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19 a 22 Setembro 2010
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Continuous Integrated On-line Monitoring for Hydrogenerators

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ABSTRACT

Advanced on-line monitors are now available for most components of a hydrogenerator. These include stator windings, bearings, air gap, and most recently rotor windings. This paper will describe continuous on-line monitors available for these components, as well as a system which can integrate their output with conventional operating data to provide complete asset management.

Partial discharge (PD) testing has become the most pervasive tool for assessing the condition of the stator winding insulation during normal operation of a hydrogenerator. In the past, the testing was done with a portable measuring instrument. More recently, cost-effective continuous PD monitoring systems have been developed and will be described.

Shaft vibration protection systems have long been standard on large critical power generation assets outside of hydro. Because of the increased need for availability of hydro assets this measurement has now become a standard part of most specifications in hydro plants for both new unit and refurbishment projects for medium and large turbines. A system has been developed which leverages the years of experience in monitoring critical power generation equipment for the specific monitoring requirements of low speed hydraulic machinery.

While many hydrogenerators do not experience alignment issues within the generator, in large diameter generators the size of the components and the forces involved during operation lead to an increased likelihood of variations in air gap due to relative flexibility of the stator and susceptibility to temperature expansion. The development on an online air gap monitoring system, rotor and stator mounted, combined with other monitoring systems is key to early identification and repair of issues in order to extend unit life.

Although salient pole field 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 themselves that there are no shorted turns on the field poles. A new continuous on-line

monitor for rotor flux has been developed and proven effective in detected shorted rotor poles in salient pole machines and will be described.

These technological advances in sensors and monitors can greatly benefit from integration into higher level diagnostics. Combining the results of these on-line monitoring systems leads to a much more comprehensive diagnostic. HydroX™ (for Hydro Expert) is a knowledge-based expert system program for on-line monitoring of hydro-generators. Working with the New York Power Authority, the system was developed over five years and a prototype sytem will be decribed which has been in operation for 2 years on two 55MVA generators at NYPA's St. Lawrence Power Project.

KEYWORDS

On-line monitoring, vibration, flux, partial discharge, air-gap.

SENSORS AND MONITORS

The cornerstone for any on-line monitoring system is the ability to monitor all the critical machine parameters and to analyze and corrlate the data from these monitors into actionable advice. As well as normal process data (load point, temperature, coolant flow, etc), specialized monitors that are important to the expert system diagnostics include air-gap, bearing vibration, stator partial discharge, core vibration, winding vibration and flux. Having suitable cost-effective monitors for these parameters is the first step in developing a comprehensive monitoring solution. This section describes a suite of monitornig technologies which are prerequisites to a total diagnostic solution.

PARTIAL DISCHARGE

Many rotating machine outages are caused by long term stator winding insulation aging ultimately leading to winding failure [1]. Thus, a large amount of the testing and maintenance costs in utility plants is devoted to assessing the condition of the stator winding, and performing required repairs or rewinds when the risk of failure is high. Since the mid 1970's, the primary tool to estimate the stator winding insulation condition for hydrogenerators is the on-line partial discharge analyzer (PDA) test [2].

Partial discharge testing involves measuring the small electrical sparks that occur in voids in the insulation system as it deteriorates. As the magnitude and the number of these PD pulses increase, the winding insulation is closer to failure. By trending the PD activity, utilities are able to assess the insulation degradation and plan maintenance outages and repairs. Typical winding aging conditions, which can be detected by partial discharge testing, include:

- loose wedges
- insulation delamination
- separation of copper-insulation bond
- deterioration of semi-conducting coating
- conducting particles or dirt deposits on the endwindings
- damaged semi-conducting/grading coating overlap area
- cracks on winding insulation
- problems related to thermal, mechanical, and/or electrical aging of the insulation

The results of PD testing are generally summary numbers derived from the standard pulse height analysis plots obtained from a PD test. Most users track the these numbers over time, compare them to other similar machines, or more recently compare their readings to a statistical database of over 140,000 PD tests collected over the past 20 years. If the summary numbers dramatically over several months or so, then further testing is initiated. A more careful look is then taken at the pulse height and, if available, the phase PD data to determine the actual cause of the PD. Furthermore, when high PD is detected, many users repeat the partial discharge tests under specific generator load and temperature regimes to further clarify the results.

