

## Using Magnetic Flux Monitoring to Detect Hydrogenerator Rotor Winding Insulation Problems

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### ABSTRACT

*The rotor windings of hydrogenerators are usually very reliable. However, the turn insulation in such machines will eventually degrade and puncture due to thermal aging, load cycling and/or contamination. Although turn shorts do not directly lead to machine failure, they can lead to high bearing vibration and may limit real and reactive power output. While off-line tests such as the “pole drop test” are available to detect rotor winding shorted turns, they are often unreliable since the rotor is not spinning for the test and the shorts may disappear (or vice versa). Forty years ago, an on-line test to detect shorted turns was developed where the leakage magnetic flux is measured in the generator airgap and the data processed to detect shorted turns. This test was valid only for round rotors, typical of 2 or 4 pole turbine generators. With funding from the US Electric Power Research Institute (EPRI), a new type of magnetic flux test has been developed that is suitable for salient pole rotors in hydrogenerators. The test requires retrofitting a small magnetic flux probe to the stator core. This paper will describe the failure processes of rotor winding insulation. The new flux technology and its application to hydrogenerator rotors will then be presented.*

### Introduction

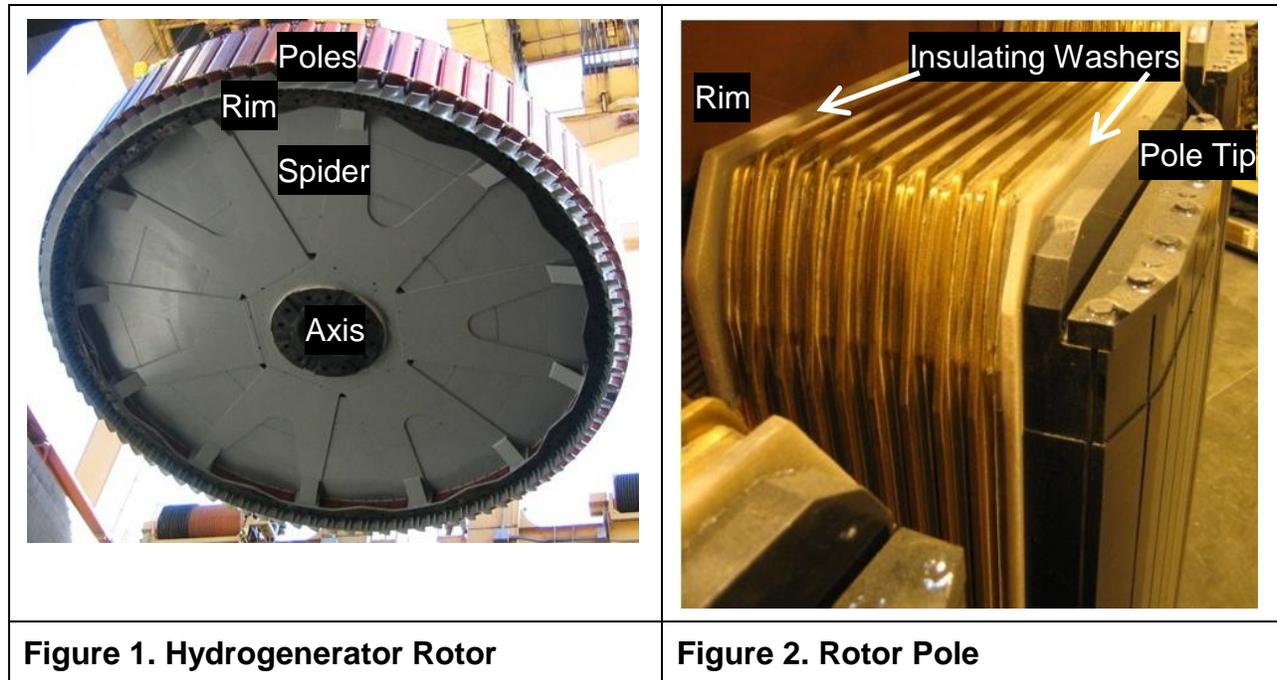
The increasing use of predictive maintenance requires tools for on-line condition monitoring. Flux monitoring is one tool that has been successfully applied in synchronous machines with round rotors, for rotor shorted turn detection. This paper presents an enhanced technology developed with support from EPRI for on-line flux monitoring to detect shorted turns in hydrogenerators and other salient pole machines.

