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Flux Probes Provide On-Line
Detection of Generator Shorted Turns

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The Use of Air-gap Magnetic Flux Probes has Proven Effective in the Detection of Generator

rotor winding shorted turns and has helped to improve the quality of predictive maintenance decisions concerning when or if rotor rework should be performed. Analysis of air-gap flux probe data can pinpoint the number and location (pole and coil) of shorted turns without having to take the generator off-line.

Shorted turns can have significant effects on a generator and its performance. If the percentage of total turns shorted out is small, the generator may be able to run at rated load for years without further problems. Larger shorted turn percentages, however, can cause operating conditions that may limit unit loads. If the problems become severe,

Typical air-gap flux probe installation.

forced outages may occur. Conditions that may result in running a rotor with shorted turns include:

- *Rotor unbalance that varies with field current changes (thermal sensitivity),*
- *Rotor/stator vibration due to unbalanced magnetic force,*
- *Higher field current than previously experienced at a specific load, and*
- *Higher operating temperatures due to higher field currents.*

FAILED INSULATION

Shorted turns are usually the result of failed insulation between individual windings in a rotor. Insulation failure

can be a result of turn-to-turn movement of the rotor windings. Relative movement of turns can degrade the intervening insulation layer or cause misalignment that can result in turn-to-turn contact. Failures in any of the subsystems designed to contain the thermal and mechanical forces that develop in the rotor at speed can also give rise to turn-to-turn movement. Some of these failure mechanisms include coil foreshortening, end-strap elongation or inadequate end-turn blocking. Metallic contamination can also result in shorted turns by forming conductive bridges between turns. In addition to the turn-to-turn contact within a single coil, turn-to-turn contact between coils in the end-turn region can occur that will remove one or two entire coils from the field circuit.

Coil foreshortening refers to a phenomenon where rotor turn copper decreases in length within a rotor slot after a number of stop-start cycles. The copper in the rotor slots tends to expand more than the rotor body as the unit heats up during operation. Frictional forces that develop when the rotor is at speed typically counter the thermal expansion of the copper, creating a compressive force that exceeds the yield strength. When the rotor is stopped and allowed to cool down, however, the frictional forces holding the copper in place are reduced and, as the copper cools, the shortened
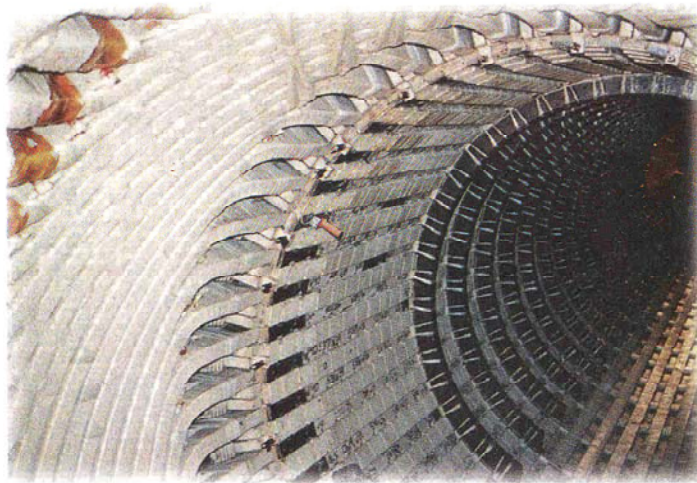
slot copper will pull the end-turns toward the rotor body. This will act to cause misalignment of the rotor end turns. In many cases, coil foreshortening has been responsible for cracking several turns in the end-winding.

End-strap elongation is a result of excessive friction between the end-straps and the retaining ring insulation. If the coefficient of friction becomes too great as a rotor is brought up to normal running speed and temperature, the top turns will move with the retaining ring. If the copper yield strength is exceeded, the turn will be permanently lengthened. This process can be repeated with every start-stop cycle to produce a ratcheting action that can produce gross elongation of the end turns. Underlying turns can also be elongated, but not to the same extent. This relative movement can result in shorted turn development.

Adequate end-turn blocking is required to maintain the positions of the rotor winding end turns. In cases where the end-turn blocking is insufficient or has shifted during operation, movement of the end turns can cause misalignment and give rise to shorted turns.

AIR-GAP FLUX PROBE

On-line monitoring using an air-gap flux probe can detect turn shorts that are established only when the rotor is at normal operating speed and temperature. The flux probe is sensitive to the time rate-of-change of the radial flux in the air gap. As each rotor slot passes the flux probe, the slot leakage flux from that slot is detected. Rotor slot leakage flux refers to flux that does not cross the air gap to reach the stator windings. Since the leakage flux does not induce stator current, the leakage flux does not contribute to power generation. However, it is local to each rotor slot and its magnitude is proportional to the current flowing through the turns found in the slot; it is diagnostic, therefore, of active turns in each slot.

