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Detection of rotor winding shorted turns in turbine generators and hydrogenerators

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SUMMARY

Shorted turns due to insulation failure in the windings of round and salient pole rotors in synchronous motors and generators often leads to high rotor vibration, and may limit the output of generators. In fact, high bearing vibration is one of the early indicators that a turn short has occurred. However, since there are many possible causes of high bearing vibration, operators would like independent verification whether such vibration is indeed caused by a rotor insulation problem or not. There are many ways to directly detect shorted turns. Off-line tests such as the voltage to earth, pole drop or the RSO test are often not reliable since the rotor is not spinning and thus faults may disappear (or in fact occur only) in the standstill condition. In addition, these tests require a unit outage and some disassembly.

Users instead prefer an on-line test where the rotational and thermal stresses are normal. The only such direct test for shorted turns involves measuring the magnetic flux in the air gap. The original "air gap flux" test developed by GE over 30 years ago and now widely used around the world on large 2 pole and 4 pole turbine generators, employs a small coil that is normally permanently mounted on one of the stator winding wedges. The sensor detects the "leakage" flux from each rotor slot as it passes the sensor each revolution. If there is a shorted turn in a slot, the leakage flux is reduced from that slot, which can be detected with suitable instrumentation. Since the leakage flux is very small compared to the main airgap flux, in the conventional test one must vary the generator load in several steps between no load and full load, to ensure that there is a "zero-crossing" of the main flux at each rotor slot. This enables the small leakage flux to be measured with some sensitivity for most of the coils.

There are two main limitations with the conventional air gap flux test. The first is that on turbine generators, the sensor can only be installed when the rotor is removed from the stator. Secondly, the load must be maneuvered over a wide range in steps, which causes certain logistical problems for plants under the control of an Independent System Operator, or where reduced load operation reduces revenues. Research in the past 5 years has lead to two innovations that overcome these limitations. The first is a new probe that can sometimes be installed with the rotor in place. The probe is a very thin printed circuit board sensor that is glued to a stator tooth (not the wedge) to measure the main (or total) magnetic flux. The second innovation is a new diagnostic algorithm and instrumentation that is sensitive to shorted turns in any slot while the generator operates at full load, by measuring the main flux. The new instrumentation and algorithm also seems to be effective when used with conventional

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wedge-mounted sensors. In addition, with some modifications, the new approach can be applied to salient pole rotors in hydrogenerators.

KEYWORDS

Magnetic flux, salient pole rotor, round rotor, shorted turns detection.

1. INTRODUCTION

Flux monitoring of turbine generators using temporary or permanently installed magnetic flux probes has been used since the early 1970's [1]. Flux measurements are used to determine the existence of turn-to-turn shorts in the rotor winding. All of the methods available are based on measurement of relatively weak stray flux (rotor slot leakage flux) using flexible or non-flexible polymer encased stator wedge mounted probes [2-4]. The stray flux is proportional to the total ampere-turns in each rotor slot. If shorts develop between turns in any slot, then the ampere turns in that slot drop, and stray flux across that slot is reduced. The magnitudes of these stray fluxes can be measured using portable or permanently installed instrumentation and shorted turns can be identified by comparing the difference in the induced voltages from pole to pole.

The main challenge in existing technology applied to turbine generators is the need to maneuver the generating unit load to achieve the maximum sensitivity to shorted turns in every slot of a rotor. This can be a significant obstacle where the dispatch of the generators is controlled by an independent system operator (ISO). Other problems are related to both the type of the probe and instrumentation/algorithms used for detection of shorted turns. [2-4]

For hydrogenerators, there is no on-line monitor that explicitly determines the condition of the rotor field windings. Salient pole field windings tend to be very reliable, yet in each major outage plant personnel spend a considerable amount of time doing the 'pole drop' test, to assure themselves that there are no shorted turns on the field poles. In addition, the pole drop test may not be effective in detecting shorted turns since it is done in the standstill condition.

Shorted turn insulation on rotors may lead to unbalanced magnetic pull, which in turn may cause an increase in bearing vibration. However, shorts can exist with no increase in vibration and thus bearing vibration is not an infallible way to detect rotor winding aging. Thus research was done to see if a variant of flux monitoring could detect shorted turns during normal hydrogenerator operation.

2. PRINCIPLES OF FLUX MONITORING

Rotor flux monitoring involves measuring the magnetic flux in the generator air-gap to determine if field winding shorts have occurred in the rotor poles. The radial magnetic flux is detected by means of a flux probe consisting of a coil of several dozen turns that is mounted in the air gap or glued to stator tooth. As each rotor pole on a salient pole machine or current carrying slot on round rotors, sweeps by the flux probe, a voltage is induced in the flux probe that is proportional to the flux from the pole or slot that is passing the probe. The voltage is then measured by a rotor flux analyzer. The recorded waveform data can then be analyzed to locate the poles or slots containing the fault, as long as one has calibrated the pole location from a 'start' location marked on the rotor shaft.

In a salient pole machine, the radial magnetic flux profile across each rotor pole depends on the MW and Mvar loading of the machine. Any change over time in the flux profile within a pole at a given load, or changes between poles is most likely due to shorted turns. An algorithm was developed to maximize the sensitivity to a pole with shorted turns. The algorithm involves integrating the data from each pole, applying autocorrelation, and comparing the integral from each pole to an opposite polarity pole.