First, the most common failure mechanisms of rotor winding insulation in hydrogenerators are listed, then a contrast between on-line and off-line tests for rotor winding, and finally the solution with the new flux monitoring system are presented, with special emphasis on the continuous monitoring application.

### Rotor Winding Failure Mechanisms

The pole pairs in the rotor periphery (**Figure 1**) act as fixed North and South magnets. The required Ampere-turns (AT) are produced by the dc excitation current circulating through the turns of the pole windings, connected in series. In large generators, the turns are made from strips of copper, either, rectangular pieces joined together, in the Picture Frame style (common in newer machines), or a continuous strip bent at the corners, in the Edge-Wise style. For both styles, in modern designs, the insulation

between turns is usually made of Nomex™ strips bonded to the copper by a thermosetting resin, and the copper edges are exposed. The pole tip side of the winding has an insulating washer and the rim side of the winding may have either an insulating washer (**Figure 2**) or insulating blocks.



The rotor winding insulation is exposed to stresses including:

- ❖ Thermal aging. The materials most susceptible to thermal degradation are organic bonding and backing materials, especially those in hot spots. The most common causes are: operating temperatures higher than design values due to overloading or high air temperatures; inadequate cooling due to poor design, manufacturing, or maintenance procedures; use of material with inadequate thermal properties; overexcitation for long periods; and circulating rotor currents caused by negative sequence stator currents during system voltage imbalance.
- ❖ Thermal cycling. Too-rapid or too-frequent load cycling for the design may cause the cracking of the insulation bonding leading to increased looseness and abrasion. Windings may become distorted when restrained from returning to their cold position.
- ❖ Pollution (tracking and moisture absorption). Exposed copper edges are most affected by conducting contaminants such as moisture (e.g. condensation), coal dust and oil dust mixtures, leading to turn failures and ground faults. Chemicals may attack the insulation.
- ❖ Abrasive particles. Cooling air with abrasive materials such as dust from brake pads may erode the insulation.
- ❖ Centrifugal force. This force at normal speed may tend to distort the coils and therefore crack their insulation. Both speed changes and inadvertent overspeed impose additional stresses to the insulation components.

- ❖ Repetitive voltage surges. Predominantly turn failures may be produced in weak insulation by transient voltages from system faults, faulty synchronization, asynchronous operation or static excitation spikes.

## Rotor Winding Tests

Depending on when tests are performed, there are on-line and off-line tests available (Table 1)

**Table 1. On-line vs. Off-line Tests [1]**

| On-line Tests  | Off-line Tests  |
|--|---|
| <p>Tests such as: bearing vibration monitoring, air gap monitoring, flux monitoring</p> <p>Require initial investment since at least sensors must be permanently installed in order to perform tests in normal operation.</p> <p>Performed during normal operation, so low cost</p> <p>With continuous monitoring, may be automated to generate remote alert</p> <p>As predictive maintenance tool, help to decide on maintenance scheduling</p> <p>Correspond to the real conditions present during the operation and affecting normal operation such as vibration and centrifugal forces from the rotation, operation temperature, and operation voltages</p> <p>Do not add any stress</p> <p>Fast</p> | <p>Tests such as: visual inspection, insulation resistance, polarization index, dc high potential, ac high potential, open circuit, impedance test, pole drop, surge test</p> <p>No initial investment</p> <p>Require at least an outage, so imply revenue loss</p> <p>Labor intensive. Some require partial disassembling</p> <p>May confirm and help to locate a specific source of a problem (e.g. visual inspection)</p> <p>May find issues that do not affect normal operation and may not find issues that appear only in normal operating conditions</p> <p>May be destructive (pass, no-pass)</p> <p>May be time consuming for high pole number (e.g. pole drop test)</p> |

