GENERATOR FIELD WINDING SHORTED TURN DETECTION TECHNOLOGY

Donald R. Albright, David J. Albright and James D. Albright
Generatortech, Inc.

ABSTRACT

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 to perform rotor rework. 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 offline. This paper will discuss the theory, methodology and benefits of detecting shorted turns in generator rotors. A number of case studies will be presented.

EFFECTS OF SHORTED TURNS IN ROTOR WINDINGS

The impact of operating a round rotor generator with rotor winding shorted turns depends upon many factors[1]. 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. However, larger shorted turn percentages can cause operating conditions that may limit unit loads. If the problems become severe, forced outages may occur. Conditions that may result in running a rotor with shorted-turns include:

1. Rotor unbalance that varies with field current changes (thermal sensitivity).

Coils with shorted-turns operate at lower temperatures than coils without shorted-turns. This is because the heating resulting from I^2R losses are lower in the effected coil (the coil current is traversing a shorter copper path, therefore the coil resistance is lower), while the cooling circuits remain the same. A rotor temperature gradient that can give rise to rotor bowing will be a function of the number of turn-shorts and their location (**FIGURE 1** and **2**), as well as the total field current. At higher field currents, any rotor temperature gradient due to shorted turns will be greater.
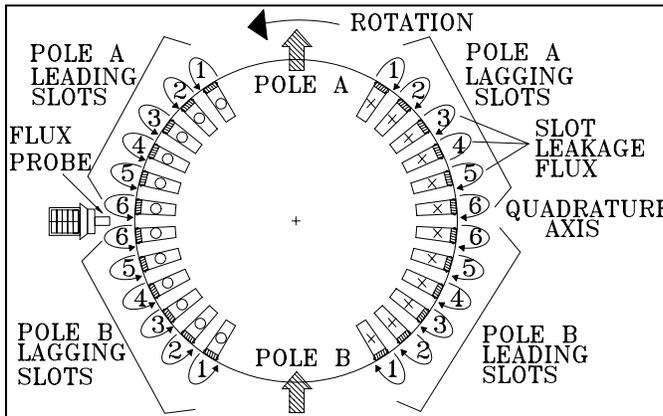
FIGURE 1 – Two-pole rotor with 6 coils/pole showing the rotor coil and slot nomenclature.
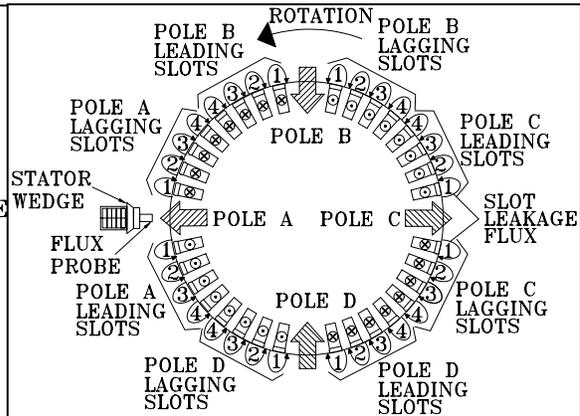
FIGURE 2 – Four-pole rotor with 4 coils/pole showing the rotor coil and slot nomenclature.

Shorted-turns in coils near the quadrature axis in 2-pole rotors will have little effect on thermal sensitive balance because the effected slots are nearly 180° apart (**FIGURE 1**). Shorted-turns in the small coils (1, 2 or 3) of one pole will have a greater effect in causing rotor unbalance problems since the asymmetrical location will result in a larger rotor temperature gradient.

Shorted turns in 4-pole rotors will also act to produce a thermal gradient (**FIGURE 2**). However, since 4-pole rotors tend to be stiffer than 2-pole rotors, thermal gradients tend to be less effective in producing rotor bowing.

2. Rotor / Stator vibration due to unbalanced magnetic force.

Shorted-turns in 4-pole rotors can also cause unbalanced magnetic forces. Shorted turns in 2-pole rotors do not generally cause an unbalanced magnetic force since the reduction in magnetic flux will affect both the north and south poles equally. In 4-pole rotors, however, shorted turns in one pole will reduce the flux generated for the pole and to a lesser extent the adjacent poles, but will have no effect on the opposite pole. The resulting unbalanced radial magnetic pull between the rotor and stator can cause vibrations. The vibrations would effect both the rotor and stator at a frequency of once per revolution.