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In turbine generator rotors, in the absence of shorted turns, corresponding peaks of each rotor slot on two or four poles should be the same amplitude.

3. DESIGN OF FLUX PROBE

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

To minimize risks associated with this, some flux probe manufacturers require that wedges where the flux probe will be installed should be drilled and support dowels installed. This operation may affect the mechanical properties of the wedge. A new type of the probe has been designed to overcome disadvantages of existing designs. The new probe comprises of a number of printed circuit layers, configured on a flexible base material. The flexible probe is designed for application on a stator tooth (Fig. 1). The new probe directly measures the main magnetic flux since it is mounted on the steel core tooth, rather than a wedge. The very low profile of the installed probe enables its use on hydro-generators with small air gaps, and can sometimes be retrofitted to hydro or turbine generators without rotor removal.

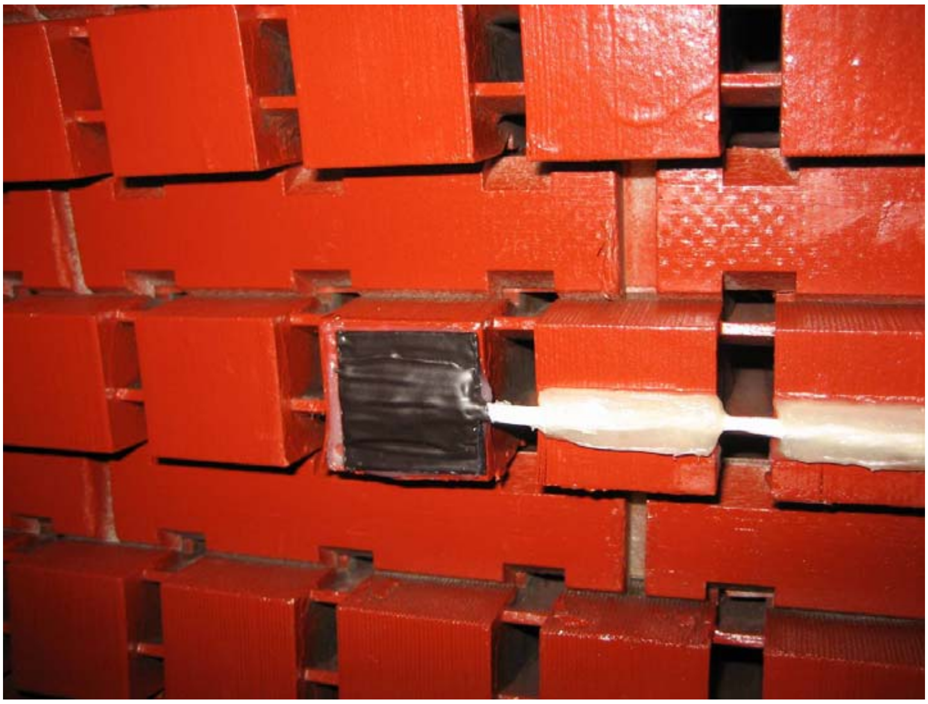

Figure 1. New style flat flux probe mounted on a tooth

4. APPLICATION ON TURBINE GENERATORS

Different factors will affect how serious is the problem caused by shorted turns. In many cases the rotor will still run without significant consequences. However, the most noticeable effect can be increased rotor vibration. Since the resistance of coils with shorted turns is lower, they are likely to operate at lower temperatures compared to coils without shorted turns. This temperature difference will cause uneven heating of the rotor forging and can cause the rotor to bow. The bowing will increase with increasing load due to higher temperatures resulting from higher excitation current.

Therefore, this situation is frequently described as thermally sensitive vibration. Two pole rotors are much more sensitive to thermal vibrations than four pole rotors.

