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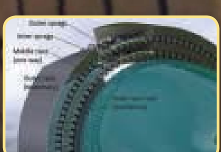
• TRENDS IN WIND ENERGY ISSUE •

Generator REPAIR 101

Finding a failure's real root cause



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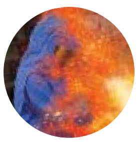

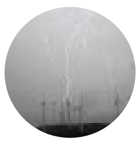

FEATURES

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ON THE COVER

Workers at Dreisilker Electric Motors rebuild a wind turbine generator in Glen Ellyn, Illinois.

Why wind generators die young and how to make them work longer

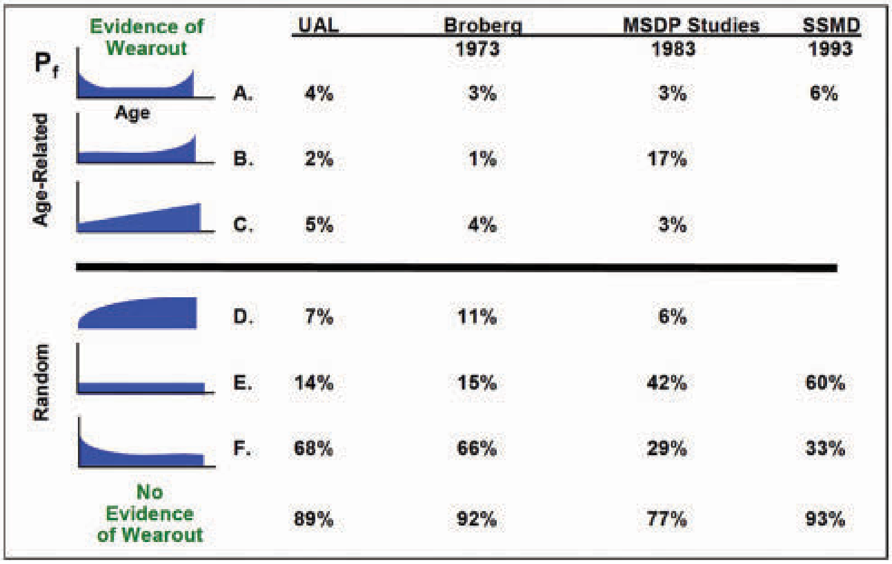
Wind-turbine generators tend to have a relatively high rate of failure. Unfortunately, a rugged system of analysis to determine a root cause of failure is stopped at symptom level, which is typically too early to identify possibilities to reduce or eliminate a problem. It does not have to be that way.

Howard W Penrose
Ph.D., CMRP / President / SUCCESS by DESIGN

The purpose of machine forensics is to preserve and investigate a failure beyond the obvious and look at design, procurement, human, physical, training, and other issues that create a chain of events that lead to turbine-component failure. This requires an understanding and view of the complete system because a component that fails is the weak-point, or fuse. A generator, however, makes for an expensive fuse, but it is acting as one just the same. The generator failure is a symptom of system issues, not the actual cause of the system outage.

A common practice is to make the assumption that the component cannot be made more reliable and that the overall system would wear out after a period of time. This concept is incorrect. For instance, prior to an investigation of several manufacturers' generators, it was assumed that the magnetic wedges in the stators were brittle and failing which resulted in a fault to ground because the wedge vibrated against the coil. Through a full review of the failure using Root-Cause-Failure-Analysis (RCFA) techniques, referred to as forensics in this article, it was discovered that wedge failure was not the case. With the help

Age reliability characteristics



Source: U.S. DoD

of prior investigations it was discovered that root causes are often far simpler than previously determined and should be able to provide a logical and understandable cause-effect-cause relationship.

This article discusses a few common misconceptions of reliability and the assumptions that must be taken when approaching an RCFA. A discussion of a forensic analysis on a wind generator will follow.

A missing wedge has caused a coil failure.

Reliability concepts

In the world of reliability engineering, it is understood that the bathtub curve of reliability is mostly incorrect. The assumption with this curve is that there is an infant mortality, or high rate of initial failure; a fairly flat-life reliability, or occasional failure; then a wear out or end of life period that appears as an increasing rate of failure. Adopting this concept makes it easy to dismiss the failure by saying the deliverable did not meet its design life.

The U.S. Department of Defense published information[1] related to a series of studies suggesting that simple components may have age-related wear out that follows the bathtub curve. But complex systems actually had random failures in which the systems break down. A wind turbine is a complex system and its generator would be considered a complex component. A turbine's resistance to failure decreases with age. But considering the generator a complex system, lets the engineer approach its failure from the concept that improvements to the system would extend its life.