3. Higher field current is required than previously experienced at a specific load.

When shorted-turns occur, higher field current is required to maintain a specific load. This is because the same rotor amp-turns must be generated with fewer active turns. Excitation capacity may limit load if greater than 5-10% of the field winding is shorted out. Decreased efficiency will result in any case.

The *Amp vs. Field-Turn* relationship is $A_S = A_N T_N / T_S$, where A_S and T_S are the field current and active turns in a rotor with shorted-turns and A_N and T_N are the same in a rotor with no shorted-turns. The field winding loss (I^2R) at a specific load can be determined by noting that the resistance of the field winding will decrease by T_S/T_N, but the I^2 component increases by $(T_N/T_S)^2$. This results in an increase in the field winding loss of (T_N/T_S) for a specific load.

For example, a rotor with 2 turn shorts out of 100 (T_N/T_S = 100/98 = 1.02) will increase the field losses by 2%.

4. Higher field currents result in higher operating temperatures.

The higher field currents required to maintain a given load will result in an increase in I^2R loss for the entire rotor winding. As a result of this higher I^2R loss, the total heat generated by the field will be increased when compared to operating at the same load factors without shorted turns. However, units which make use of Volts/Amp field temperature instrumentation will falsely indicate lower operating temperatures after the onset of shorted turns. This is a result of the instrumentation algorithm used to calculate field temperature assuming a constant field resistance at any given temperature. In fact, shorted turns will reduce the total field resistance, which will be interpreted by the instrumentation as a drop in temperature.

Winding temperature rise above cold gas is proportional to I^2. As an example, two turns shorted out of a total of 100 turns will result in a 4% higher hot-spot rise over cold gas. **TABLE 1** shows an example at full load for a rotor with 2% and 10% shorted-turns.

e.g., Hot spot rise for 2 shorted turns out of a 100 = 84° C * $(1 + 2/100)^2$ = 87.4° C

TABLE 1			
	No turn shorts	2% shorted-turns	10% shorted-turns
Cold gas	**46° C**	**46.0° C**	**46.0° C**
Hot spot rise	**84° C**	**87.4° C**	**101.6° C**
Hot spot	**130° C**	**133.5° C**	**147.6° C**

Although field current comparisons at known load points can provide an indication of shorted-turns (though not their locations), generators which use rotating rectifier excitation systems may have no direct

readings of field volts or current. On these units, impedance tests and V/A field temperature test data can not be used to provide an indication of shorted turns. Air-gap flux probe testing can provide definitive online shorted turn detection results on these units.

CAUSES OF SHORTED TURNS IN ROTOR WINDINGS

Shorted turns are usually the result of failed insulation between individual windings in a rotor. As units age, shorted turn problems are more likely to be experienced. The stresses involved in each stop-start cycle play an especially important role in the development of shorted turns. However, newly rewound fields have also been shown, on occasion, to have shorted turns.

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 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. However, effective frictional forces exist when the rotor is at speed that counters the thermal expansion of the copper. Thermal expansion of a slot's center copper when the copper near the slot's ends is locked in place by friction will create a compressive force for the center copper. If the compressive strength of the rotor winding is exceeded, the copper in the slot can become deformed. When the rotor is stopped and allowed to cool down, 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 an extreme case, coil foreshortening was 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. As a rotor is brought up to normal running speed and temperature, the diameter of the retaining rings will increase. The surface between the end-strap top turns and the ring insulation must provide a slip plane that will limit the tensile stress imposed on the top turn end-straps. If the coefficient of friction becomes too great, 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 was insufficient or shifted during operation, movement of the end-turns has caused misalignment that gave rise to shorted turns.

