

# **EXPERIENCE WITH ON-LINE CONTINUOUS MONITORING OF TURBINE GENERATOR STATOR AND ROTOR WINDINGS**

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Rotor flux monitoring and on-line partial discharge monitoring are well known tools that help plant owners to detect many developing rotor and stator winding problems in air and hydrogen cooled turbine generators. Both monitors are widely used by the utility industry. Most users periodically monitor the flux and PD using portable instrumentation that is connected to permanently installed sensors for a short period of time, usually once or twice per year. However, since 1994, continuous PD monitoring was commercially introduced, and shortly after, continuous flux monitoring started to be deployed.

This paper will describe the continuous winding monitoring systems that are currently in use, and outlines the advantages and limitation of such systems. Case studies of the use of such continuous monitors will also be presented.

## **INTRODUCTION**

As utilities try to control costs while at the same time implementing corporate goals to move to condition based maintenance, there is increasing pressure to apply continuous diagnostic monitoring to detect the most likely problems that can occur in large turbine generators. This is most apparent in the widespread use of continuous vibration and thermal monitoring of the generators. In the past decade, advances in automation, and computer communications has resulted in technology to allow the continuous monitoring of partial discharge to detect stator insulation problems, and continuous rotor flux monitoring to detect rotor winding turn insulation shorts.

This paper first describes experience with PD monitoring, and then discusses rotor flux monitoring.

## **PD MONITORING**

Over the past 20 years on-line partial discharge (PD) monitoring has become the most widely applied method to determine the condition of the electrical insulation in generator stator windings. Presently over 50% of large generators in North American utilities are equipped with the required sensors. Partial discharges (sometimes also known as corona) are small electrical sparks that occur in deteriorated stator winding insulation systems. Over 55 years of experience with on-line PD testing shows that it will detect most (but not all) of the common manufacturing and operations-related problems, including:

- Loose coils in the slot (slot discharge)
- Overheating (long-term thermal deterioration)
- Winding contamination by moisture, oil, dirt, etc.
- Load cycling problems
- Poor resin impregnation during manufacture
- Inadequate electric stress control coatings in the slot or endwinding
- Insufficient spacing between coils in the endwinding area.

Problems such as endwinding vibration, water leaks and/or metallic debris in the machine will often not produce PD as a symptom. Nor will isolated insulation problems that are remote from the machine high voltage terminals – since there will be insufficient voltage to produce the PD.

There are many methods available to measure the PD activity in operating generators [1-3]. The electrical techniques rely on monitoring the current or voltage pulse that is created whenever a partial discharge occurs. The earliest on-line PD measurement methods detected the PD pulse currents by means of a high frequency current transformer at the neutral point [2,3], but today most machines around the world use 80-pF high voltage capacitors on the output bus or special antennae (called SSCs) within the stator slot called SSCs to measure the PD [1,5].

The majority of on-line PD measurements on generator stator windings are done with a portable test instrument, which is connected to the permanently installed PD sensors for perhaps 30 minutes, two times per year. However, there are situations where continuous on-line PD measurement may offer advantages to generator owners. The following these situations, describes the continuous monitoring systems that have been developed and provides some case studies after a brief review of PD measurement technology.

## **CONVENTIONAL ON-LINE PD MEASUREMENT TECHNOLOGY**

A particular challenge with PD measurements is encountered when the generator is operating normally. Since the machine is connected to the power system, electrical interference (noise) is often present. Noise sources include corona from the power system or electrostatic precipitators, slip ring or commutator sparking, sparking from poor electrical connections, and/or power tool operation. This electrical noise obscures the PD pulses, and may cause the technician to conclude that a stator winding has high levels of PD, when it is actually the noise. The consequence is that a good winding is incorrectly assessed as being defective, meaning that a false alarm is given suggesting that the winding is bad, when it is not. Such false alarms reduce the credibility of on-line PD tests, and even today, many feel that on-line PD testing is a ‘black art’ best left to specialists.

