INITIAL EXPERIENCE WITH ON-LINE HYDROGENERATOR ROTOR WINDING CONDITION ASSESSMENT USING FLUX MONITORING

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Abstract: Monitoring systems to assess the on-line condition of generator stator windings, bearings and the air gap are now widely employed by hydrogenerator plant operators. Although salient pole rotor windings tend to be very reliable, in each major outage plant personnel spend a considerable amount of time doing the 'pole drop' test, to assure that there are no shorted turns on the field poles. In addition, the pole drop test may not be effective in detecting shorted turns in the standstill condition. Unfortunately, there is no on-line monitor that explicitly determines the condition of the rotor field windings.

Over the past 3 years, research has occurred to determine if rotor shorted turns can be detected during normal generator operation by measuring the magnetic flux from each pole as it passes a probe that is placed in the air gap. Such monitoring has been used for years on high-speed turbine generators. The paper presents the results of tests on several hydrogenerators that show there is some promise in the method. This technology can also be applied to salient pole rotors, of 4 or more poles, typically used in very large air compressor motors.

INTRODUCTION

Generally, the salient pole rotor windings in hydrogenerators and large salient pole motors are very reliable. However, over the years the insulation in the rotor windings may age, first leading to shorted turns, and then eventually ground faults. Insulation aging occurs as a result of overheating, load cycling and/or contamination of the winding by partly conductive materials such as insects or dust mixed with oil or water [1]. The most common type of salient pole rotor used in moderate and large sized hydrogenerators and pump-storage generators, is the 'strip-on-edge' type of winding on each pole. That is, the winding is composed of strips of copper that are fabricated around the pole piece much like a picture frame. For large air compressor motors, either the strip-on-edge construction, or simple magnet wire may be used. Fiberglass reinforced epoxy and/or the film insulation on magnet wire is used to insulate each copper turn from adjacent turns, as well as provide ground insulation between the copper and the rotor pole. Most plants will trip the generator once a rotor ground fault occurs.

Once a shorted turn occurs, an unbalanced magnetic pull may occur, which in turn may cause an increase in bearing vibration. Virtually all generators and motors are monitored for bearing vibration. Unfortunately, there are many causes of high vibration, of which rotor shorted turns is just one. Thus bearing vibration is not an infallible way to detect rotor winding aging. It would also be helpful to know that the cause of high vibration is not shorted rotor turns.

The most reliable and common way to detect shorted turns (and incipient ground faults) is to perform a 'pole drop' test [1]. In the pole drop test an AC voltage, for example 120 V AC, is applied between the positive and negative slip rings when the hydrogenerator is shut down and partly disassembled. The voltage across each pole is then measured. If shorted turns are present, there will be a smaller than average voltage drop across that pole. This test has three significant disadvantages:

- It can only be performed with the generator shut down - implying a loss of revenue.
- It is time consuming to perform, especially on a large rotor with many dozens of poles
- Since the rotor is not rotating, the centrifugal forces are not occurring, and thus some shorts may not be present in the pole drop test, which nevertheless will be present at normal rotating speeds.

As organizations try to minimize the work (such as pole drop tests) performed during unit shutdowns due to restricted resources, and as they move to predictive maintenance to plan any repair work based on on-line condition monitoring, there is a need for an on-line tool that can replace the pole-drop test. For the past 20 years, utilities have been implementing magnetic flux monitoring in the air gap between the rotor and stator to detect shorted turns on the cylindrical rotors of high speed steam-turbine generators [1]. This technology has rarely been applied to salient pole windings, possibly because the salient pole rotors are very different from cylindrical pole rotors and interpretation of the flux patterns is not obvious. In 2003, EPRI and the New York Power Authority initiated a research project to determine if a variant of flux monitoring could be applied to salient pole rotors, so that an online monitor could produce a reliable indication of rotor shorted turns. This paper discusses the results from this research project.

FLUX MONITORING FUNDAMENTALS

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 flat coil (or probe) consisting of several dozen turns that is glued to stator teeth [2]. As each rotor pole sweeps by the flux probe, a voltage is induced in the coil that is proportional to the flux from the pole that is passing the coil. The voltage is measured by electronic instruments such as a digital oscilloscope or analog-digital (A/D) converter. 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 in the flux profile within a pole at a given load must be due to shorted turns.

As each pole in the rotor passes, there will be a peak in the induced voltage caused by the change in magnetic flux from the pole. The voltage can then be recorded and the "average" flux across one rotor pole can be calculated. Any turn shorted turn in a pole reduces the effective ampere-turns of that pole and thus the signal from the flux probe associated with that pole. The recorded waveform data can then be analyzed to locate the poles containing the fault, as long as one has calibrated the pole location from a 'start' location marked on the rotor shaft.