SHORTED TURN CHARACTERISTICS

The establishment of a shorted turn may initially result in a partial turn short. However, calculations of the heat produced by the higher resistance of a partial shorted turn contact suggest that this condition cannot be maintained for long. **FIGURE 3** shows the KW loss for one turn of a 1500-KW field with 100 total turns that has been paralleled with varying percentages of a short circuit. Even at the level of a 10% shorted turn, the KW loss at the shorted turn contact is 1.35-KW. This amount of heat produced at a small contact point can easily exceed the melting point of the copper to produce a low resistance spot weld. The creation of a low resistance contact (full turn short) between turns will reduce the total KW loss for the

turn to near zero. Depending upon the location of the coil with the shorted turn, a rotor temperature gradient may develop that could give rise to a rotor bow.

A low resistance spot weld developed during operation may not survive any turn-to-turn movement that results when the unit is brought down. This can prevent the detection of a shorted turn condition at standstill that existed when the rotor was at speed. Additionally, the development of a copper oxide coating over the broken surfaces of the previous spot weld may prevent the reformation of the turn short when the unit is restarted. Thus, it is possible for turn shorts to heal themselves. However, during the next few start-stop cycles, turn-to-turn movement may alter the turn alignment in such a way to favor reestablishment of the turn-to-turn contact. Online 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.
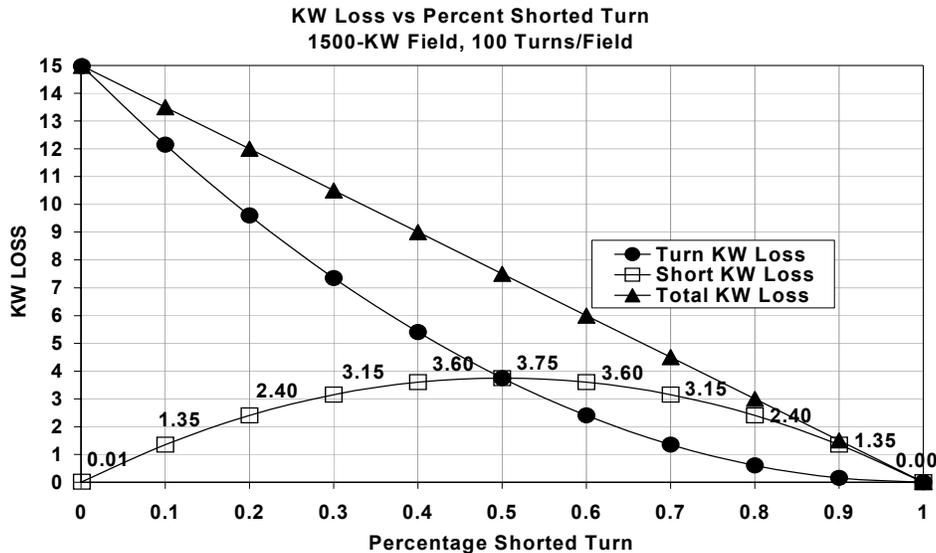

FIGURE 3 – Effect of a partial shorted turn on KW loss of one coil turn.

DETECTING ROTOR WINDING SHORTED TURNS USING FLUX PROBE MEASUREMENTS

In order to discuss the method of detecting shorted turns using an air-gap magnetic flux probe, it is useful to define some terms describing the source of magnetic fluxes that exist in the air-gap.

- **Main Rotor Flux:** flux that **crosses the air gap** resulting from current through the rotor field windings.
- **Stator Reaction Flux:** the armature reaction flux due to current flowing through the stator armature windings. This flux depends on the magnitude of the stator current and will be a minimum for a stator open-circuit condition and a maximum for a stator short-circuit condition.
- **Rotor Slot Leakage Flux:** 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 and is therefore diagnostic of active turns in each slot.
- **Air-gap Flux Density:** combination of all three of the above fluxes in the generator air-gap.

Detection of the **Rotor Slot Leakage Flux** is accomplished using a magnetic flux probe positioned in the air-gap of the generator. A single flux probe is generally mounted on a stator wedge in a position to be over a continuous ring of non-magnetic rotor wedges. Magnetic rotor wedges can significantly reduce flux probe sensitivity by shunting the slot leakage flux through the magnetic wedge. The flux probe cable is

routed out of the stator core, through the stator end-windings and out to the generator casing. A gland that provides a gas tight penetration for the flux probe cable is welded to the outside of the generator casing. An analysis system is used to record flux probe waveforms by connecting to the casing gland BNC connector using a length of coaxial cable.