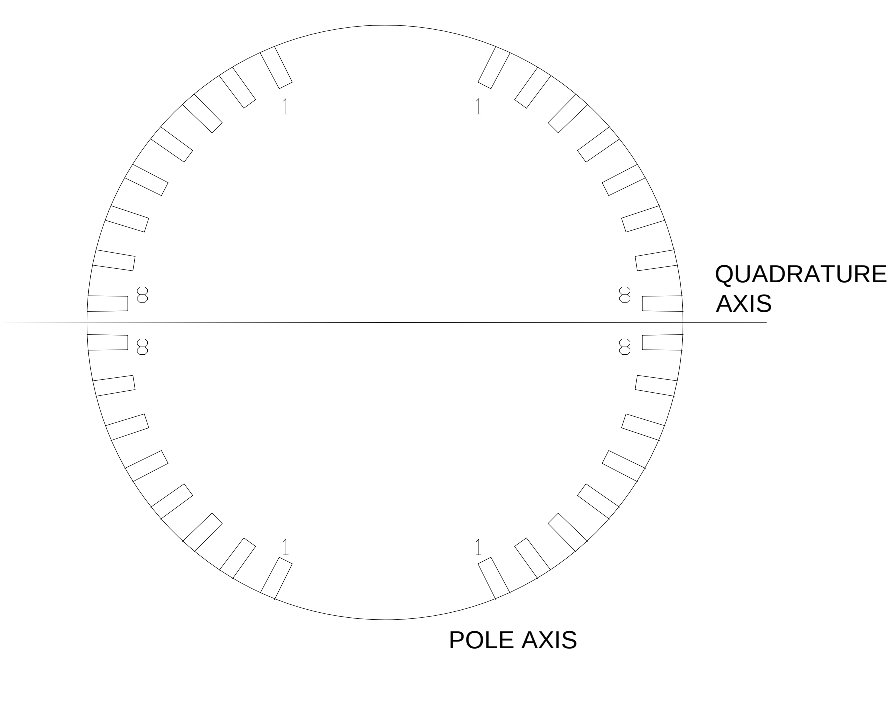

Figure 2. Cross-section of a two pole turbine generator rotor

The main reason for thermal bowing of a rotor is its asymmetrical design. A rotor forging is made of magnetic steel and designed to carry the flux produced by the rotor winding. A rotor body consists of a pole face area and winding slots machined axially. Pole face areas, see Figure 2, are cut in half by the Pole axis. The coil closest to the pole face is coil 1. Coils with higher numbers, usually 7-9 on two pole rotors, are located closest to the Quadrature Axis. The bowing of the rotor and magnitude of vibrations will depend on the design of the rotor, number of shorted turns and the location of coils with shorted turns [6]. Generally, shorted turns in coils 1 and 2, closest to the pole face produce higher magnitude vibrations compared to shorted turns in coils closer to Quadrature axis. The reason for this is that shorts in lower coil numbers produce less elongation in the axial direction of pole face compared to higher numbered coils due to the lower temperature at pole face. Coils without shorted turns are running at higher temperature and thus greater elongation compared to coils with shorted turns. Consequently, the bowing will increase with increased rotor current, and may limit MW output due to excessive vibration. Thermal vibration is directly linked to changes in rotor current. With a reduction of rotor current, vibrations will go down and vice versa. The degree of thermal sensitivity is determined by measurement of vibration at different loads. In cases where vibrations are higher than or very close to the operational limits, trim balancing of the rotor is usually the first step taken to alleviate the problem. This operation does not require removal of the rotor but does not fix the root cause of the problem, shorted turns in rotor winding. If successful, trim balancing can reduce the vibration at full load and enable the generator to be operated within safe vibration limits. However, trim balancing weights placed on the rotor to minimize vibration at full load will introduce vibration at lower loads (lower temperatures), when rotor bowing is not significant. The best way to determine whether rotor shorted turns are the cause of rotor vibration is to analyze both on-line vibration monitoring and on-line air gap flux monitoring results.

The main challenge in existing flux monitoring technology is the need to maneuver the turbine generating unit load to achieve the maximum sensitivity to shorted turns in every slot of a rotor. This is particularly challenging in detection of shorted turns on coils 1 and 2, installed close to the pole face. To assess condition of coils 1 and 2, using existing technology, generators need to produce maximum active load and maximum negative reactive load. Since this is not possible in many power

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systems, many suppliers of existing technology do not provide assessment of the condition of coil 1 at all [4].

5.1 Case Study 1

One of the difficulties in existing shorted turn detection techniques is the detection of shorted turn at machine loads that do not provide maximum sensitivity (i.e. the position of Flux Density Zero Crossing (FDZC) did not match the coil evaluated) to a coil with shorted turn. To achieve the maximum sensitivity to a shorted turn, the FDZC position had to be changed by the machine load change.

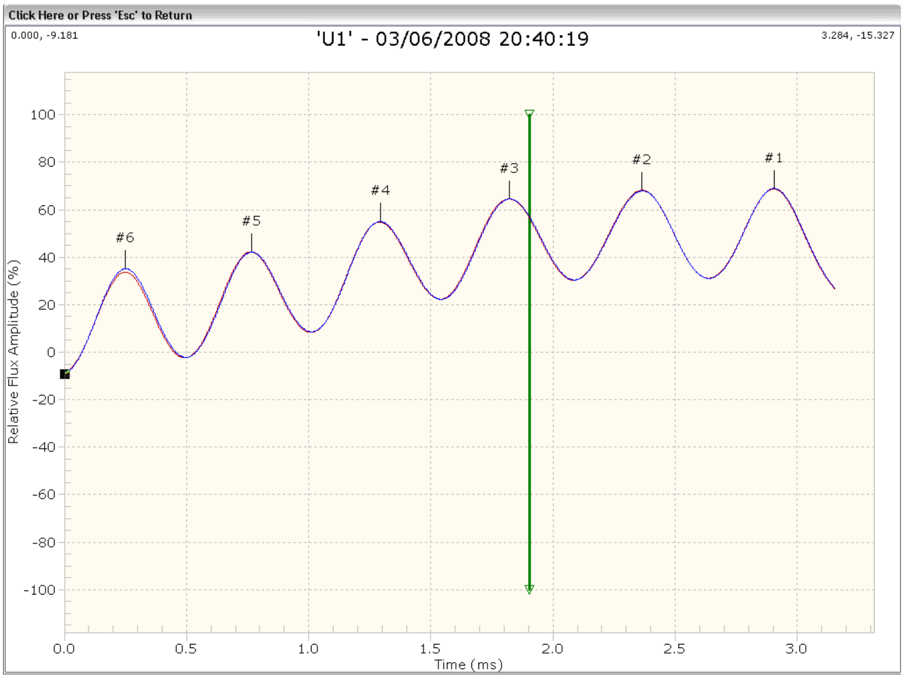

Figure 3. Turbogenerator leading poles comparison, FDZC close to coil 3, short detected at coil 6

This requirement could be a serious obstacle to detect a shorted turn in higher number coils in base load units running consistently at or close to full load. At full load FDZC is closer to coils 1 or 2 (closer to the pole axis) and traditionally used methods were not sufficiently sensitive to reliably detect shorted turns in higher number coils.

