FLUX MONITORING IMPROVEMENT

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For online condition monitoring of turbine generator rotors

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FLUX MONITORING VIA AIR GAP flux probes is a proven technology used for many years in synchronous machines to determine the presence of turn-to-turn shorts in a rotor winding. This information is critical in planning maintenance outages and augmenting online vibration analysis. Traditionally, flux measurements are done using flux probes installed on a stator wedge and a portable or permanently connected instrument. To achieve a reliable diagnostic, the signals from the flux probe had to be measured under different generator load conditions ranging from no to full load. This requirement presented a serious obstacle in the application of this method on base load units where load adjustments are difficult. A new design of the flux probe, installed on a stator tooth, and a novel approach in algorithms used to analyze measurements can help minimize the need for tests at different load conditions and still provide reliable diagnostics. This article describes the implementation of new hardware and

Digital Object Identifier 10.1109/MIAS.2010.939656
Date of publication: 28 June 2011

1077-2618/11/$26.00©2011 IEEE

software and case studies that demonstrate the effectiveness of the new method in eliminating the need for load maneuvering.

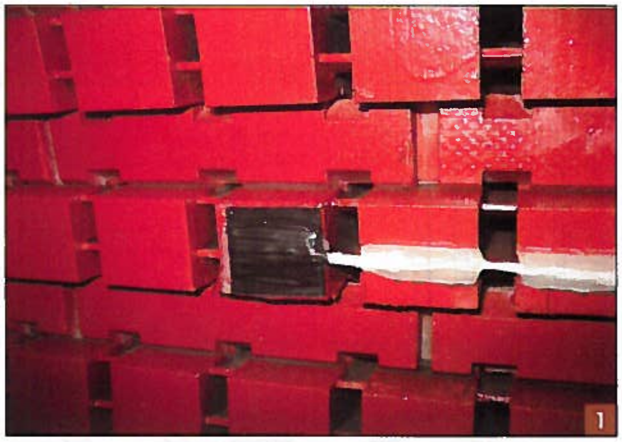
Turbine Generator Rotors

A turbine generator rotor consists of a solid forging made from magnetic alloy steel and copper windings, assembled in slots machined in the forging. The winding is secured in slots by steel, bronze, or aluminum wedges. At each end of the rotor, sections of the rotor winding are supported by retaining the rings. Modern rotor winding insulations are made from epoxy/polyester glass/Nomex laminate strips and channels. The strips are used to provide interturn insulation and the molded channels for ground insulation. The rotor insulation should be designed in a way such that it withstands electrical, mechanical, thermal, and environmental stresses. Shorted turns are the result of failed insulation between rotor turns and a relatively common occurrence in large turbine generators. Major causes of shorted turns in rotor windings are contamination with conductive debris and turn-to-turn movement of the rotor windings caused by high centrifugal loads and axial thermal expansion forces. The condition of the rotor winding insulation is difficult to assess during a shutdown due to limited access and the frequently intermittent nature of faults during the operation versus at standstill. Consequently, online testing is an effective way to detect and locate shorted turns during the operation that can then be repaired during scheduled outages.

Flux monitoring using temporary or permanently installed flux probes has been used since the early 1970s [1]. Flux measurements are done to determine the existence of turn-to-turn shorts in the rotor winding. All the methods available are based on the measurement of the relatively weak stray flux (rotor slot leakage flux) using flexible or nonflexible polymer-encased stator-wedge-mounted probes [2]–[4]. The stray flux from each rotor slot is proportional to the total ampere turns in each slot. If shorts develop between the turns, then the ampere turns in that slot drop, and the stray flux is reduced. The magnitudes of these stray fluxes can be measured using portable or permanently installed instruments, and shorted turns can be identified by comparing the difference in the induced voltages from one pole to another. The main challenge in earlier technologies is the need to maneuver the generating unit load to achieve the maximum sensitivity to shorted turns in every slot of a rotor. Other problems in diagnosing turn-to-turn shorts are related to both the type of the probe and the instrumentation/algorithms used for the detection of shorted turns [2]–[4].

Total Flux Probe Design

Some limitations of existing probe designs are related to their design and installation methods. Commercially available leakage flux probes typically consist of a custom-wound wire coil on a flexible mount or encapsulated in an epoxy body [5]. Such probes typically include a solid ground plane shield, producing eddy currents when exposed to strong magnetic fields present in the air gap of a rotating machine. These eddy currents may interfere with stray flux measurements. Another disadvantage of the existing flux probe designs is that these designs can be displaced under high wind forces generated in the air gap, due to their mass and size, or can be damaged during rotor insertion after major outages.