Experience has shown that if the PD activity increases significantly with load (at a constant winding temperature), then the windings are likely too loose in the slot. Also, if the PD activity decreases with increasing winding temperature at a constant load, then delamination of the insulation due to overheating or load cycling has resulted. Tracking PD activity as a function of generator operating conditions helps to differentiate amongst the failure processes, and thus the maintenance required.

Although the PDA test is now widely used to warn of stator winding problems, effort is still required to make the test results more meaningful, and reduce the costs of acquiring the data. The dependence of PD activity on generator operating conditions can lead to problems when trending the PD activity. For the trending to be meaningful, the tests must be done under tightly controlled generator operating conditions. If these conditions are not the same from test to test, then the trend data may be in error, leading the maintenance engineer to false conclusions on the condition of the winding. In pumped-storage plants or other units which are frequently cycled, performing the PDA test under the same operating conditions is particularly difficult since the load may frequently change. Therefore, the cost and resources necessary for reliable PD testing using portable instrumentation can be significant. These difficulties, as well as the move toward more automated plants and diagnostic sytems, have led to the application of automated PD testing instrumentation.

VIBRATION

History

Condition monitoring of rotating machinery based on vibration analysis has been widely accepted and used in many sections of the petrochemical and power generation industries for decades. In the early 1960's the first generation of non contacting eddy current based proximity sensors were introduced followed shortly by the first generation of continuous online monitoring systems to detect levels of vibration measured by the sensors [10].

Over the following decades, vibration monitoring systems have changed a great deal with advanced filtering and measurements as well as the interconnection to software for data viewing and correlation. While more complex and thorough monitoring systems gained acceptance in many power generation areas many hydro turbine/generator machines still had very simplistic protection systems such as vibration switches if any system at all.

Initially the same monitoring systems used on high speed power generation equipment was simply applied to hydro turbines. While at the concept level vibration monitoring of a hydro turbine generator is the same as other equipment it has distinct differences as well. Current monitoring systems address these issues and provide functionality specific to the new realities of the hydro market [9].

One of the primary differences is the low rotational speed. From a vibration standpoint this is significant because centrifugal forces and frequencies intermixed with system natural frequencies due to high speed are one of the primary causes of malfunctions in turbomachinery. On hydroturbines the dynamic components are often low and are not amplified because machinery operates below any natural frequencies.

The second distinction is the orientation of the machine. Vertical machines behave differently than horizontal axis machines, especially in monitoring bearing vibration where the effect of gravity preloading is not significant and thrust bearings where the weight of the machine is entirely supported by the thrust bearing.

The third major difference is the interaction between the hydraulic behavior of the turbine and the mechanical structure of the machine. In many cases the primary driver of vibration, particularly at the turbine guide bearing, is the hydraulic interaction between the turbine and water. Examples of this include rough load zone (Figure A), cavitation, water hammer, flow separation, etc. This is significant because it often generates vibration signatures not tied to the running speed of the machine and requiring specific signal conditioning.