Twenty-five years ago, the North American utility industry (via the Canadian Electrical Association) sponsored research to develop an objective on-line PD test for machines that could be performed and interpreted by plant staff [1,4]. The type of PD test emphasized separating PD pulses from electrical noise pulses. For turbo generators less than a few hundred Megawatt, 80 pF capacitors detect the PD, while blocking the high AC voltage. In these machines noise separation methods depend on digitally comparing the time of pulse arrival between a pair of 80 pF capacitive couplers on each phase and/or analyzing the shape of the individual pulses [1,4]. To maximize the signal-to-noise ratio, and thus also to reduce the risk of false indications, the sensors detect the PD at frequencies of 40 MHz and higher. For larger turbo generators, it was found that some sorts of noise from within the generator – for example from stator lamination sparking or poor electrical contacts at the gas seal bushing, could be misinterpreted by the capacitive sensors as stator PD – leading to false indications. This led to the development of the SSC sensor which is installed within the stator slot, and seems to be very immune to false indications [5].

Globally, well over 8000 machines have the required PD sensors. Interpretation of the PD results is done by analyzing each test result and trending the stator PD over time. The false indication rate using the appropriate sensors and noise suppression methods is less than about 1.5% of “high” readings. Experience shows if the PD magnitude doubles, under the same operating conditions in 6 months or so, the rate of insulation deterioration is increasing significantly [1,4]. More recently, based on a statistical analysis of data from >85,000 tests, tables of what constitutes a high reading as a function of generator ratings and PD detection system have been published [1,6].

## CONTINUOUS ON-LINE PD MONITORING SYSTEMS

Stator winding insulation deterioration is a relatively slow process in which the time between when significant PD can be detected and when winding failure may occur, is usually two or more years in air-cooled machines, and even longer in hydrogen-cooled machines. Thus, periodic measurements done once every six months or so are often adequate for detecting stator winding problems with sufficient warning to conveniently implement corrective action. However, there are several situations where continuous monitoring may be advantageous:

- Expert systems are being deployed which continuously monitor all the sensors in a generator (for example temperature, vibration, air gap, current, voltage, etc.) to determine if any problems are occurring anywhere in the generator [7,8]. This provides plant operators as well as maintenance personnel with warnings that a problem may be developing, and also gives advice on corrective action. Since the partial discharge activity is an important source of information with regard to the stator winding condition, it is desirable that generators equipped with such expert systems have ready access to PD data.
- The stator winding PD activity is often affected by generator operating conditions such as winding temperature, load and voltage, as well as environmental humidity or hydrogen pressure [1]. For example, if a winding is loose (i.e. the stator bars can vibrate in the slot), an increase in generator load will cause the PD activity to dramatically increase. Although these operating-condition-dependent results help in interpreting the type of deterioration occurring, they often make it difficult to trend PD data over time. To obtain trendable data, which is critical for interpretation, the machine must be tested under the same load, temperature and voltage conditions. For units that are subject to frequent load cycling, it is often difficult for the plant operators to recreate exact operating conditions from test to test. Continuous PD monitoring solves this problem by continuously measuring the generator operating conditions, and then storing the PD measurement at which the proper operating conditions occur naturally during normal operation of the machine.
- Many generating plants are located in remote areas, making it is expensive to transport test personnel to the site for doing a conventional PD test. A continuous monitor can allow the PD measurements to be made remotely, without the need for sending personnel to the plant. This will reduce overall operation and maintenance costs.
- Sometimes periodic on-line PD monitoring has identified a stator winding that has a high risk of failure, but operating considerations prevent an immediate repair or rewind. By installing continuous PD monitoring, plant maintenance and operating personnel can keep a closer watch on the stator winding, possibly extending the winding life with a lower risk of a catastrophic in-service failure.

For the above reasons, first generation continuous PD monitoring systems were developed for hydro generators, and after some teething pains, were successfully deployed [9-11]. However, these early systems had a relatively high installation cost and did not enable generator operating data to be extracted from the plant computer. Under a joint development project between the USA-based Electric Power Research Institute and the New York Power Authority, a next-generation continuous monitor called HydroTrac was developed. This technology was then extended to the more difficult situation (from a noise point of view) of turbo generators. Today, more than 1000 machines have been equipped with continuous PD monitoring systems.