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New probe designs mounted on a stator core tooth. (Photo courtesy of Iris Power LP.)

To minimize risks associated with this, some flux probe manufacturers require that wedges where a flux probe will be installed to be drilled and support dowels installed. This operation may affect mechanical properties of the wedge and is highly invasive to the machine. More current probe designs are able to overcome disadvantages of the existing designs. The new design probes are composed of a number of printed circuit layers, configured on a flexible base material. The flexible probe is designed for applications on a stator tooth (Figure 1). The new probe directly measures the main magnetic flux since it is mounted on the steel core tooth, rather than on a wedge.

New Flux Measurements

Along with the more current design of the probe, a second generation of electronics and interpretation software has been developed. The software and electronics are available for both salient pole and round rotor machines. The instrument is equipped with inputs for different types of flux probes, and three different synchronization methods are possible: using a dedicated synchronization shaft-mounted marker, internally to ac power input, or externally to any other ac signal in the 40–240 V range. This key-phasor

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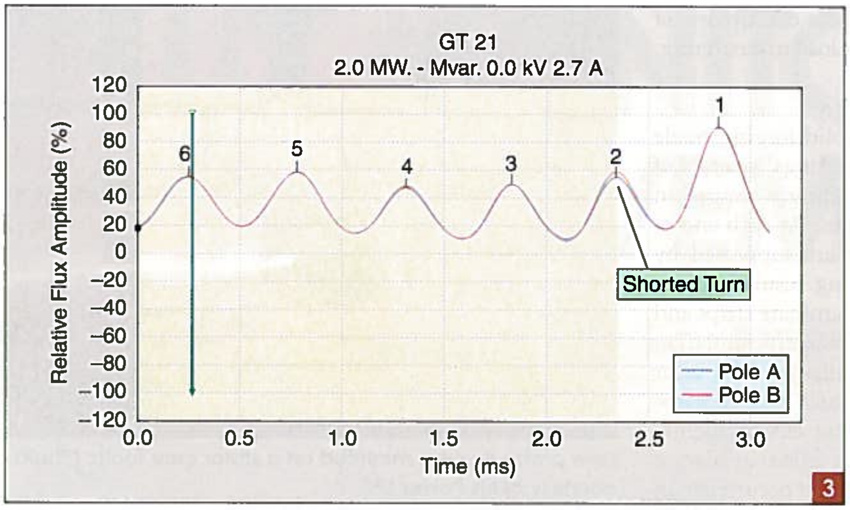
A portable rotor flux analyzer. (Photo courtesy of Iris Power LP.)



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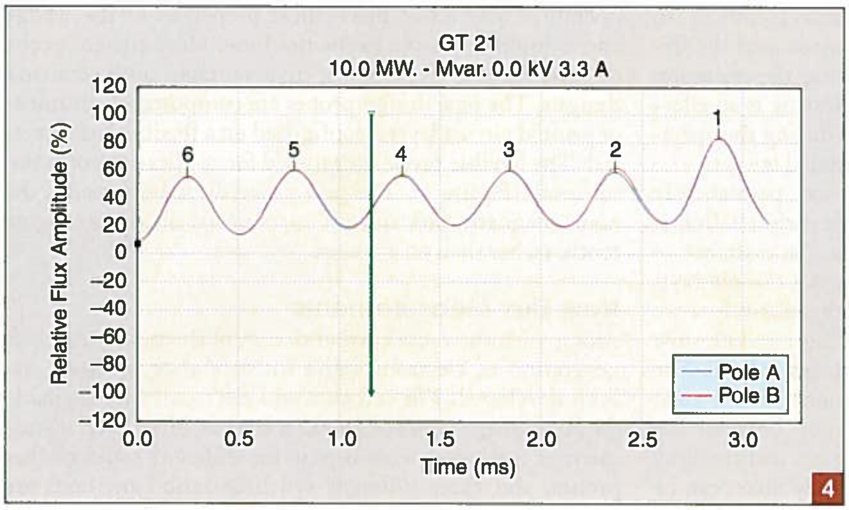
The plot shows a comparison of the leading pole flux signals. The *X* axis is the time, and the *Y* axis is the normalized flux in percent. The FDZC is close to coil 6 (green line), and a short is detected in coil 2.