A series of tests were made using a new instrument with high temporal resolution and the new analyzing algorithms indicated consistent sensitivity to shorted turn in the highest numbered coil on a two pole 13.8 kV, 115 MVA turbine generator under different loading conditions. Figure 3 indicates pole A to pole B leading slots comparison at the maximum load available, 80 MW, 12 Mvar.

A turn short in coil 6 is clearly identified in Fig. 3, although the FDZC is far away from this coil. Figure 4, is again comparison of pole A to pole B leading slots, this time at the minimum load available during the test. In both graphs, the vertical green line is an indication of Flux Density Zero Crossing position, between coils 2 and 3 for 80 MW load and close to coil 6 at no load condition. Coils without shorted turns are expected to have equal peak amplitudes, compared to opposite pole coils.

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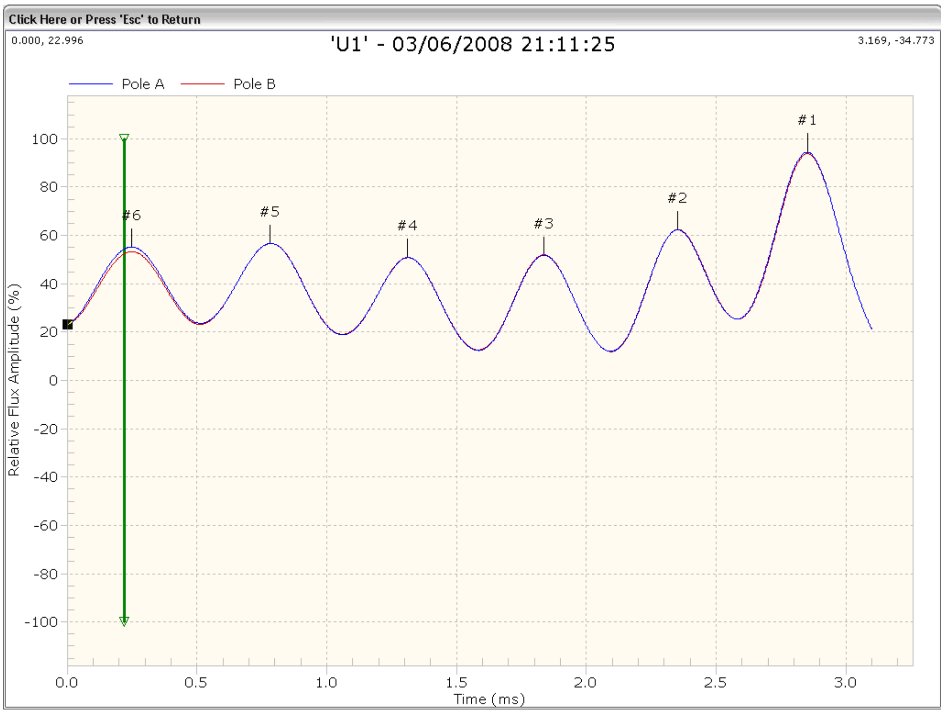

Figure 4. Pole A to pole B comparison, no load test, with FDZC and short located at coil 6

Figure 5 indicates the normalized pole to pole difference for all coils for all loads available during the tests on this generator. The normalized difference in percents (shown on Y axis) of two poles for different positions of FDZC (shown on X axis) for all coils is shown in Figure 5. Coil 6, indicated by the red square had a normalized difference pole to pole of more than 3% in all loading conditions. At the same time, all other coils did not show pole A to pole B difference higher than 1%. As demonstrated, this new system yields uniform sensitivity to a short in coil 6 at different loads which is not possible with traditional measurements.