### Hardware

The new continuous monitor employed exactly the same noise separation methods that had been used for many years for periodic monitoring. Also, great care was taken to make sure the same PD quantities such as  $Q_m$  (peak PD magnitude) and NQN (essentially the integrated PD activity) were

produced, to facilitate seamless trending with past data obtained from portable instruments. A block diagram of the hardware is shown in Figure 1.

A key difference between the new system and past continuous monitors is how the generator operating and environmental data is collected. Instead of measuring the generator operating and environmental quantities such as kV, MW, MVar, hotspot temperature and humidity using a direct analog feed from the measuring detectors in the generator – this information is obtained from the plant computer. This greatly reduces costs, not the least of which is associated with running analog signal wiring to the monitoring system hardware.

Since every utility seems to be using different proprietary communications systems and protocols, the system had to be designed to be very flexible in both physical connection options and communications protocols. For local configuration and control, the acquisition units have an RS232 port. For remote operation and integration with other systems, an RS485 port is utilized. An addressing scheme on the RS485 bus allows for connection of up to 127 instruments (Figure 1).

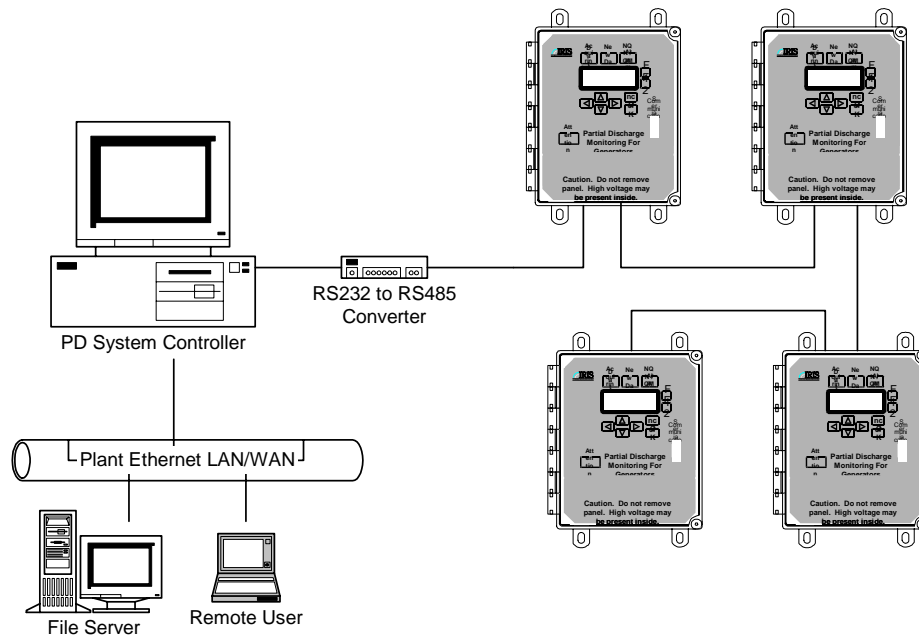


Figure 1: Connection of multiple PD monitors to a single control computer.

The RS485 network can physically be fiber optic or shielded twisted pair cable. Ethernet communication is possible through any number of third-party terminal servers to convert either one or more monitors to TCP/IP Ethernet. At that point, additional communications options such as WiFi are possible.

Utilizing any of these physical communications schemes, the system can be controlled via a remote Windows™ application. This control software is used to configure the monitors at each generator, trigger PD data collection on a defined schedule, and archive the data in a database for later review. Even if communications should fail to the control application, the instrument continually collects and archives data in its local memory, storing up to 24 months of summary PD data. This data can also later be accessed either locally or remotely communications for trending and review.

The control software also has the ability to trigger PD data collection based on the generator state. PD levels fluctuate with parameters such as MW, MVar, stator winding temperature, and humidity. Knowing these variables can smooth PD trends and provide additional diagnostic information on the stator winding condition. These parameters can be fed to system via a 'PI' interface from a plant PI

server (OSI Soft™). Many other plant SCADA and diagnostic software packages also contain bridges to PI.