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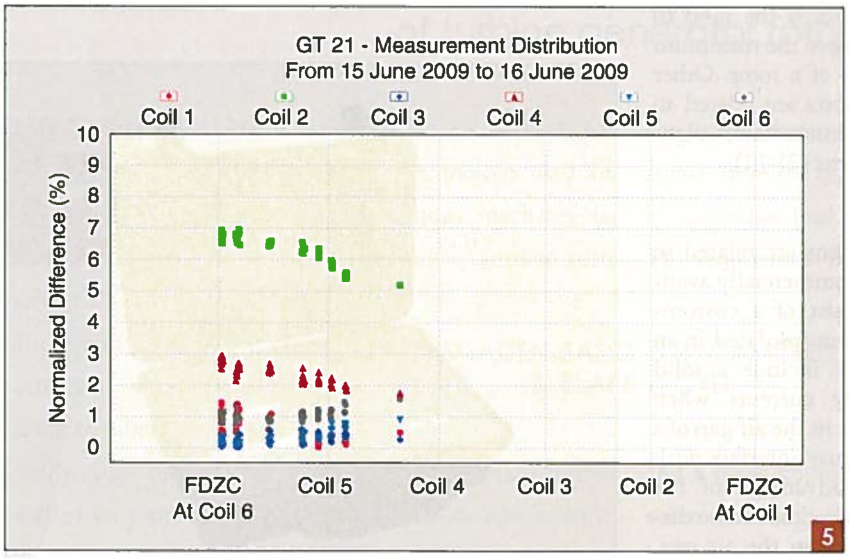
A comparison of pole A to pole B, 10-MW load test. The *X* axis is the time, and *Y* axis is the flux in percent.



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The *X* axis is the FDZC position on the rotor, and the *Y* axis is the normalized flux difference from pole A to pole B.

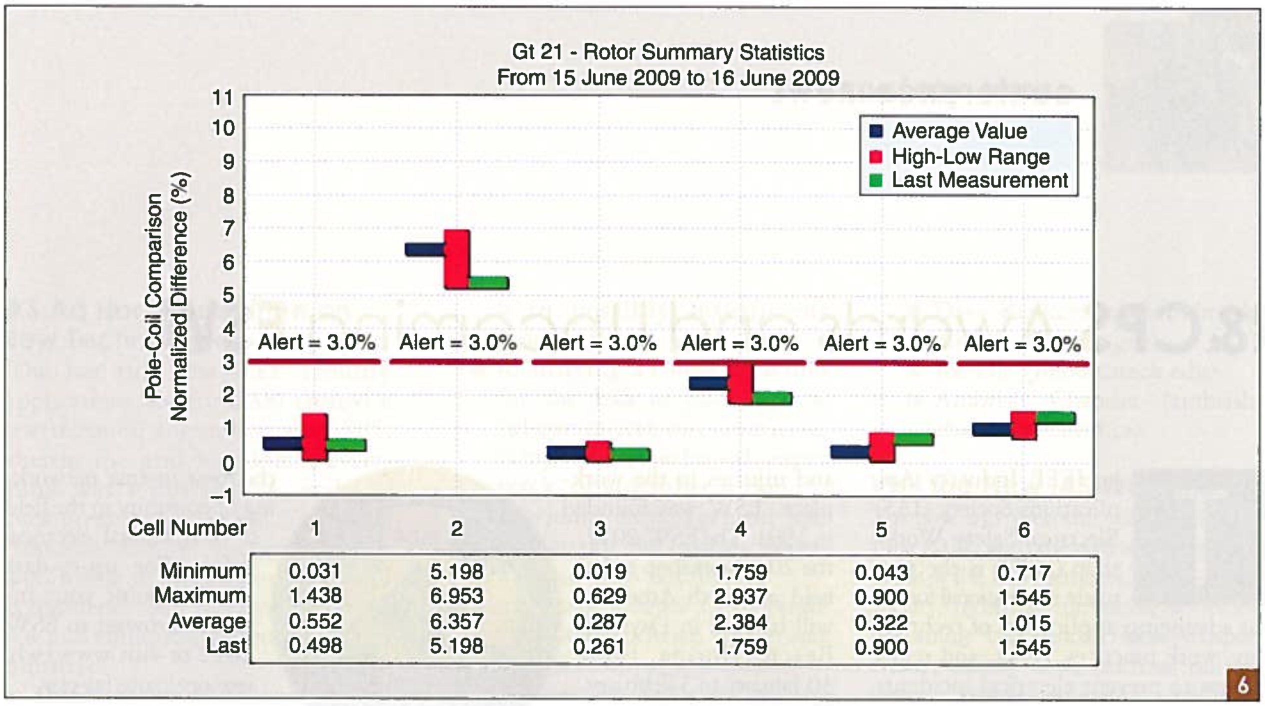
signal is used to locate the shorted pole for repair. Both portable and continuous flux monitoring instruments can be applied. The electronics is similar in both and is based on a custom-designed field programmable gate array-based circuit capable of fast data acquisition at a high sampling rate. This sampling rate enabled the use of new algorithms for the detection of shorted turns. Different communication protocols [Universal Serial Bus (USB) or Ethernet] can be used for connection to a PC. Time-based measurements can be used to collect data in user-specified time intervals, as short as one measurement every 5 s. This method is very useful to collect different load data automatically at different loads during fast load changes (Figure 2).

