator may still be VPI'd with the use of ripple springs.
- Tighter top and side packing for smaller machines using solid materials such as Nomex®. This may mean that wedges will have to be manufactured in shorter sections versus one or two long wedges.
- Shorter wedges that conform better to the wedge slots in order to reduce the amount of wedge vibration.

The above solutions resolve a number of potential problems, including the theory of failure outlined in this paper and wedge failure theories previously identified, increasing the reliability of the stator. If Alweine and Chen are correct in the survey of failure modes with approximately half of electric machines failing due to bearings and half due to stator failure, solving the winding failure will significantly improve overall wind fleet availability.

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