Some plants prefer to use 4-20 mA analog outputs to facilitate trending the PD activity over time on plant SCADA, DCS, or other monitoring systems. In addition to the physical interfaces described above, external systems can connect using an "OPC" software interface. In this case, the OPC Server software must be running on a Windows™ computer connected to each continuous PD monitor. This server exposes an OPC Data Interface to any number of OPC clients. The OPC Server controls the PD monitors and exposes PD summary data and pulse magnitude analysis data as a set of OPC tags. Finally, the system has an alarm output relay, which can be wired to a remote system and will be activated when predetermined PD levels are exceeded.

## PD CASE STUDIES

### Case 1

A large US chemical plant with 4 turbo generators began portable PD testing in 2001 with the installation of Stator Slot Coupler sensors on 2 new units before commissioning at site. These units, G1 and G2 were air-cooled, two-pole machines with epoxy mica insulation and rated 13.8kV, 125 MVA. Over 3 years of periodic testing, one of the machines began to show pronounced increases in PD levels (Figure 2).

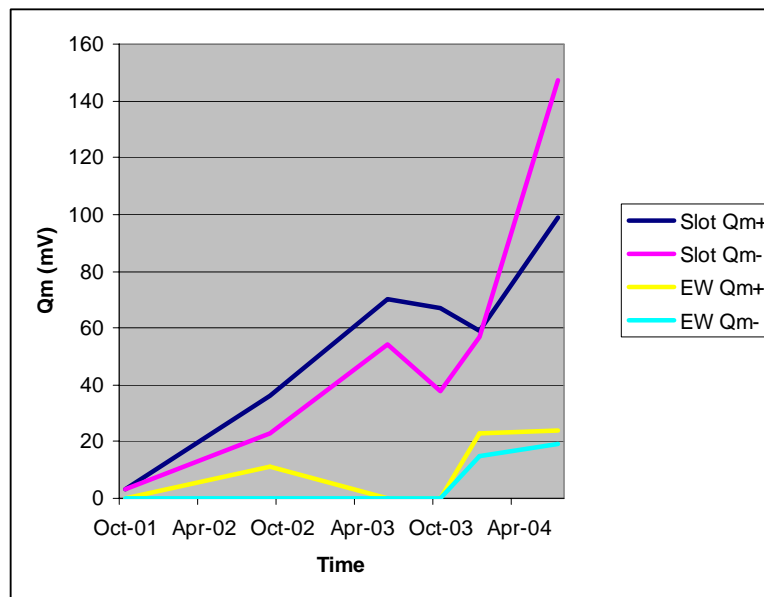


Figure 2: Significantly increasing trend over several years from portable instrument testing

Data analysis indicated some thermal deterioration was leading to delamination. Also the pulse pattern in 2 slots showed some form of open-air arcing, which would typically be caused by an ineffective interface between the semi-conductive, and voltage grading layers. The situation was monitored as closely as possible with periodic portable instrument tests but inevitably one of the 2 identical units failed in service. Figure 3 shows some of the arcing at the semi-conductive voltage grading area during an inspection of the second unit. The root cause was a very high operating temperature on one end of the stator, together with an inappropriate PD suppression system design.



*Figure 3: Deterioration at bar exits from core*

Based on these findings, both units were rewound. For the rewind machines, the customer chose to install two 80 pF PD sensors per phase, allowing them to opt to use a less expensive continuous monitoring instrument. Since installation in 2004, PD data on the new windings has remained relatively stable with a slight increase on one unit.

## **Case 2**

A Canadian utility installed continuous PD monitors on 2 identical air-cooled generators rated 13.8kV, 3600 RPM and 60MW. These machines were new in 2001, and because of their relatively small size 80 pF sensors were utilized. In smaller machines, sources of internal generator noise are minimal, thus couplers on the bus can be very cost effective in detecting machine PD without concern for false alarms. In this case, the machine outputs also fed long cable runs and therefore sources of external system noise could be separated from stator PD on the basis of pulse shape, since noise pulses are distorted as they propagate along the power cable [1, 6]. Thus only one PD sensor per phase was used, enabling the deployment of an inexpensive continuous monitor, more typical of what is used for motors.

The machines were air-cooled, 3600 RPM, 60MW, with a modern epoxy mica stator insulation. As part of installation and commissioning of the PD monitors, a baseline set of measurements is taken to determine the optimal alarm sensitivity. Typically the alarm level is set at the 90% level from a statistical PD database of similar machines. In this case, one of the machines already had PD levels on one phase external to the winding beyond this level, which caused immediate concern. Figure 4 shows the maximum  $Q_m$  levels for each machine.