## New Flux Monitoring System

Flux monitoring is an on-line test for the rotor winding of synchronous machines originally developed by GE over 40 years ago [1]. The test was intended for round rotor machines that have windings with coils distributed in pole slots (such as 2 or 4 pole turbogenerators). During normal machine operation, the flux from each passing pole induces a voltage  $e$  in a flux probe, here called conventional flux probe, or CFP.

$$e \propto NA \frac{d\phi}{dt}$$

$e$ = induced voltage

$N$ = number of turns

$A$ = average turn cross sectional area

$d\phi/dt$  = magnetic flux change rate

The CFP is fixed on a stator wedge, at the turbine end, at 10 or 2 o'clock position of the turbogenerator, avoiding magnetic segments of rotor wedges. The flux contribution of each coil is reflected as a peak in the induced voltage  $e$  when passing an individual pole slot. By symmetry, in absence of shorted turns, the absolute peaks of  $e$ , from corresponding slots in a pole pair, must be similar. A difference between those peaks will indicate shorted turns.

The conventional flux monitoring system has been enhanced to be used in hydrogenerators and other salient pole machines. The new system has a flux probe called TFProbe™ wired to a termination box, and an instrument called either RFA//™ in the portable version for periodic monitoring or FluxTrac//™ in the permanent installed version for continuous monitoring.

### ❖ Flux Probe

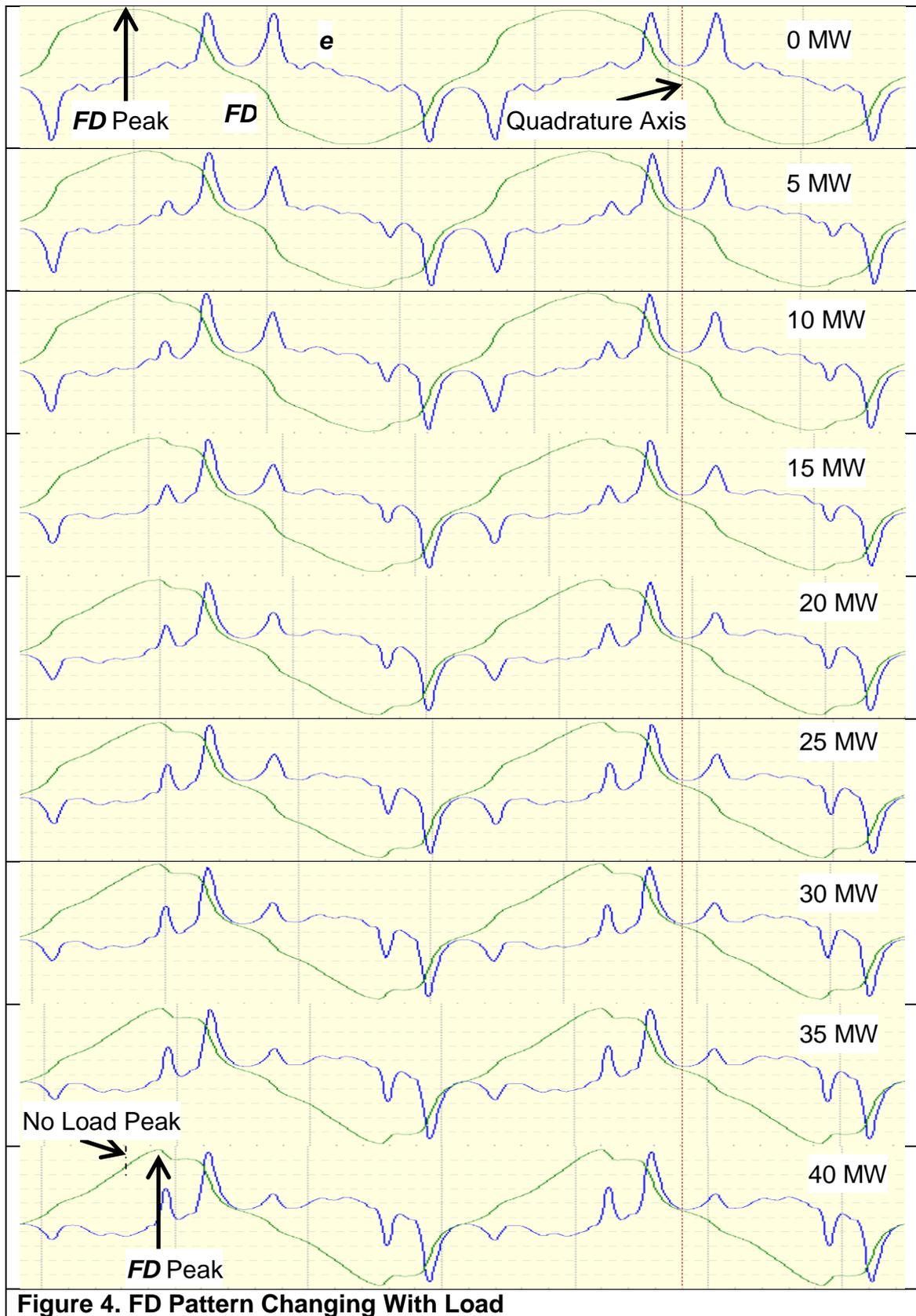
The new flux probe is glued on a stator core tooth to measure the main (total) flux form each rotor pole as it passes (**Figure 3**). One probe is required per machine.