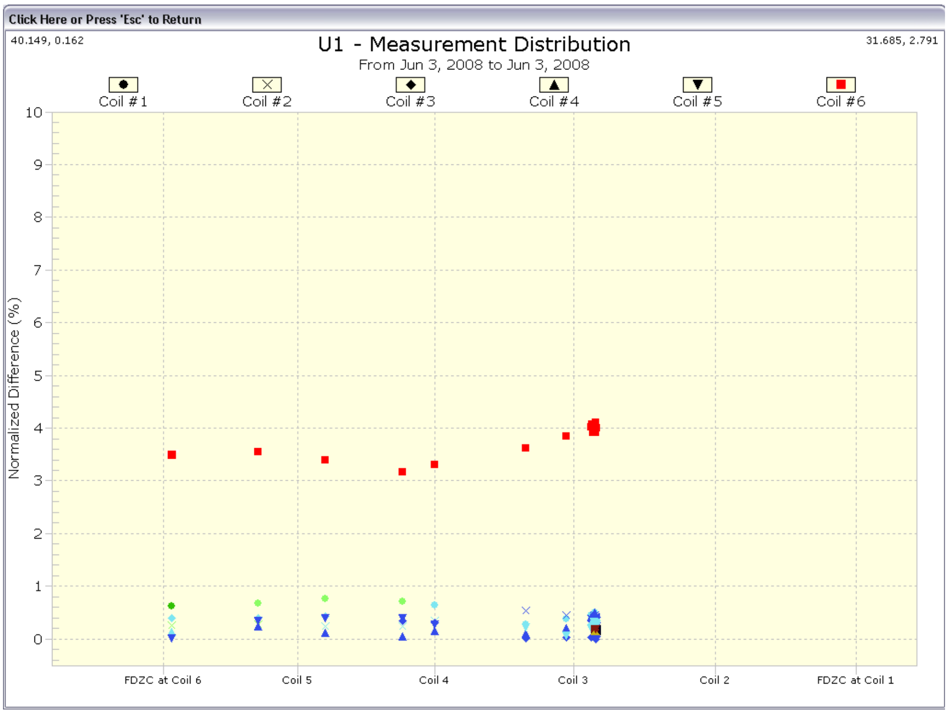

Figure 5. Normalized pole A to pole B difference at different FDZC positions

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It can be observed that with the new algorithms the difference is actually slightly higher at the least sensitive FDZC position, close to coil 3, compared to the most sensitive FDZC position, close to coil 6.

Figure 6 indicates pole A to pole B difference for coil 6 over a period of the time for all loads available during the test. Shedding of the load was performed over 6 minutes from 21.05 to 21.11, and during that time FDZC position moved from coil 3 to coil 6. Similarly to Figure 5, it can be observed in Figure 6 that pole A to pole B difference stayed close to 4% in all tests, indicating that load change (i.e. different position of FDZC) did not negatively affect the quality of the measurement.

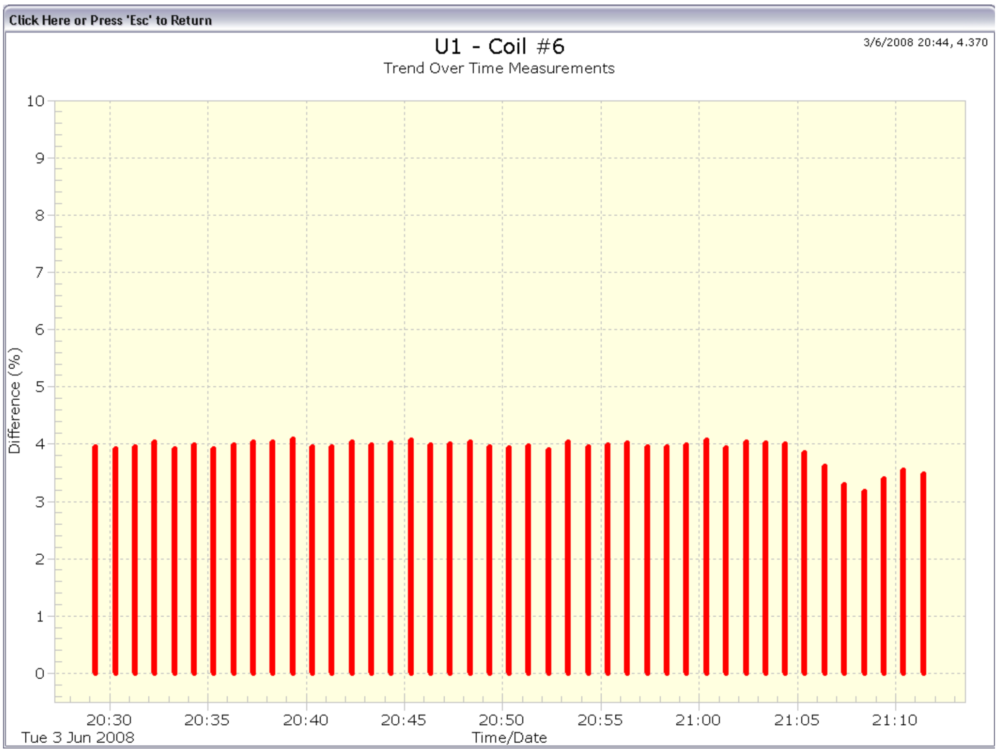

Figure 6. Coil 6, trend over time

4.2 *Case Study 2*

A 100 MVA turbine generator was equipped with the flat, tooth mounted probe during a scheduled shut-down. Although the generator had increased vibration for a number of years, the cause was not known and repairs were not attempted during this shut-down. A few months later, the first flux measurements were made at maximum loading, see Figure 7. Comparison of pole A to pole B leading slots indicated a difference in amplitude close to 9% in coil number 1. This measurement was performed at full load and the position of Flux Density Zero Crossing (FDZC), using traditional approach, would not provide sufficient sensitivity to evaluate condition of coil number 1 [4]. However, application of new algorithms made detection of shorted turns in coil 1 possible. Although flux measurements could not be made at different loads, vibration monitoring has confirmed thermal dependence of vibration amplitudes.