TABLE 1
Machines where flux probe data was collected

Company	Power (MW)	No. of Poles	Turns per Pole	Machine(s) Measured	Comments
A	60	76	17	U17, U25, U26	Measurements spanned two trips
B	330	64	21	U1, U2, U3, U4, U5, U6	Installed Shorts across Turns
C	140	30	42	U2, U3	
D	125	52	27	U3	
D	120	48	?	U8	

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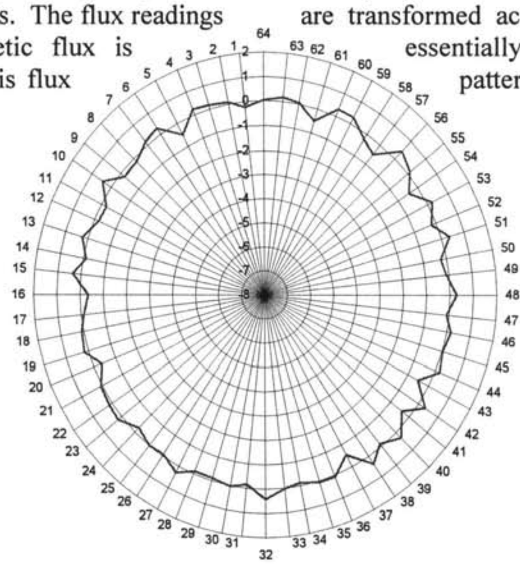
An algorithm was developed to maximize the sensitivity to a pole with shorted turns. The algorithm involves integrating the data from each pole, applying autocorrelation, and comparing the integral from each pole to another pole [3].

PRELIMINARY MEASUREMENTS

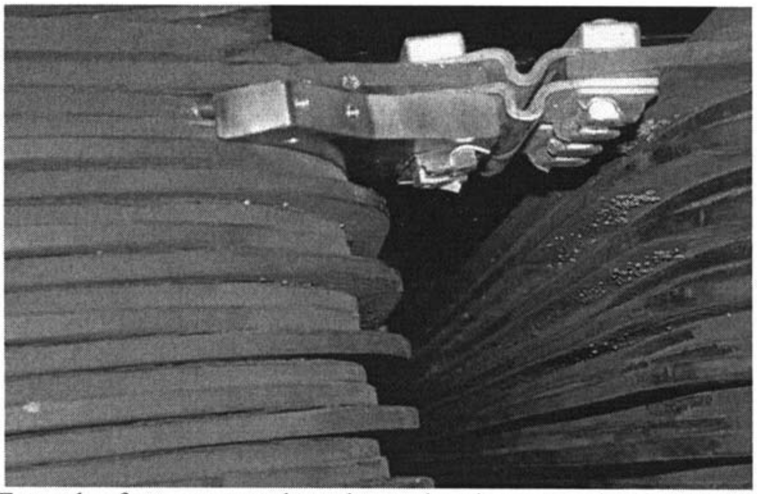
To obtain a reliable indication of the noise conditions, and partly to see the variety of signals, data was collected from 5 different machines (Table 1). Unfortunately, none of the machines measured had real pole winding shorts. Any change in signal from pole to pole on a 'good' machine is considered noise, This change in signal can be due to physical differences from pole to pole.

We were able to install temporary shorts on the 330 MW pump storage machine, since none of the machines equipped with the flux probes had existing turn shorts. Figure 2 shows a photograph of a single shorted turn. Either 1 or 3 turns were shorted, on two different poles. Figure 3 shows the magnetic flux when two poles (numbers 8 and 48) contain temporary shorts. Pole 8 has one shorted turn whereas pole 48 has three turns shorted. In comparison to the plot in Figure 1, it is clear that the algorithm cannot only identify the poles with shorts, but how severe the^shorting is.