The flux probe waveform displays a peak for each rotor slot. The magnitude of that peak is related to the amp-turns in the slot. Since amp-turns are directly related to the number of active
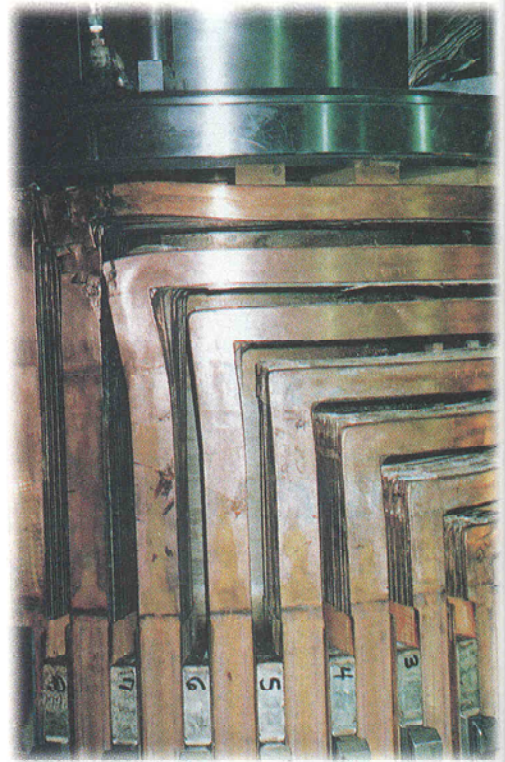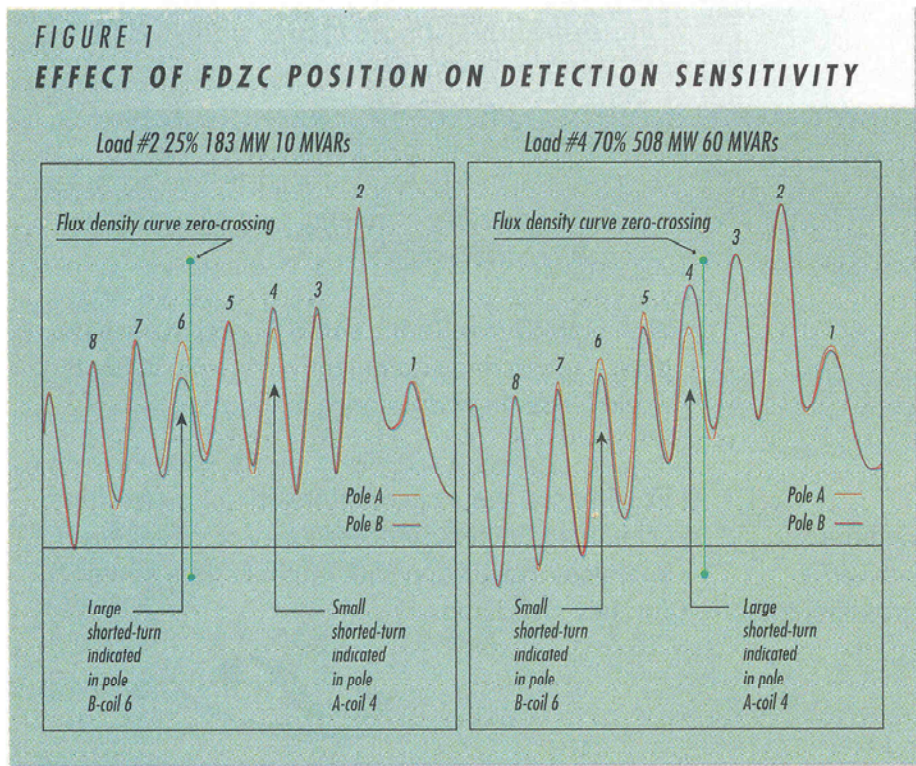

Top turn of No. 7 coil shorted to top turn of No. 8 coil.

turns in the slot, a coil with shorted turns will display a smaller peak than a coil without shorted turns. By comparing slot peak magnitudes between poles, the number of shorted turns can be calculated for each coil in the rotor.

To fully characterize a generator rotor, a series of load points is needed whose flux density curve zero-crossings (FDZC) align with each of the leading coil slot peaks in the flux probe waveform. With this data set, each coil can be analyzed at the maximum possible sensitivity.