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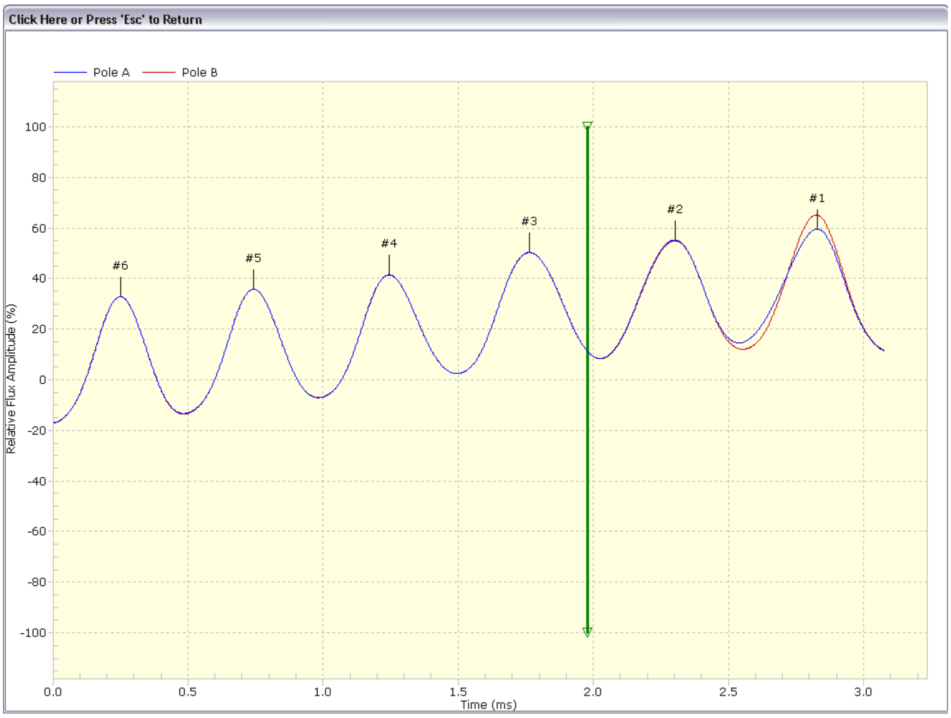
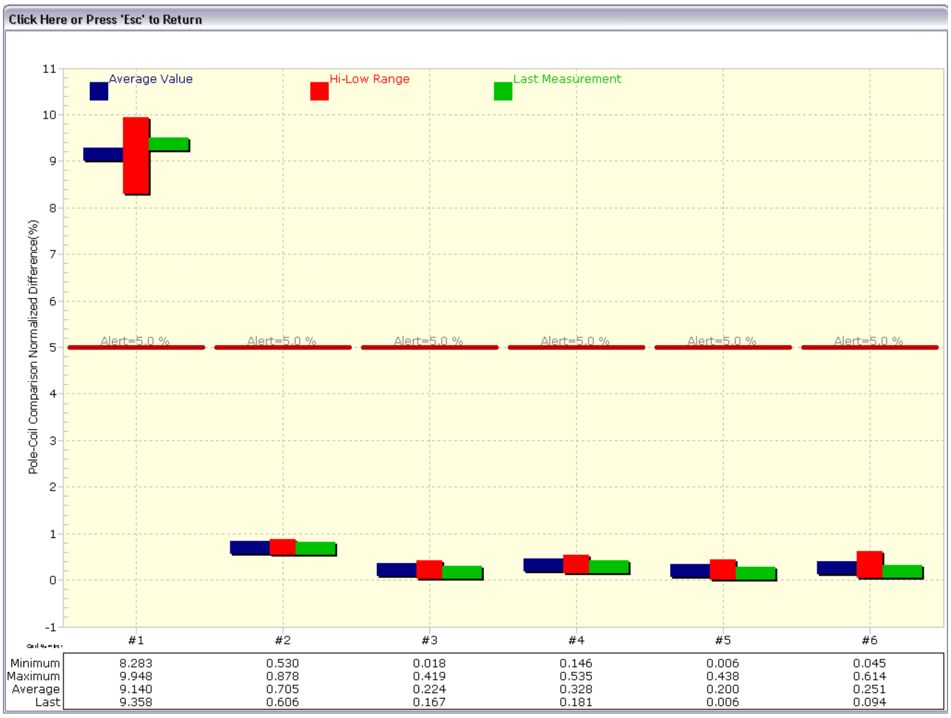


Figure 7. Leading slots normalized peaks, pole A to pole B comparison

Figure 8. indicates a summary of multiple measurements at slightly different loads, for each coil. Coil 1 normalized pole to pole amplitude difference ranged from 8.2% to 9.9%, while all other coils had difference lower than 1%.



	#1	#2	#3	#4	#5	#6
Minimum	8.283	0.530	0.018	0.146	0.006	0.045
Maximum	9.948	0.878	0.419	0.535	0.438	0.614
Average	9.140	0.705	0.224	0.328	0.200	0.251
Last	9.358	0.606	0.167	0.181	0.006	0.094

Figure 8. Statistical distribution of Coil to Coil normalized differences on a turbine generator

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5. APPLICATION ON HYDROGENERATORS

5.1 Case Study 1

Data collected from a flat, tooth mounted flux probe installed in a hydro-generator are shown in the Figure 9. To correlate which part of the rotor pole is associated with what part of the signal, a photograph of four rotor salient poles is shown above the signal recorded. The generator was operated at no load conditions, 0 MW and 0 Mvar, resulting in a symmetrical shape of both raw signal measured (blue line) and integrated values of raw signal (red line). Since the shape of the signal is changed at different loadings of the machine, see Figure 10, raw data should be integrated for further processing.