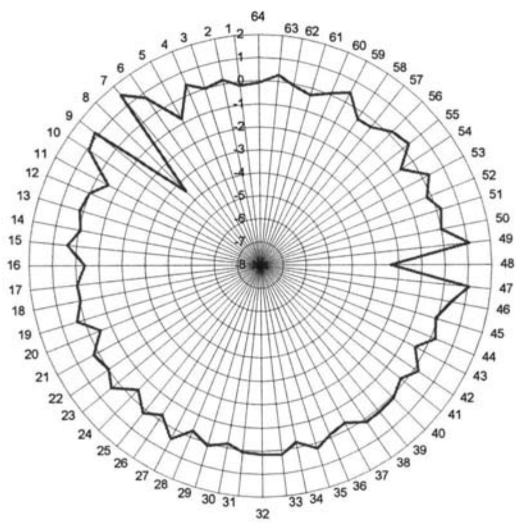
Figure 1 shows a polar plot of pole number (circumferential axis) vs. relative magnetic flux for the 330 MW, 64-pole rotor with no shorts. The flux readings are transformed according to the algorithm described above. The magnetic flux is essentially uniform around the circumference of the rotor. This flux pattern was similar on all 5 rotors that were measured.



Polar plot of the transformed magnetic flux (on a normalized scale) versus rotor pole number for a rotor with no shorted turns. Ideally the trace would be a perfectly round circle. Differences from perfect roundness are due to normal physical differences around the rotor.
FIGURE 1



Example of a temporary shorted turn placed on one pole of a 330 MW machine with a strip on edge winding.
FIGURE 2



Polar plot of a transformed magnetic flux versus pole position when two poles (8 and 48) contain 1 or 3 shorted turns, respectively.
FIGURE 3

CONTINUOUS MONITOR

A prototype continuous monitor (Figure 4) has been developed that collects the data from the flux probes. The monitor then digitizes the signals with extremely high resolution and applies the algorithm to reduce the effect of the main magnetic field to detect the minor perturbations caused by shorted turns on a pole. The monitor can communicate with the plant computer via an Ethernet connection. There are four initial installations with more to occur in 2006.