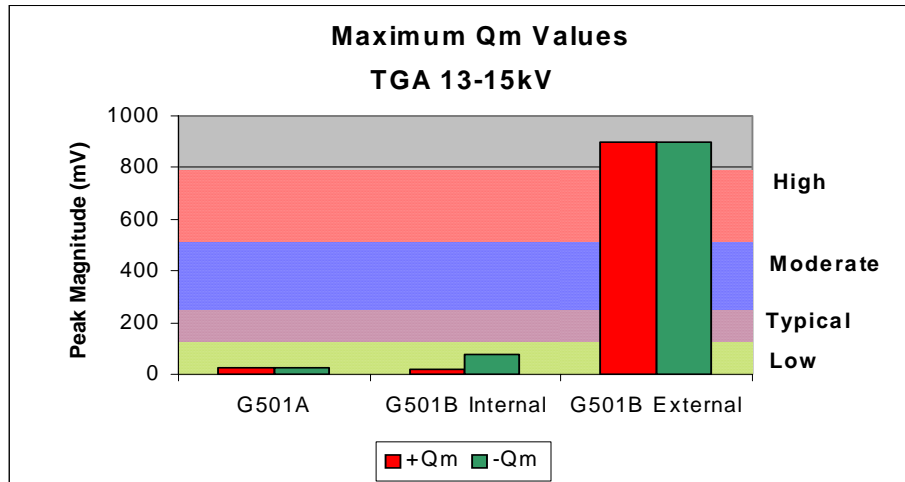


Figure 4: PD level comparisons between two identical stators (G501A and G501B), together with the external noise (G501B external)

Based on these readings, in spite of some very high signals that were detected, the insulation system for both generators was considered good. The overall condition of the B unit is comparable to the A unit and showed many of the same sources of PD. However the discharges that appear to be from a source exterior to the B machine led to much concern. Further investigation showed that discharges external to the B machine were coming from a source on phase A and then in turn were being cross-coupled to the other phases at a reduced magnitude. This situation was monitored over several months and was determined to be stable. During the next available outage a loose connection was found on phase A during a visual inspection of the terminal box. After cleaning and tightening, the unit was returned to service and has displayed moderate PD levels since.

## FLUX MONITORING

A turbine generator rotor consists of a solid forging made from magnetic alloy steel and copper windings, assembled in slots machined in the forging. Wedges secure the winding in the slots with retaining rings used to support the end sections. Problems with rotors result from exposure of winding copper and insulation to high centrifugal loads and thermal expansion forces, leading to breaks in winding insulation and to copper cracking and dusting.

Modern rotor winding insulation is most frequently made from epoxy/polyester glass/Nomex laminate strips for interturn separation and molded channels for insulation to ground in rotor slots. In the end winding additional insulation blocking is used to mechanically support the coils and a molded insulation ring is assembled from laminate materials to insulate the top turns from the retaining rings. Slip planes are provided in regions where the largest relative thermal expansion are expected; this reduces the risk to insulation damage and limits the shaft thermal unbalance and excessive vibrations.

The rotor insulation must withstand electrical, mechanical, thermal and environmental stresses, including:

- Mechanical wear, distortion, breakage and migration due to centrifugal mechanical loading and thermally induced expansion and contraction cycles; - Overheating due to overloading/over excitation and inadequate or diminished cooling. Local overheating may occur at high resistance braze joints and at shorted turns

- ❑ Contamination from copper dusting, or induced from ventilation, bridges creep distances with conductive deposits resulting in surface tracking between turns or to ground;
- ❑ Over voltages from voltages induced from system events or from firing circuits in static exciters can puncture turn and ground insulation in regions already weakened from other causes

The condition of the rotor winding insulation is difficult to assess even during generator maintenance outages. Access to the winding is severely restricted without removal of the retaining rings and winding wedges. Off-line tests for detection of shorted turns and ground fault locations are often unreliable due to the intermittent nature of faults at speed and at standstill.