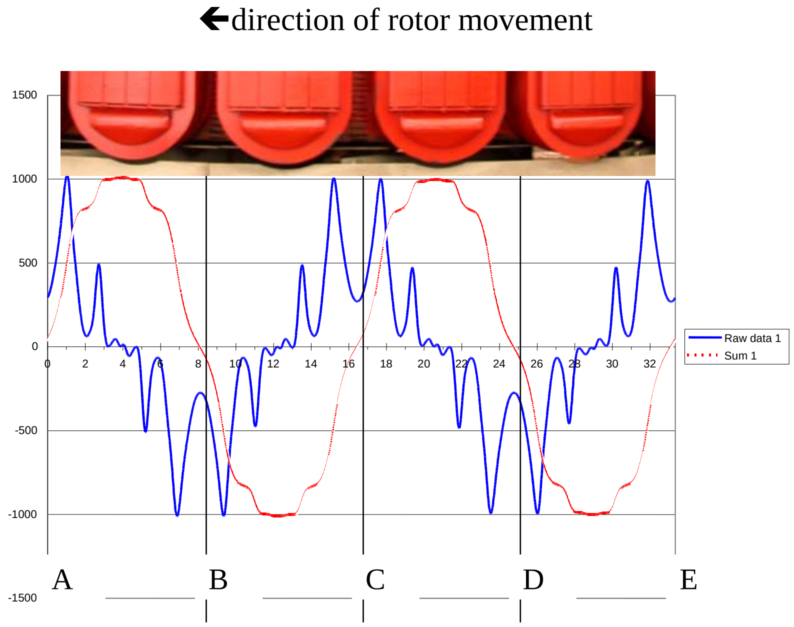

Figure 9. Shape of the signal at 0 MW, 0 MVAr from a hydrogenerator rotor

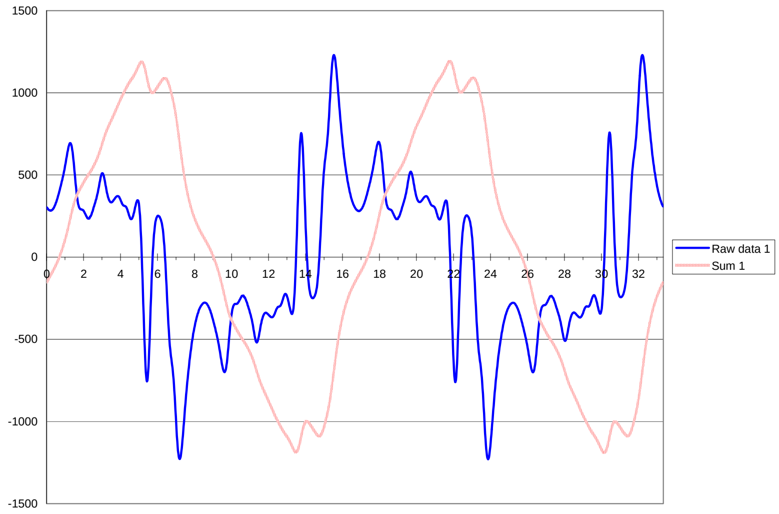

Figure 10. Shape of the signal at 125 MW, 0 MVAr

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Given that a change in the flux profile within a pole at a steady load must be due to shorted turns, comparison of one pole to another can be used as an indication of shorted turns. Such comparisons are usually shown as polar plots, see Figure 11.

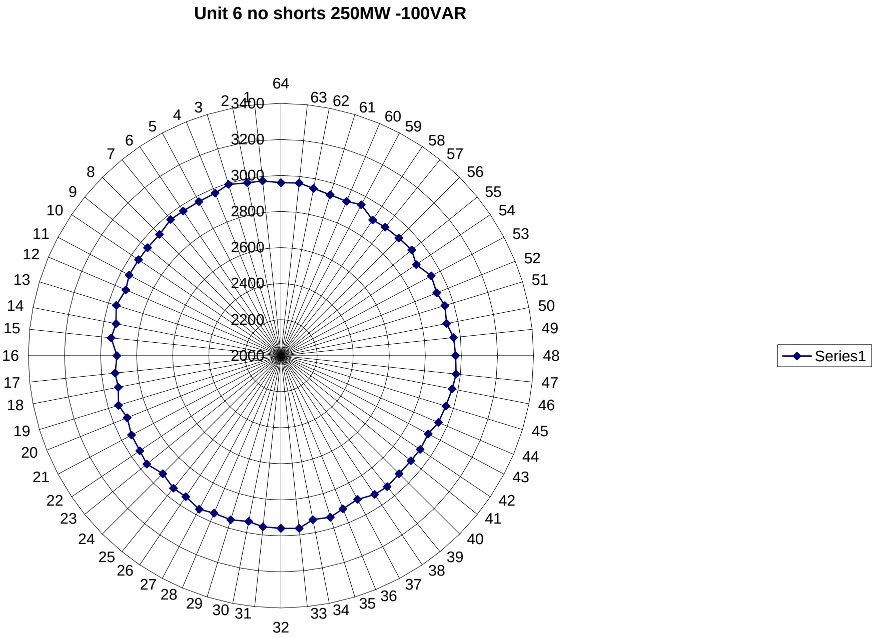

Figure 11. Polar diagram of 64 pole rotor with no shorts. The radial axis is the magnitude of the radial magnetic flux and pole numbers are indicated on the circumference.

Minor differences between poles and excentricity of the rotor will result in less than perfect circle, as seen in Figure 11. Figure 12 is result from the same 64 pole rotor with artificial shorts that were temporarily installed on poles 8 and 48.