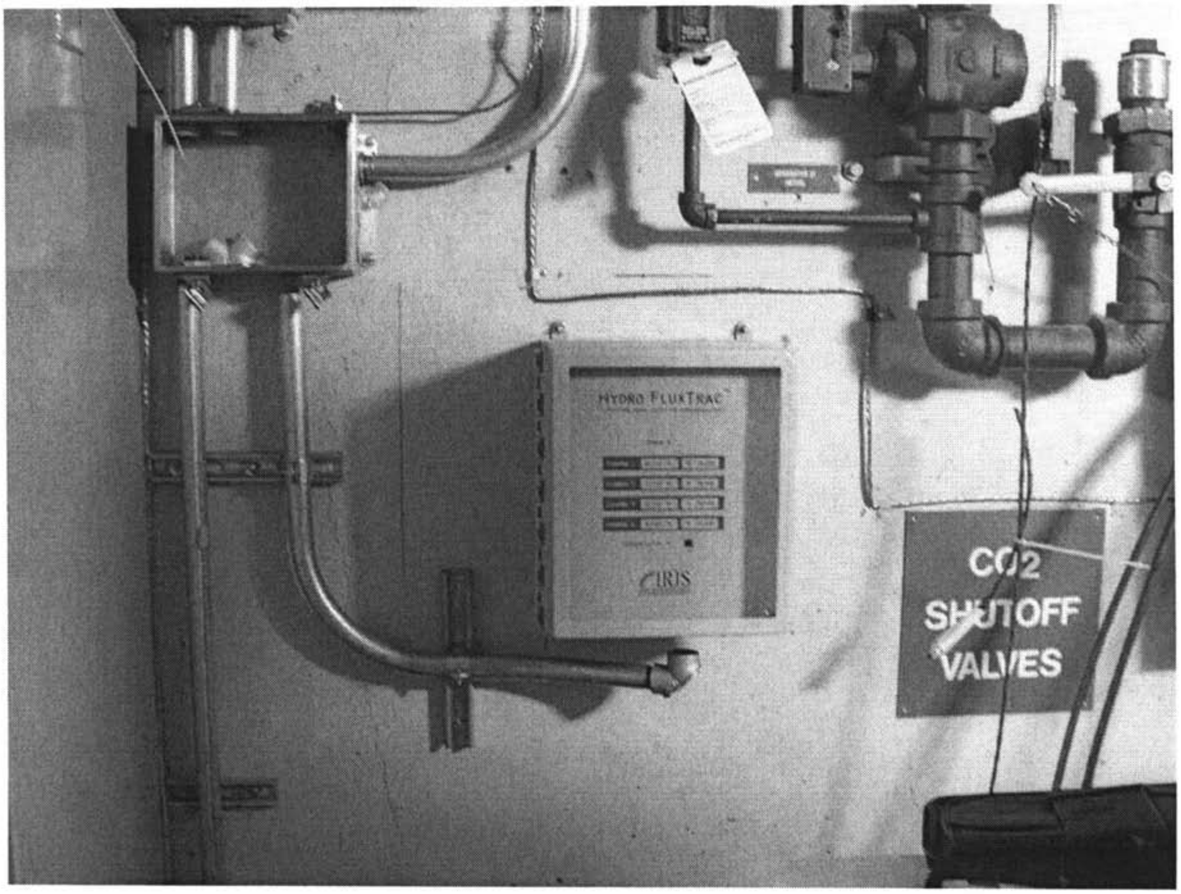
CONCLUSIONS

The on-line detection of shorted turns on salient pole rotor poles during normal operation of the machine now seems feasible. With a suitable shaft marker, the shorted poles can be identified and the severity of the short (as determined by the number of turns that are shorted) can also be estimated. A continuous monitoring instrument has been prototyped that will automatically perform the measurement and analysis. The instrument will provide an alarm in the event of a shorted turn and indicate which poles have problems. When deployed, this new technology can remove the need for off-line pole drop tests, eliminate or confirm shorted turns as a cause of high vibration, and will allow plants to plan when salient rotor winding maintenance is prudent.

REFERENCES

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

2. US Patent No. 6,466,009 Bl, *Flexible Printed Circuit Magnetic Flux Probe* issued 15 October 2002



Photograph of the prototype monitor that continuously monitors the magnetic flux signals of salient pole rotors to detect shorted turns.

FIGURE 4

3. Stein, Jan, *Field Testing of Continuous Hydrogenerator Air-Gap Flux Monitor:* Feasibility Study (1011282), 2004

BIOGRAPHIES

GREG C. STONE is an electrical engineer who graduated from the University of Waterloo, Canada in 1975. He subsequently obtained a Ph.D. in electrical engineering from the same school. From 1975 to 1990, Dr. Stone worked for the Research Division of Ontario Hydro, at the time the largest electric power utility in North America. He eventually became responsible for the testing of high voltage equipment such as the 1200 large motors and generators in Ontario Hydro's system. Greg Stone was also one of the developers of on-line partial discharge test methods to evaluate the condition of the high voltage insulation in stator windings that are used on most large generators and many large motors in North America. Since 1990, Dr. Stone has been employed at Iris Power in Toronto Canada, a company he helped to form. Iris Power designs, manufactures and sells on-line partial discharge test equipment for machines as well as creates and sells expert system software to help maintenance personnel evaluate motor and generator winding condition.

Greg Stone has published over 125 technical papers and has been awarded 3 patents. He has chaired several IEEE committees that created standards for evaluation and testing of rotating machines. He is past President of the IEEE Dielectrics and Electrical Insulation Society, and continues to be active on many other IEEE committees. He represented Canada on the International Electrotechnical Commission's IEC 2J (Rotating Machine Insulation), and later became its Chair. He is also the Canadian delegate to IEC 15E (Insulation Test Methods).

In 1992 Dr. Stone was elected a Fellow of the IEEE, he was awarded the IEEE Forster Distinguished Service Award in 1993 and was awarded the IEEE Third Millennium Medal in 2001. Dr. Stone is a registered professional engineer in Ontario.

STEVE R. CAMPBELL is one of the four founders of Iris Power. Mr. Campbell is primarily in charge of all instrumentation design, and is responsible for such instruments as SurgeAlert, PDAlert and the TGA family of instruments. Mr. Campbell graduated as an electronics technologist from Sheridan College in 1981.

After graduation he was employed in the Research Division of Ontario Hydro, designing, constructing and evaluating electronic measurement instrumentation. In particular, while at Ontario Hydro he has designed sophisticated electronics for recording high speed surges from vacuum switchgear. fast light pulses from photomultiplier tubes, high speed phosphor emission decay, and 'black body' radiation.

In 1989, Mr. Campbell received the Ontario Hydro Research "Director's Award" for his contributions to the TGA test. While at Iris Mr. Campbell has provided virtually all of the major design concepts for all of Iris' instruments. He has extensive experience in high speed digital design (including ECL), use of programmable logic, use of embedded processors, interfacing to IBM compatible computers and high speed printed circuit design. He has set up and conducted hundreds of field measurements for recording partial discharge and surges. He has co-authored many technical papers, and has a patent as sole inventor of the Stator Slot Coupler. He is also the co-inventor on the TGA-S patent and is co-inventor on one other patent. Steve is presently Vice President of Research for Iris Power

EVENS JOURDAIN is an engineer at the New York Power Authority in the Research & Technology Development group. He's currently responsible for the development of several condition monitoring as well as wireless monitoring systems at NYPA.