The FDZC varies with the load placed on the generator. At zero MW load, the FDZC will be positioned at the quadrature axis (i.e., between the two largest coils). As real power increases towards full load, the FDZC moves along the leading slots toward the No. 1 lead coil slot. The reactive load also affects the FDZC position. Positive MVARs will move the FDZC towards the quadrature axis, while negative MVARs will move the FDZC towards the No. 1 leading coil slot. Reactive

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FIGURE 1
EFFECT OF FDZC POSITION ON DETECTION SENSITIVITY

Load #2 25% 183 MW 10 MVARs

Flux density curve zero-crossing

Pole A
Pole B

Large shorted-turn indicated in pole B-coil 6

Small shorted-turn indicated in pole A-coil 4

Load #4 70% 508 MW 60 MVARs

Flux density curve zero-crossing

Pole A
Pole B

Small shorted-turn indicated in pole B-coil 6

Large shorted-turn indicated in pole A-coil 4

power alterations can be used to move the FDZC in the desired direction when operations limit the range of real power the generator can accommodate during the testing period.

To calculate the shorted turns for a particular coil, the load point whose FDZC most closely aligns with the lead slot of the desired coil is selected. The shorted turn indications for that coil are then calculated. Optimally, there would be a load point whose FDZC aligned with the lead slot for each coil. When there is no load point available whose FDZC closely aligns with the lead slot for a particular coil, any shorted turn condition will be underestimated.

Shorted turn calculations are performed by measuring the magnitude of each lead slot peak and then making a pole-to-pole comparison for each coil. For example, if 10 percent of the turns in a coil are shorted out, the pole's coil slot peak would be expected to decrease by approximately 10 percent. This is only true when the FDZC is aligned with the affected coil's lead slot peak. The occurrence of symmetric shorted turns, where the same coil has experienced shorted turns in each pole, will mask the detection of shorted turns. Comparison to a baseline set of data with no turn shorts must be used to detect the presence of symmetric shorted turns.

CASE STUDIES

The first case study illustrates the effects of the FDZC on shorted turn detection sensitivity. Figure 1 displays two lead slot overlay graphs for a two-pole rotor with one shorted turn in both

Pole A-Coil 4 and Pole B-Coil 6. The left graph is at 25 percent of full load and has a FDZC position near the lead slot of coil 6. The left graph shows a significant shorted turn indication for Pole B-Coil 6, while the shorted turn indication for Pole A-Coil 4 is quite small. The right graph is at 70 percent of full load and has a FDZC position near the lead slot of coil 4. In this graph, the Pole B-Coil 6 indication has been reduced, while the Pole A-Coil 4 indication has been magnified. This example emphasizes the importance of recording a series of load points from zero to full load. It has been observed on many occasions that shorted turn indications would have been missed if only one load point was used for the entire analysis.

The waveforms displayed in Figure 1 also show the effect of the use of magnetic rotor wedges. (Magnetic rotor wedges can significantly reduce flux probe sensitivity by shunting the slot leakage flux through the magnetic wedge.) The No. 1 coil slots made use of magnetic wedges in this rotor. As can be seen in the graph, the No. 1 coil peaks are much reduced in amplitude relative to the other coil slot peaks.

The second case study presents a two-pole rotor with seven coils/pole in which coils 6 and 7 of one pole were shorted out of the field circuit. This occurred when the top turns of coils 6 and 7 on one pole became shorted together. Figure 2 displays this particularly severe case of shorted turns. The figure displays a dramatic absence of signal for the lead slots of coils 6 and 7 of one pole. The unit was only able to run at reduced loads due to excitation limits.
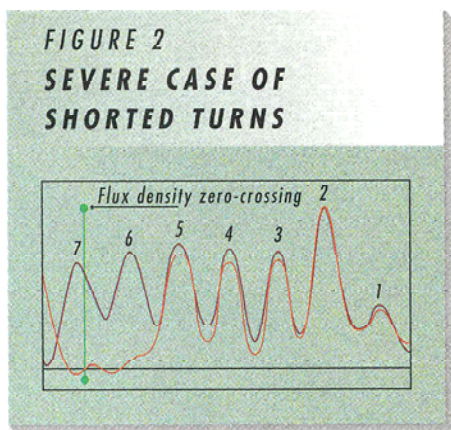
Thermal sensitive balance problems were minimized because the location of the slots for coils 6 and 7 are nearly 180 degrees apart and because the unit was running at reduced field excitation.

This type of shorted coil condition is not as rare as one might think. The authors have flux probe data from two more machines in the past two years that have lost one or two complete coils. Additionally, three other units, without flux probes, were found to have two coil shorts that were identified by inspection during disassembly.

Flux probe monitoring is recommended prior to maintenance shutdowns and at start-up if rotor work has been performed. Monitoring should also be performed if changes in operating characteristics are observed. **PE**

FIGURE 2
SEVERE CASE OF
SHORTED TURNS

Flux density zero-crossing

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Authors—
The authors have operated Generatortech, Inc. in Scotia, N.Y. since 1989. Generatortech specializes in shorted turn detection equipment sales and testing/consulting services. Donald Albright (EE) has 45 years' experience in the design, manufacture and testing of generators. David Albright (ME) has 18 years' experience in biomedical research and software development. James Albright (CE) has 22 years' experience in plant engineering.