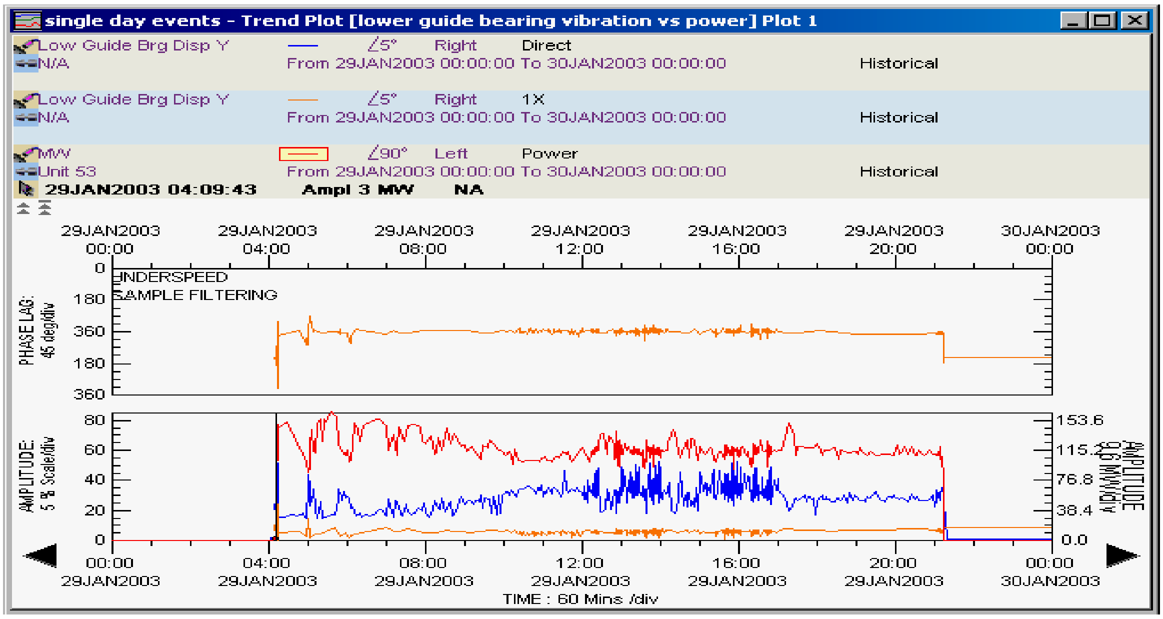

Figure A - Graph showing rough load zone behavior as MW loading varies

Hydro Vibration

Bearing Vibration

Bearing vibration is the primary vibration measurement performed on hydro turbine/generators. Bearings are typically the closest clearance locations within the machine train and will be the first element damaged due to high vibration. In addition the bearings provide the primary support for the machine train and any motion in or around the bearing can directly impact the machine support structure. There are two primary types of measurements at the bearing level. Relative motion between the shaft and the bearing is measured using an eddy current proximity probe and the output of 2 orthogonal sensors can be combined to show the vibration in each axis as well as the 2-D shaft orbit as shown in Figure B below. These sensors must be able to measure motion from DC to a minimum of 1 kHz and should be operable in an environment that contains dirt, moisture and oil.