From a reliability-engineering standpoint, a study of the system and common failure characteristics allows for improvements. However, a forensic analysis of the common failure characteristics would identify the true root cause allowing a more robust engineering correction. That is replacing a wear component with one more resistant to wear may extend the life of the system, but eliminating the source of wear on the component would provide a much longer impact overall.

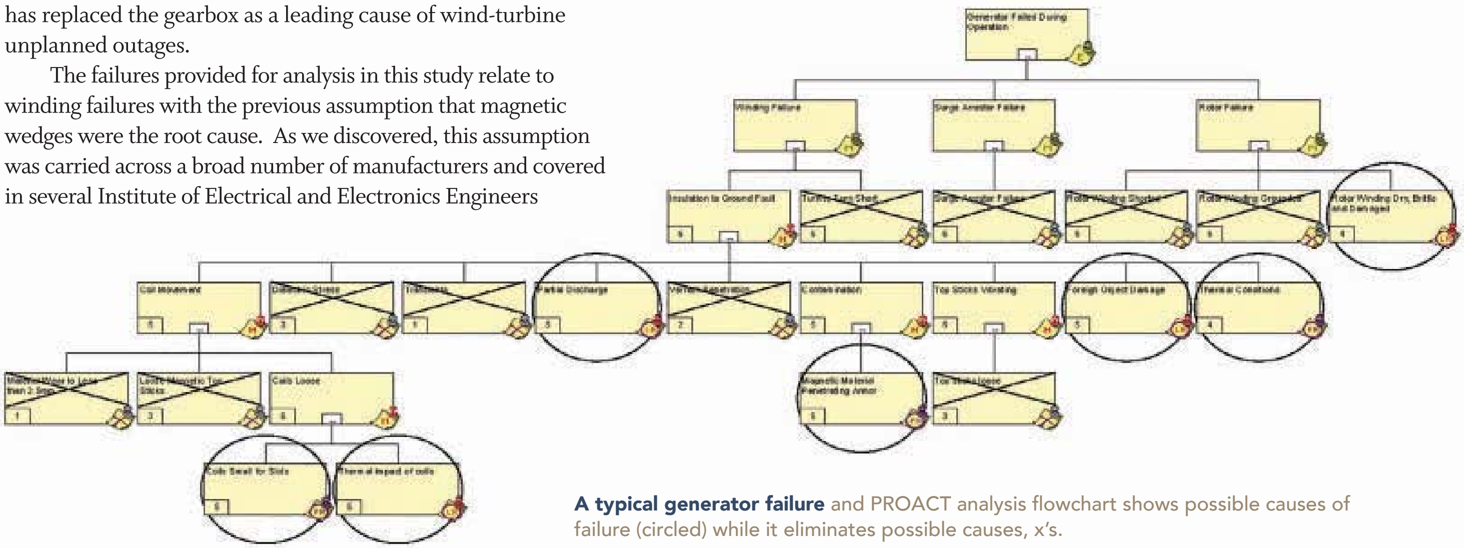
Latino[2] identified that a failure is normally comprised of a series of seven to 11 faults that compound until a system fails to operate as designed. Breaking the chain of faults eliminates similar problems in the future. This has led to development of the PROACT RCFA technique in which the analyst follows a series of events by (PR) eserving the evidence, (O)rdering the team, (A)nalyzing the error, (C)ommunicating findings, and (T)rend and track results. While there are many tools for performing advanced RCFA beyond a standard 5 Whys and Herringbone approaches, PROACT RCFA is used for this case study.

Considerations in generator failure

The WMEP[3], Germany's Scientific and Evaluation Program, identifies that bearing wear out is the primary cause of generator failure. Reviewing the data and assumptions further reveals that the bearing cause of failure is an assumption that stems from a lack of detailed data. A database called CREW[4], operated by Sandia National Labs for the U.S. Department of Energy, does not specify which components of a generator fails, just that generator failures accounts for 5.2% of wind-turbine unavailability in 2011. WMEP states that 0.15 failures/turbine/year, with an average of six days per failure have been found to rise significantly as the wind turbine ages. Data published by Alewine and Chen[5] says that the cause of failure in generators is assumed evenly split between bearing and winding-insulation failures.

The failure rate of these machines is extraordinarily high and has replaced the gearbox as a leading cause of wind-turbine unplanned outages.