On-line flux monitoring via permanently mounted air gap flux probes is a proven technology in synchronous machines to determine if turn-to-turn shorts have occurred in the rotor winding. Flux measurements are the most powerful means of monitoring the condition of rotor windings on-line and can provide information on the integrity of the rotor winding inter-turn insulation. This information is critical in planning maintenance, explaining abnormal vibrations, and verifying new and rewound rotor integrity [1,12].

To maximize the sensitivity to shorted turns in all rotor slots, the signals from the flux probe needs to be measured under different load conditions ranging from no load to full load [12]. At a zero crossing of the total flux (which is a function of the real and reactive load of the machine), the sensitivity to the leakage flux is highest. Thus, flux readings are taken at various load points depending on the number of slot pairs in a pole pair. With the waveforms digitally recorded at each load step, specialized software can determine the number of shorted turns in each slot, as well as identify the slots with the shorts.

Traditionally, flux measurements have been done utilizing portable instrumentation to digitize the signals and specialized software or expert interpretation. With cost effective modern electronics now available, the rotor flux test lends itself to automated data collection via a permanently connected instrument. In automated plants where generator load data is available, integrating a permanently connected flux monitor with generator load data and operating conditions can completely automate flux measurements, and guarantee the collection of accurate and trendable data. In addition, automated software can directly interpret the collected flux data, providing alarms to plant staff.

## **CONTINUOUS FLUX MONITOR**

A Continuous on-line flux monitor was first installed in 2000 and has been employed on 34 turbo generators to date. The continuous flux monitoring system is an advanced micro controller based instrument designed to monitor sequentially up to four flux probes, or four generators rotors at a plant. The instrument can be calibrated for a wide range of input signal levels and can process signals from existing wedge mounted probes supplied by most generator manufacturers. The data acquisition software has a range of computer connection options and can be operated either locally or from a remote location to collect and store flux data on demand. In a typical configuration the instrument is installed near the generator(s) and connected to the plant LAN. Process data for generator load can be obtained via a PI or OPC interface to a plant SCADA system, similar to that described for continuous PD monitoring.





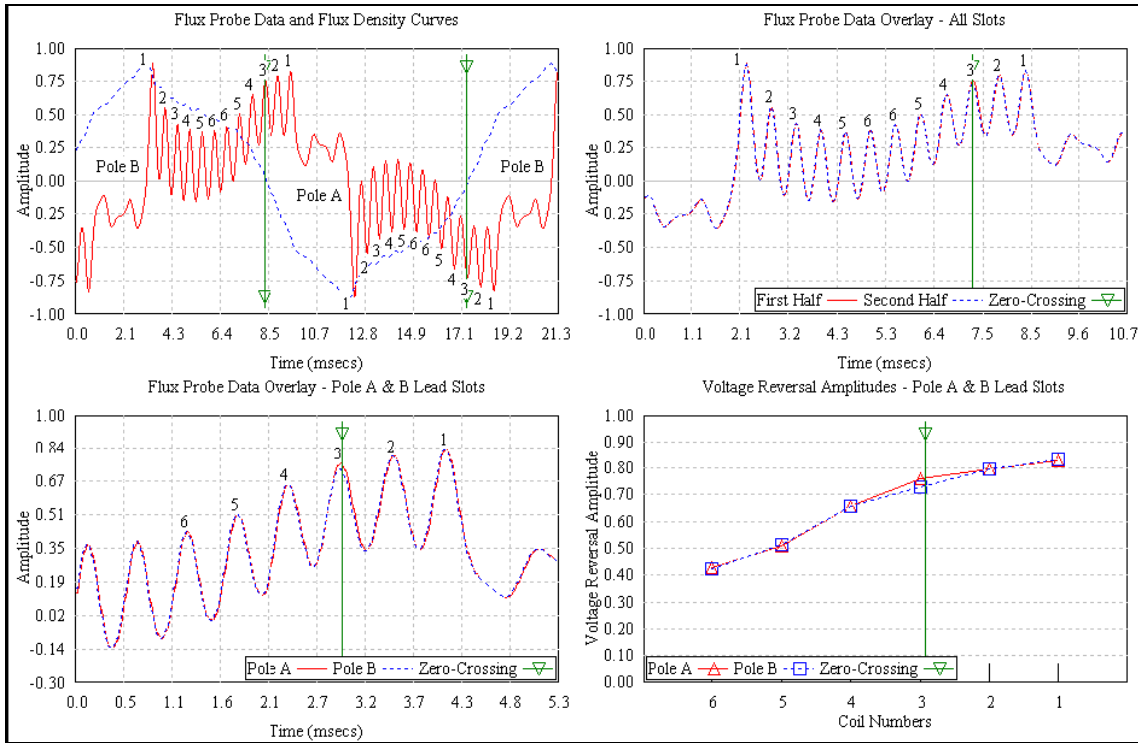
*Figure 5: Continuous flux monitor installed centrally to generators to be monitored.*