**Figure 3. Flux probe installed in core tooth**

Some features of the probe include:

- ✓ Developed by the US Bureau of Reclamation [2,3]
- ✓ Coil is a printed circuit board with conductive turns on one side of a flexible material [3]
- ✓ Flat, thin, light probe. Suitable for small airgap size machines such as hydrogenerators
- ✓ Low profile presents minimal resistance to windage generated by rotating rotor
- ✓ Glued on a stator core tooth
- ✓ May be installed with rotor in place provided that spacing between poles is at least twice the stator slot pitch. Alternatively, a rotor pole may be removed
- ✓ It is used in conjunction with a sync sensor, a proximity switch that provides a once-per-revolution signal when it detects a target on the machine shaft (e.g. a small square with epoxy). The sync sensor is used to locate shorted poles, which is important in case of high number of poles. For motor-generators used in pumping stations, three targets may be used to get the type of operation (direction of rotation).



**Figure 4. FD Pattern Changing With Load**

❖ **Instrument**

Both the portable instrument and the continuous monitor are based on a custom designed field programmable gate array allowing fast data acquisition at a very high sampling rate. The instrument integrates the induced voltage  $e$  to get back a signal proportional to the magnetic flux  $\phi$ , and therefore proportional to the flux density (magnetic flux per unit area, or  $FD$ ).

$$FD \propto \int e dt$$

$FD$  = flux density

$e$  = flux probe signal (induced voltage)

When the load changes, the flux density pattern changes, as shown for a generator in **Figure 4** (symmetrical signals without load become unsymmetrical with load). Because the salient pole machine winding has only one coil per pole, instead of the peaks of  $e$  (as done in round rotor machine analysis for individual slots), the  $FD$  peak value for each pole is used for comparison, to find shorted turns.