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. The flux probe waveform displays a peak for each rotor slot (see **FIGURE 4**). 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 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 calculate the presence of symmetric shorted turns (same coil in all poles) requires comparison to a base set of data recorded before the development of the shorted turns.
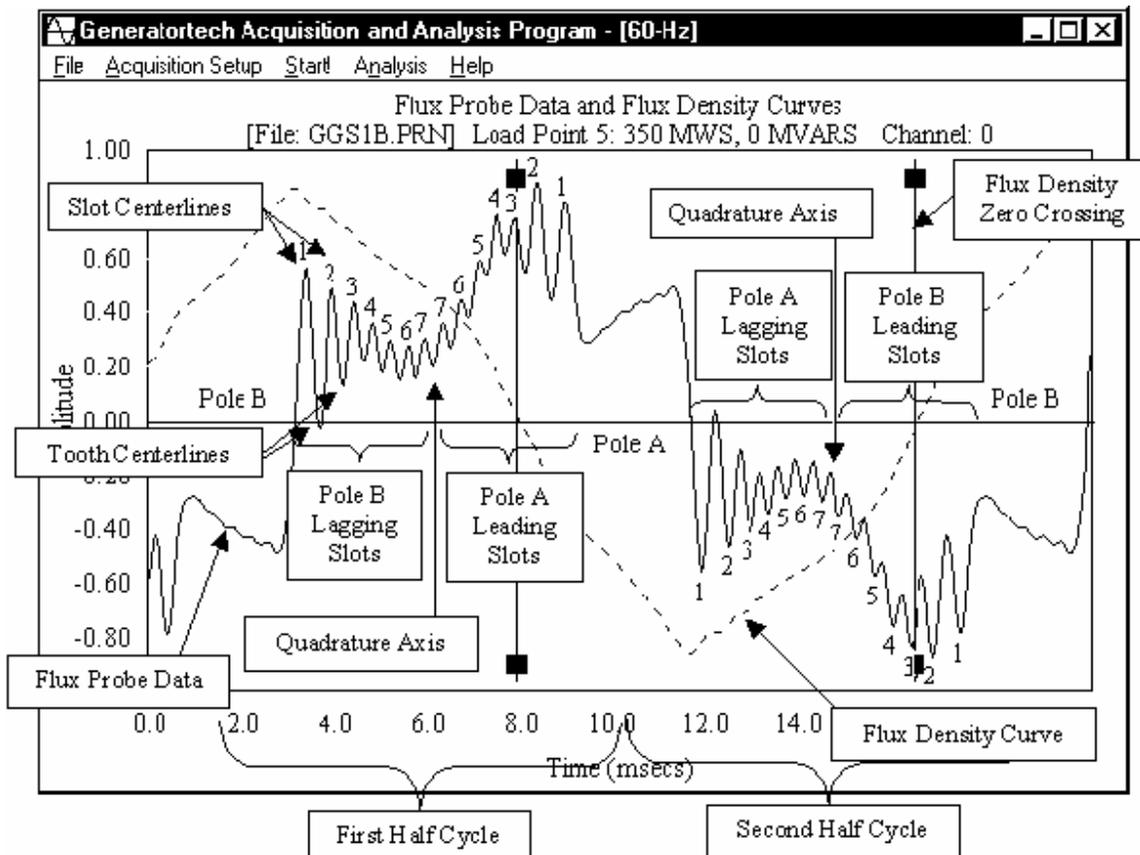
FIGURE 4 – Flux probe data for a 7 coil/pole rotor illustrating important nomenclature

A confounding factor in the analysis of shorted turns is that the slot peak magnitudes in the flux probe waveform are not a simple function of the magnitude of the slot leakage flux. Modulation of the air-gap flux density by the higher reluctance found in the rotor slots acts to increase the magnitude of the slot peak heights. In addition, the rotor iron flux can saturate at higher flux densities which will reduce the rotor slot flux signal. This modulation and saturation effects vary with the magnitude of the flux density and is at a minimum where the flux density is zero. To determine the point of maximum sensitivity, the flux density curve can be obtained through integration of flux probe waveform (see **FIGURE 4**). The point at which the flux density curve passes through zero marks the position on the flux probe waveform of maximum sensitivity for detecting shorted turns, since it is here that the slot peak magnitude is almost entirely due to that slot's leakage flux. Any particular waveform will have a maximum sensitivity for detecting shorted turns at only that one point.