The failures provided for analysis in this study relate to winding failures with the previous assumption that magnetic wedges were the root cause. As we discovered, this assumption was carried across a broad number of manufacturers and covered in several Institute of Electrical and Electronics Engineers



A typical generator failure and PROACT analysis flowchart shows possible causes of failure (circled) while it eliminates possible causes, x's.

papers on the topic. The symptom has been determined that the wedge comes loose or falls out and somehow damages the insulation system due to wedge fit, or a similar issue. It is assumed that the wedge is brittle due to an 80 to 90% iron fill and breaks easy. Therefore it is the primary cause.

So, why not just replace the magnetic wedge with a standard wedge? In simplest terms, the purpose of the magnetic wedge is to let the designers decrease losses and heating in an energy-dense generator. The wedges allow for a smaller, efficient generator that produces less electrical noise. Replacing a magnetic wedge with a standard wedge requires de-rating the generator.

The brown material is iron dust and some other evidence of tunneling caused by what's called magnetic termites.

Burned material in insulation layers as magnetic termites gather at a single point.

The question then becomes: Are the wedges truly the root cause? To answer this question a significant number of generators were reviewed with winding failures from a variety of original equipment manufactures (OEMs).

Forensics. The forensic investigations included multiple doubly-fed inverter generators and induction generators which had failed windings. Voltages ranged from 690 to 12,400 and across a series of turbine sizes between 1.5 and 2.5 MW. The ages of the generators varied depending on a series of conditions including climate.

Each machine was carefully disassembled and investigated. It was important to note that in every stator winding failure, the fault was to ground. What's more, it was clearly visible where wedges had worked free of the associated slot and that there were no failures around loose or solid wedges (see accompanying image).

All removed components were evaluated, from mechanical fits to splitting the removed bearings to investigate their condition. In most cases, the generator components showed relatively little wear with the only visible defect being the winding fault. The compared forensics all followed a similar template.

The purpose of the forensics is to follow a logical path as shown in *A Sample Flow For A Forensics Investigation* chart. The opening statement to the investigation should be relatively generic, such as: Generator failed to operate. In this case, the investigation is more at the component level, so the question as to the generator failing to operate has already been answered by choosing the generator's failed condition. This helps identify which generator component failed, such as the stator or rotor. It was found that the stator failed in each case. The possibilities associated with the failure were then outlined:

- Coil movement - coils moving and knocking the wedges out of the stator
- Dielectric stress - the electrical operating characteristics caused a breakdown of the insulation system
- Material - incorrect insulation material
- Transients - electrical component causes or lightning strikes
- Partial discharge - corona effect on the insulation system
- Varnish penetration - improperly varnished coils or voids in the insulation system
- Contamination - any form
- Vibrating wedges - wedges vibrate in the magnetic fields
- Foreign object damage - parts or other objects loose in the generator
- Thermal conditions - from the generator or environment.

Based upon the operational data and inspection of the insulation components, it was apparent that dielectric stress and transients were least likely. Material issues were evaluated when the insulation of one OEM ignited at temperatures under 210°C (410°F). Although the insulation systems were rated Class F (155°C), it is unusual for insulation materials to ignite at this temperature and was the first time since 1969 that Dreisilker Electric Motors, where the investigation was taking place, had experienced this condition on any insulation system of any rating. It was determined that each of this OEM's machines would be cold stripped, or the coils removed without warming.

The stripping process is unique to the investigating repair shop in that a warming process is used and the coils and insulation system can be removed intact for investigation. In most repair facilities the stator is placed in an incinerator and the insulation reduced to ash. This limits the ability of forensic investigators to evaluate all components, which may have partially led to incomplete material investigations in the past. The wedges were removed by either splitting them or by sliding the loose wedges out of the stator. Initially, there was little reason behind whether a wedge was loose or tight until inspecting the packing below the wedge.

Higher voltage stators used a significant amount of mica which eliminated partial discharge as a major failure mode. Investigations also showed no sign of corona on any of the stators. It was determined that the layers should be peeled back on the insulation systems of all designs and investigated microscopically. This step is part of the varnish penetration investigation.

Also, the coils were found to be relatively loose on all stators. The top coils were removed, often without warming, by hand or with crowbars using light pressure. Bottom coils were mixed tight and loose. Some coils were found to have varying degrees of wear on their armor tapes, indicating slot movement. However, the slots measured relatively uniform and were eliminated as a potential cause of failure.

On several generators, a few plastic components were found to be brittle, indicating extreme exposure to cold below -40°C ambient. Furthermore, the machine's space heaters were ineffective on keeping components warm. This indicates that significant temperature swings were not only possible, they were probable.