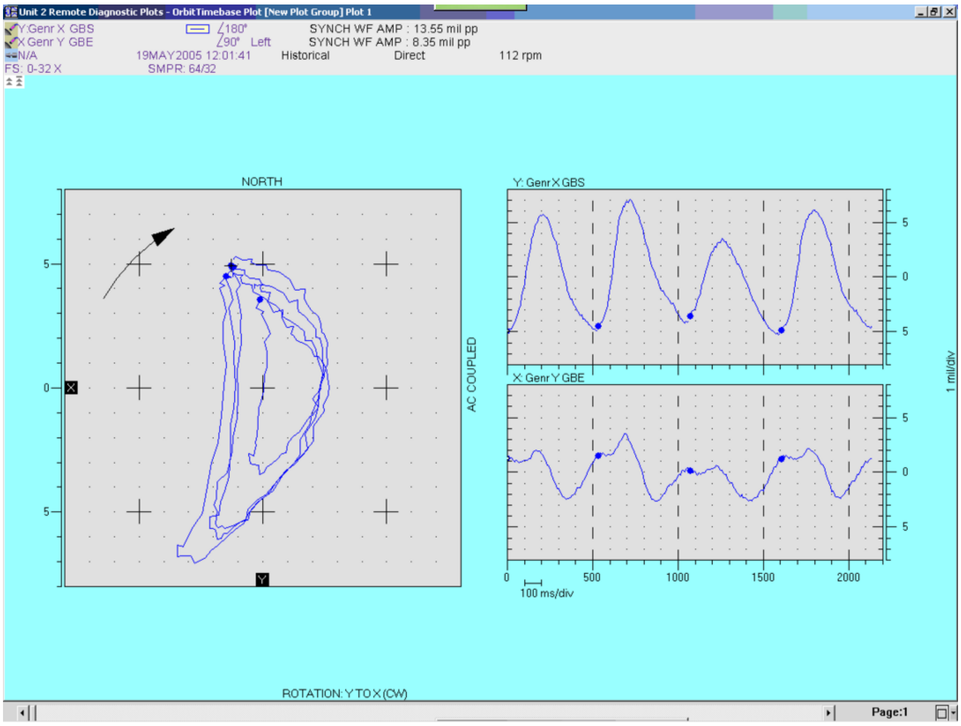

Figure B - Graph showing generator guide bearing vibration waveforms

The second measurement is the motion of the bearing housing using a velocity or acceleration sensor. Due to the low running speed of the machine, for maximum sensitivity the measurement should be made using a moving coil velocity seismoprobe and the output integrated to displacement. Because of the low running speeds of these machines, these sensors should have a minimum frequency response of 0.5 Hz.

Thrust monitoring

Thrust monitoring on hydro generators is unique among machine types because many of them have thrust pads mounted on spring beds. This style of bearing can make monitoring of the bearing operation difficult because as the machine goes from stopped to loaded the axial position can easily change more than 100 mils. Compared to the oil film thickness of 2 mils to 5 mils it is difficult to measure the bearing operation. In this case thrust position can be monitored to verify proper axial position.

On machines with fixed pad or hard pivot tilting pad bearings the oil film thickness can be measured directly using 1 or more eddy current proximity probes viewing the location of the thrust collar on the shaft as shown in the example data in Figure C.