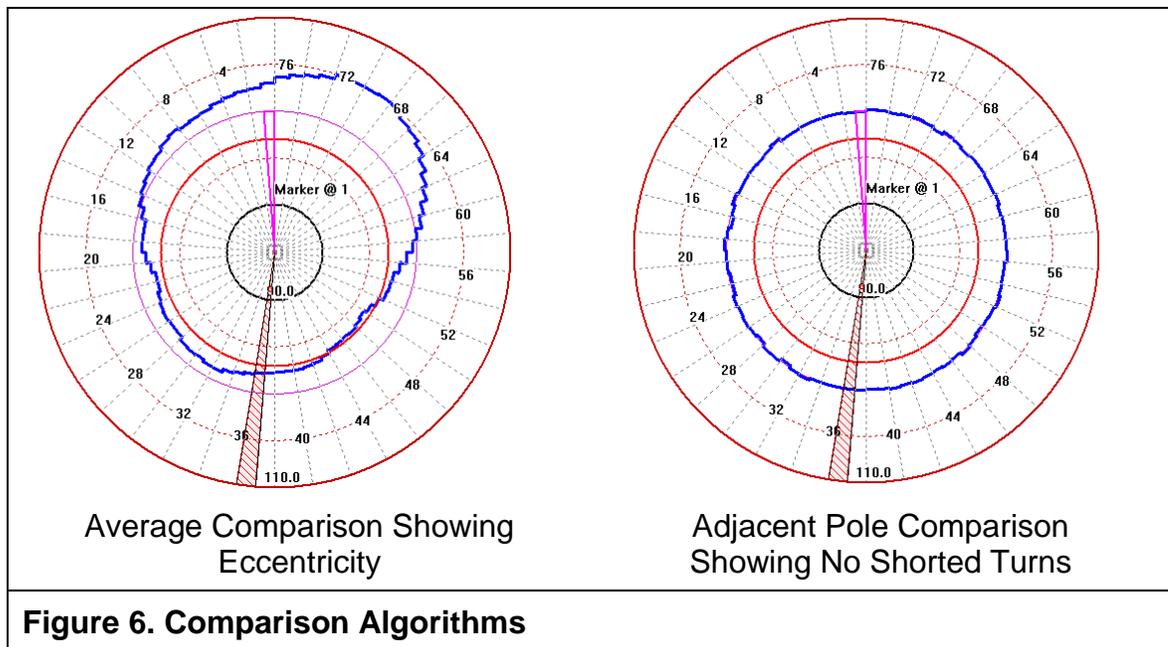
**Figure 5. Sync Sensor**

The instrument uses a Sync sensor (**Figure 5**), a proximity switch that provides a once-per-revolution signal when it detects a target on the machine shaft. The Sync sensor information allows fast location of the shorted poles relative to the target. In case of motor-generators in pumping stations, the instrument may recognize the operation mode by detecting the rotation direction with the Sync sensor and three targets in the shaft ( $0^\circ$ ,  $60^\circ$ , and  $180^\circ$ ).