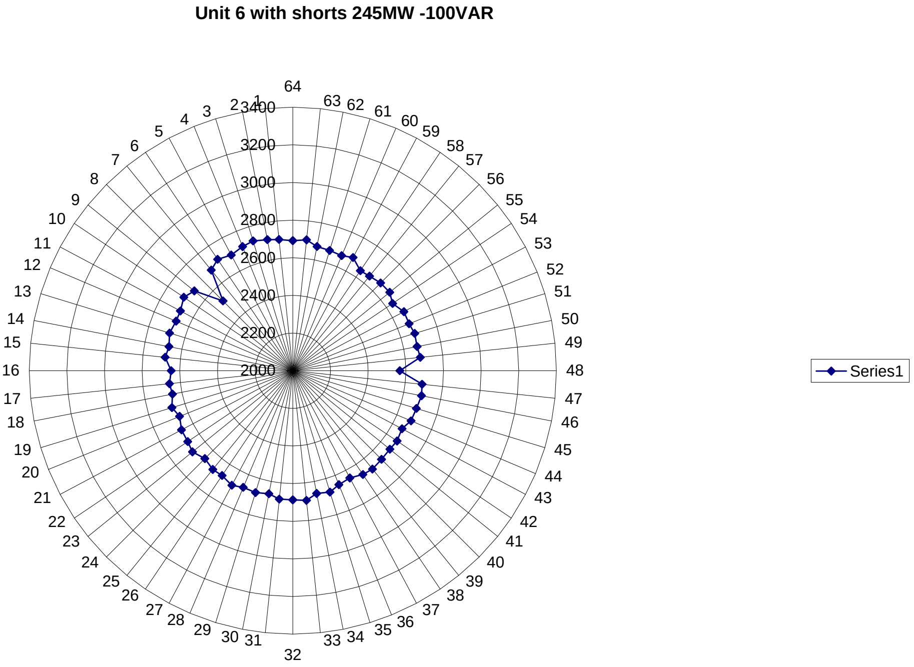

Figure 12. Polar diagram of 64 pole rotor with shorts detected at poles 8 and 48

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In most of the field tests, good correlation of on-line flux shorted poles detection and off-line pole-drop tests was not possible. One reason is lack of positive pole number identification in off-line and on-line tests. The other reason is that two tests are significantly different in approach and in test conditions. The off-line pole drop is an AC test, more sensitive to first turn shorts, but less sensitive to other turns shorts. The on-line flux measurement is a DC test, sensitive to all shorts proportionately. In some tests, both methods identified one pole with shorted turns. Because there was no rotor sync we cannot be completely sure that these tests indicate the same pole. Also, shorts detected in the on-line flux test when the rotor is spinning, may disappear when the rotor is at standstill-when the pole drop test is done.

In Figure 13, results from two off-line voltage and power measurements and on line flux measurements are shown, indicating that one pole has shorts detected using three different methods.

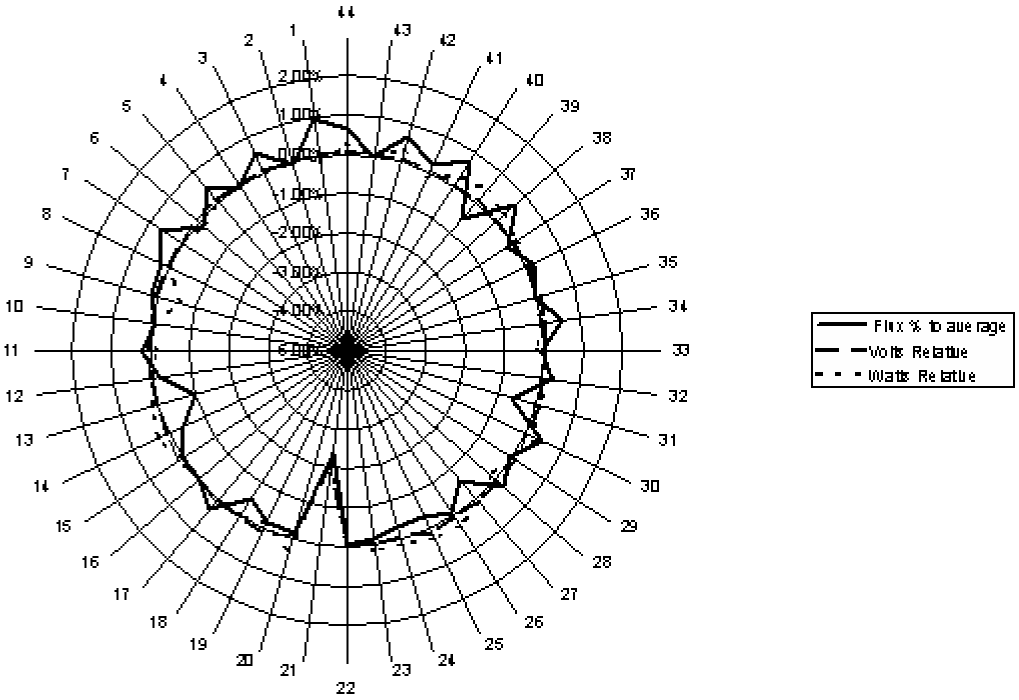

Figure 13. Off-line and on-line test results comparison, indicating shorts on pole 21

6. CONCLUSIONS

An improved system for detection of shorted turns on salient pole and round rotor coils has been developed. The system consists of an easily installed probe that measures the main flux in the air gap, and a portable Analyzer instrument, with new algorithms for rotor short detection. As a result of these improvements, the overall system sensitivity to shorted turns has been greatly improved from conventional techniques. This new system can detect the presence of shorted turns often without the need to obtain measurements at various load conditions.

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