All collected measurements are stored in the instrument's internal memory and can be downloaded to a Microsoft Access data base, consisting of a number of folders representing stations and machines tested. Although different acquisition methods are enabled, unlike with traditionally used techniques, the instrument measurements do not have to be performed at different generator loading points to achieve maximum sensitivity to shorted turns.

High-resolution signal acquisition and the use of multiple analysis algorithms have significantly improved the reliability of detecting shorted turns even at nonoptimum load points. In addition, analysis results can be shown in many ways, enabling easy trending of measurement results and rotor summary display.

Case Study

One of the difficulties in the existing shorted turn detection techniques was the detection of shorted turns at machine loads that did not provide maximum sensitivity. Maximum sensitivity to the leakage flux is obtained when the main flux goes through zero. To achieve the maximum sensitivity to a shorted turn, the flux density zero crossing (FDZC) position had to be changed by changing the machine load (the traditional measurement technique). This requirement can be a serious obstacle for the detection of a shorted turn in a higher number of coils in base load units running consistently at or close to full load. At full



Cell Number	1	2	3	4	5	6
Minimum	0.031	5.198	0.019	1.759	0.043	0.717
Maximum	1.438	6.953	0.629	2.937	0.900	1.545
Average	0.552	6.357	0.287	2.384	0.322	1.015
Last	0.498	5.198	0.261	1.759	0.900	1.545

The *X* axis is the rotor coil number, and the *Y*-axis is the normalized difference between poles A and B. A range of results, all rotor coils over time.

load, the FDZC is closer to coil 2 or 3 (closer to the pole axis), and traditional methods were not sufficiently sensitive to reliably detect shorted turns in a higher number of coils. At the same time, if shorts are in a coil with a lower number due to design limits, it is impossible to move the FDZC closer to coil 1 and properly assess that coil.

A series of tests were conducted using the new instrumentation, and the new analyzing algorithms indicated consistent sensitivity to a shorted turn in the highest numbered coil on a two-pole 13.8 kV, 20 MVA turbine generator under different loading conditions. Figure 3 shows a comparison of pole A to pole B leading slots at the minimum load available, 2 MW. A turn short in coil 2 is clearly seen in Figure 3, although the FDZC is far away from this coil. Figure 4 shows a comparison of pole A to pole B leading slots, this time at the maximum load available during the test. In both graphs, the vertical green line is an indication of FDZC position, between coils 5 and 4 for 10-MW load and close to coil 6 at no load condition. Compared to opposite pole coils, coils without shorted turns are expected to have equal peak amplitudes.

The normalized difference in percent (shown on the *Y* axis) of two poles for different positions of the FDZC (shown on the *X* axis) for all coils is shown in Figure 5. Coil 2, indicated by the green square, had a normalized pole-to-pole difference of more than 5% in all loading conditions. At the same time, all other coils did not show a pole A to pole B difference higher than 3%. As demonstrated, this system yields uniform sensitivity to a short in coil 2 at different loads, which is not possible with traditional measurements. It can be observed that with the advanced algorithms the difference is actually slightly higher at the least sensitive FDZC position, close to coil 6, compared to the most sensitive FDZC position during this test, close to coil 4.

Figure 6 shows a pole A to pole B difference for all coils over a period of the time for all loads available during the duration of the time-based tests.

Conclusions

The flexible printed circuit magnetic flux probe has been developed to improve shorted coil sensitivity. The probe can be easily installed to measure the main flux in the air gap. Combined with a portable or continuous online analyzer incorporating proprietary algorithms, the rotor short detection sensitivity has been significantly improved. This allows the detection of shorted turns even at machine load conditions, which are less than ideal.

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