The investigation was conducted on intact and missing wedges. A collection of magnetic dust or iron from the missing wedges had gathered in the direction of rotation at the top edge of the coils, including near the point of failure inside the stator. Magnetic materials show a peculiar effect when exposed to alternating current fields: they tend to spin. In this case, the point where every generator inspected had failed was along the top edges of the coils, iron dust was collecting and penetrating the insulation as if it were magnetic termites. In a few places, enough material was gathered to generate hot spots in the insulation system, burning the insulating material. In all cases the varnish penetration in the coils was excellent.

Bringing it together

A review of the collected data indicates that the coils were assembled with relatively large clearances between the coils and the sides of the slots. It is assumed that this is to shorten coil installation times while counting on Vacuum Pressure Insulation (VPI) varnish to hold the coils in place. Also, several OEMs were found to use limited packing or sponge-like packing under the wedges, counting on the VPI varnish to create a rigid bond between the coils and wedges. Ground-based generators, however, are firmly anchored to the floor of a facility and have a thermal insulating barrier at least on the underside of the machine or are located in a temperature-controlled environment.

The wind generator is typically located in an area where the ambient temperature is present on all sides with a limited thermal barrier and is not rigidly attached to earth. The generator is quickly loaded when brought on-line resulting in a relatively steep increase in operating temperature. This creates a condition known as thermal shock, a significant change in temperature over a relatively short period. The result of thermal shock is that the stator, coils, and insulating materials start to release from each other due to expansion and impact on the insulating material properties. In effect, the coils begin to loosen. The combination of brittle insulation, followed by softening as the generator comes to temperature, causes compacting of the sponge-like materials underneath the wedges. When the generator is de-energized, depending on the operating environment, it cools quickly with materials contracting at different rates, with the same result of material releasing and compacting.

Eventually, the coils begin to move significantly and radially in the slot (towards and away from the rotor) as each coil magnetically loads and unloads. These forces are significant, if coils have even a relatively small space for movement, forces can be significant and eventually result in ejecting wedges into the air gap. Any small portion of the wedge can rub against the rotor. The material then collects and the iron dust begins to burrow as the coils wear more where the wedges are missing. Eventually, the iron dust provides a path resulting in a coil short where there is significant material at the top of the slot.

Solutions

The key to resolving this particular failure mode and to extend the life of a generator is to break the chain of events. While the root cause is associated with either design or manufacturing decisions, solutions exist which will not significantly impact the manufacturing cost while designing out a reduced resistance to failure. One method would be to change the wedge material, which eliminates the iron dust and decrease its brittle state. However, it will extend the life only a little because coils will still eject the wedges and then the coil movement will eventually cause failure. The trade-off is the potential de-rating of the generator.

The magnetic wedge is less likely to vibrate and fail if constant tension is applied to it. This opens a number of solutions that can be implemented during new manufacture or during a generator overhaul. For example:

- 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-spring packing and in higher voltage applications, semi-conductive ripple springs are available.
- Tighter top and side packing for smaller machines using solid materials, such as Nomex. This may mean that wedges have to be manufactured in shorter sections versus one or two long wedges.
- Shorter wedges that conform better to the wedge slots to reduce the amount of wedge vibration along with rigid packing.

These simple additions, which are not uncommon in standard machine manufacture and re-manufacture, engineer out the reliability issues associated with loose-coil manufacturing and thermal shock. If Alewine and Chen are correct, this will reduce the primary cause of failure of the generator stators, which make up at least half of generator failures, thereby significantly increasing the availability of the wind fleet.

FOR FURTHER READING:

[1] *NAVSEA Reliability-Centered Maintenance (RCM) Handbook, S9081-AB-GIB-010, Naval Sea Systems Command, US Navy, April 2007*

[2] *R. J. Latino, K. C. Latino, and M. A. Latino, Root Cause Analysis 4th Edition, Taylor and Francis, Boca Raton.*

[3] *P. Lynding, S. Faulstitch, and P. Kuhn, "Establishing a Common Database for Turbine Failures," Sandia National Labs, 2010.*

[4] *V. Peters, B. McKenney, A. Ogilvie, and C. Bond, "Continuous Reliability Enhancement for Wind (CREW) Database," U.S. Fleet Public Report, Sandia National Labs, 2011.*

[5] *K. Alewine and W. Chen, "A Review of Electrical Winding Failures in Wind Turbine Generators," Proc. Of the 2011 Electrical Insulation Conference, IEEE, pp 392-397, 2011.*