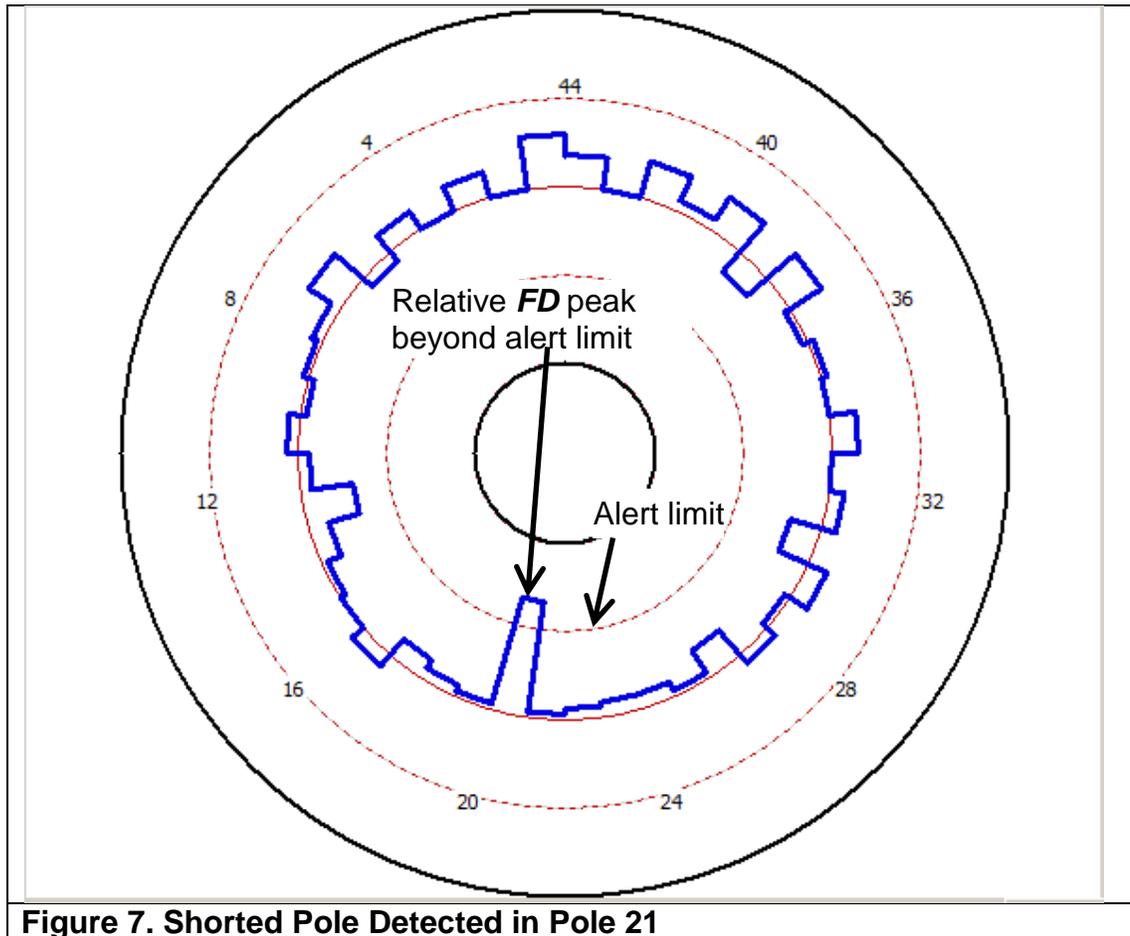
The portable instrument covers most of the flux testing needs allowing manual testing and stand-alone operation based on time, and upon selection, avoiding saving tests with repeated **FD** pattern [4]. However, in some cases, additional monitoring capabilities may be required such as alerts when shorted turns are detected, remote communication for automation and supervision, data transfer for third party on-line applications, access to test results at any moment, or avoiding visits to plants due to safety or security concerns. For those cases, the continuous monitor, permanently connected, is recommended.

❖ **Software**

The software allows data downloading, displaying, and further analysis. In addition to shorted turns, other factors affect the magnetic field from each pole, such as: airgap size change, rotor out-of-round or off-centre, loose pole – key migration, stator migration, and natural variations of pole's physical position. The software allows calculation, and tabular and graph display of relative values of the **FD** peaks for further analysis with respect to the following values: average, adjacent pole, and average with poles of the same sign. **Figure 6** shows, for a machine without shorted turns, two different comparisons: average and adjacent. The average graph shows clearly the eccentricity. In these plots the radial direction is proportional to flux density and the circumferential direction is the rotor pole number.



**Figure 7** shows in an adjacent view, a shorted turn in pole 21 with its relative **FD** peak beyond the limit value for alert.



## Conclusion

Flux monitoring has proven to be a suitable tool for rotor shorted turn detection in synchronous machines. The on-line tests of rotor windings, including flux monitoring, are an attractive solution for hydrogenerator rotor testing. However, due to the small airgap size and rotor construction, hydrogenerators and salient pole machines in general require different flux probes and different analyzing algorithms.

The new flux monitoring system detects shorted turns in hydrogenerators while being immune to false indications caused by air gap problems.

## References

1. G.C. Stone, A. Boulter, I. Culbert, H. Dhirani, "Electrical Insulation for Rotating Machines", IEEE Press-Wiley, Jan. 2004.
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