TESTING PROCEDURES

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 flux density curve zero-crossing (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 towards the #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 #1 leading coil slot. Reactive 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% of the turns in a coil are shorted out, the pole's coil slot peak would be expected to decrease by approximately 10%. This is only true when the FDZC is aligned with the effected 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.

Software and hardware has been developed to automate the analysis of the flux probe waveforms for indications of shorted turns. The hardware consists of a notebook computer, a PC-Card analog-to-digital converter card and a Signal Conditioner. The analog-to-digital converter card is used to digitize the flux probe waveform. A second channel is available for recording a Once/Rev (Keyphasor) signal. The Once/Rev signal is used to identify the physical pole to which a coil with shorted turns belongs. For four-pole rotors, the Once/Rev signal is used to trigger the A/D acquisition to insure that the waveform starts at the same pole each time.

A Microsoft Windows™ based software program controls the recording of the flux probe signal and automates the shorted turn analysis of the waveforms. Each waveform in the test set is scanned to extract the location of features that allow for the automatic identification of each rotor slot peak. The magnitudes of each rotor slot peak are calculated and are used to perform a pole-to-pole comparison to identify the location and number of shorted turns in each coil. The flux density curve is calculated by integrating the flux probe signal and the curve's zero-crossing points are noted. The immediate availability of the FDZC location allows the operator to determine whether additional MWS or MVARS adjustments should be made to increase sensitivity for a particular coil.
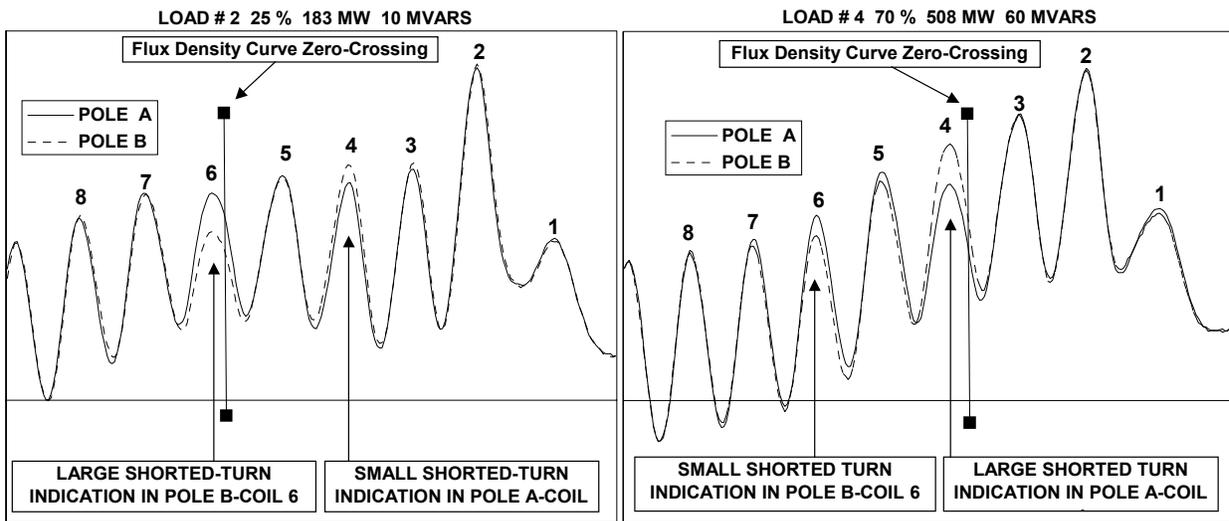
CASE STUDIES

Hundreds of air-gap flux probes are installed in generators around the world. The accumulated data sets have demonstrated a large variety of rotor shorted turn conditions.