The advantages of continuous, automated monitoring for flux measurements can be summarized as:

- ❑ Reductions in staff across the industry make it difficult to perform the portable flux test, especially since staff need to be present at the plant at inconvenient times when generators are scheduled to be run up (or dropped down) from full power. The automated testing capability allows the test data to be collected in the normal operating regime, as the desired load points become available. No staff are needed at site to take the measurements, saving test and travel costs.
- ❑ The system can monitor up to four generators at a plant and provide flux data to remote sites.
- ❑ Data can be automatically analyzed for detection and trending of shorted turns with an already available expert computer software. The plant operators and maintenance personnel obtain early warnings of the developing problems and provide them with opportunities to schedule the required preventive or corrective maintenance.

## **CASE STUDY**

A FluxTrac monitor has been installed for monitoring of four generators at an eight unit combined cycle generating plant in the US. These units are daily peaking units and thus undergo significant start/stop conditions. One of these units indicates possible rotor shorts. The machine is a 1991 13.8kV, 115MW turbine generator. The rotor winding layout is six coils per pole, 20 turns first coil, 25 turns coils 2 to 6. For the plots below, the generator output point was adjusted so that the main flux zero crossings coincide with leading coil sides of both poles in slots slot 3. In this rotor the analysis program [12] indicates a probable shorted turn in coil #3 (Figure 6).



Number of poles= 2 Coils/pole= 6 Max Load MWS=112.0							
Turns/Coil: 1=20, 2=25, 3=25, 4=25, 5=25, 6=25,							
Load Point= 1 MWS= 67.0 MVARs= 8.0 Field Amps= Field Volts=							
Flux Density Zero-Crossing= 2.9, Filter=none, Rotor RPM=3600.0 Peak Height=Modified							
	Pole A	Pole B	Ratio of	Ratio of	Pole A	Pole B	
	Peak	Peak	Sizes	Sizes	Shorted Turn	Shorted Turn	
<u>Coil</u>	<u>Size</u>	<u>Size</u>	<u>A/B</u>	<u>B/A</u>	<u>Indication</u>	<u>Indication</u>	
1	0.845	0.847	0.997	1.003	---	---	
2	0.809	0.813	0.996	1.004	---	---	
3	0.773	0.743	1.040	0.961	---	0.97	
4	0.670	0.668	1.002	0.998	---	---	
5	0.518	0.522	0.992	1.008	---	---	
6	0.435	0.432	1.006	0.994	---	---	

Figure 6: Overlay Plot at 67MW and Shorted Turn Data Table

Detailed design features such as winding layout, slot dimensions, wedge materials, damper winding arrangements, ventilation passages machined in forgings, may influence the flux density distributions under a flux search coil. These need to be identified for their possible influences on analyses results. Further work is needed to enhance the data interpretation of the flux monitor data to reduce false diagnoses caused by these factors.

## CONCLUSION

Continuous on-line monitoring that can be easily integrated with turbo generator plant computer system is now a proven, cost-effective means to determine maintenance requirements for stator and rotor winding insulation systems. These systems enable plant maintenance staff to identify which stators and rotors need attention, and to evaluate the effectiveness of corrective maintenance. Utilizing such an automated continuous system will also allow links to expert system diagnostic software. A line of continuous automatic instruments have been developed and is available for monitoring of PD data and stray flux waveforms. The measurements can be remotely triggered at selectable generator load points and data stored for processing by analytical software.

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