CASE 1

The first case study illustrates the effects of the flux density curve zero-crossing (FDZC) on shorted turn detection sensitivity. **FIGURE 5** displays two lead slot overlay graphs for a two-pole rotor with 1 shorted turn in both Pole A-Coil 4 and Pole B-Coil 6. The left graph is at 25% 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, however, the shorted turn indication for Pole A-Coil 4 is quite small. The right graph is at 70% 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 5** also show the effect of the use of magnetic rotor wedges. The #1 coil slots made use of magnetic wedges in this rotor. As can be seen in the graph, the #1 coil peaks are much reduced in amplitude relative to the other coil slot peaks.

FIGURE 5 –Flux Density Curve Zero-Crossing Position affect on shorted turn detection sensitivity. The rotor had 1 turn short in Pole A-Coil 4 and Pole B-Coil 6. Each coil has 6 total turns.

CASE 2

The second case study presents a two-pole rotor with 7 coils/pole in which coils 6 and 7 of one pole were shorted out of the field circuit. This result occurred when the top turns of coils 6 and 7 on one pole became shorted together. **FIGURE 6** 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
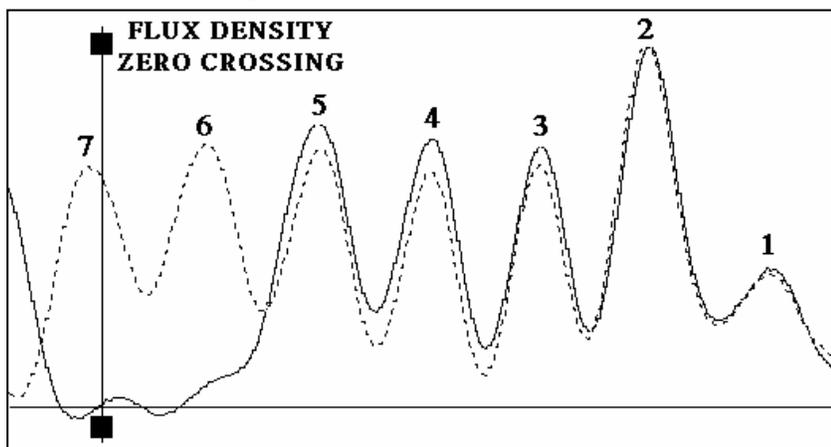
FIGURE 6 – Overlay of lead slot data showing coils 6 and 7 of one pole completely shorted out of the circuit.

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 1 or 2 complete coils. Additionally, three other units, without flux probes, were found to have two coil shorts that were identified by inspection during disassembly.

SUMMARY

Shorted turn detection technology provides the ability to define the location and number of shorted turns in a rotor winding while the generator remains online. This information can assist your plant operators and engineers in making major maintenance decisions about when and whether to perform rotor service.

The online testing discussed in this paper is a significant extension of the stator short circuit testing technique that was described in a 1970 IEEE paper[2]. Stator short circuit testing at a power plant has been considered to be difficult to setup and potentially dangerous to perform.

Air-gap flux probe testing of generator rotors has proved itself to be a highly reliable test for detecting shorted turns. Disassembly and inspection of rotor windings has confirmed the location and number of shorted turns that were indicated during flux probe tests.

The use of shorted turn detection technology can also be used to verify the quality of newly rewound rotors. Several companies have been able to obtain warranty service on problems that were revealed using flux probe testing. Service companies that perform rotor rewinds have begun to use flux probe testing in their spin pits in order to confirm the absence of shorted turns before shipping the rotor. Importantly, shorted turns that only appear at speed have been detected through the use of flux probe tests in the spin pit[3].

Periodic monitoring of rotors for shorted turns (once or twice per year) is recommended to catch any changes in the rotor winding insulation condition. Also, if rotor balance or field excitation requirements change, flux probe testing should be used to confirm whether the changes are the result of new shorted turns. Recording a data set just before and after a shutdown is often done to assess the need for and the success of rotor winding repairs.

Obtaining a baseline set of data before the development of any shorted turns significantly increases the sensitivity of future tests. Since the development of symmetric shorted turns can not be detected using a single set of load data, comparison with a baseline set of data is required to detect symmetric shorted turns.

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