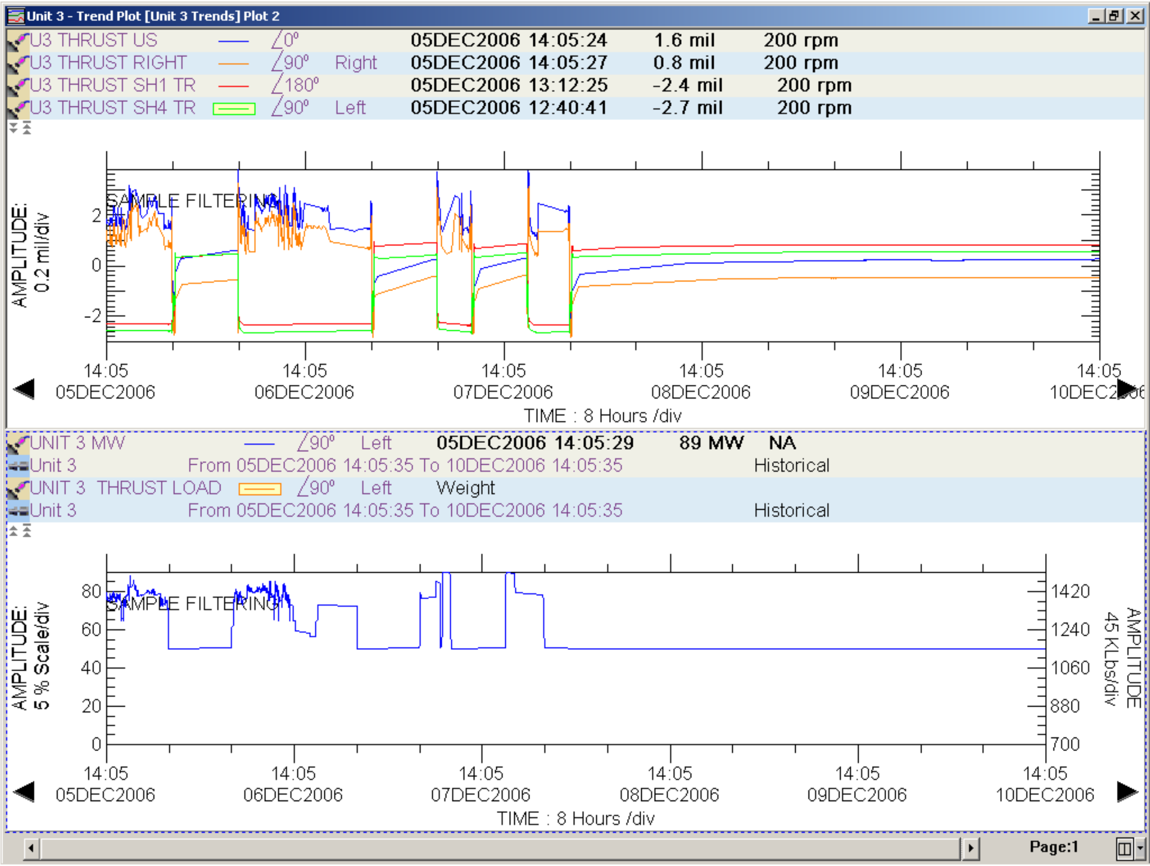

Figure C - Graph showing thrust bearing oil film thickness as MW varies

Stator Vibration

Stator cores and frames are subjected to huge cyclic loads and should be monitored for the deterioration of the support stiffness. In operation the generator poles apply magnetic loading on the stator iron that fluctuates in magnitude as the rotor poles pass. This generates a mechanical load at twice line frequency. Monitoring of the stator is performed using acclerometers mounted to the frame and/or core and the signal filtered to line frequency and 2x line frequency to monitor for increases in the level of motion of the stator over time.

AIR GAP

Air gap measurements are used to determine the geometrical state of alignment of the generator. The underlying principal is simple, the generator rotor and stator need to be round, plumb and concentric. Typically when a generator is put into service the air gap is verified before the unit is finally closed up prior to startup. In addition to this offline measurement, the online monitoring system provides real time measurement while the machine is operational, providing the added benefit of seeing how the unit changes with respect to centrifugal forces, temperature, and magnetic loading.

There are many causes of distortion in the generator air gap. Construction defects, design defects are often caught during construction and commissioning. The online monitoring system can be used to commission a unit but also has the benefit of detecting issues not present during the commissioning period. One cause of air gap faults is thermal change. In large generators there are typically slip planes allowing thermal growth to occur during operation. Issues with slip planes will cause a distortion of the air gap leading to an air gap minimum leading to localized heating and greater magnetic loading. In order to be effective, the monitoring system must be able to provide a view of the entire air gap of the generator during any operating state of the machine.

Stator

Stator mounted air gap sensors are the industry standard method to measure air gap. The measurement provides the shape of the rotor by direct measurement and if performed correctly can provide an indication of the shape of the stator as well. The sensors are mounted directly to the stator wall and measure the distance between the stator and rotor. This provides a continuous measurement of the gap to the rotor, plotting this provides the direct measurement of the rotor. By installing multiple sensors on the stator and measuring the gap to the rotor for each sensor you get a measurement of how far each sensor is from the rotor. This means you can measure how far the stator is from the rotor at each point where a sensor is installed. Installing more sensors provides higher resolution of the stator shape. This is why most air gap installations require a minimum of four air gap sensors installed at 90˚ increments around the stator, larger diameter generators should have more sensors installed [8].

Stator mounted sensors measure the rotor profile and calculate a gap value for each pole on the generator rotor, this gives a profile resolution on the rotor shape equal to the number of poles on the generator. The monitoring system will calculate certain values for trending and alarming purposes including the maximum, minimum, and average air gap for a given revolution of the machine. The monitoring system will combine this measurement with any once per turn event such as a Keyphasor® and provide not only the gap but the location of maximum and minimum gaps as seen by that sensor. In the event the once per turn event is not available or has become invalid the maximum and minimum will still be provided but the location cannot.

Software is used to view the rotor profile, air gap, and the combined rotor and stator profile by combining multiple stator mounted sensors as shown in the example data in Figure D.

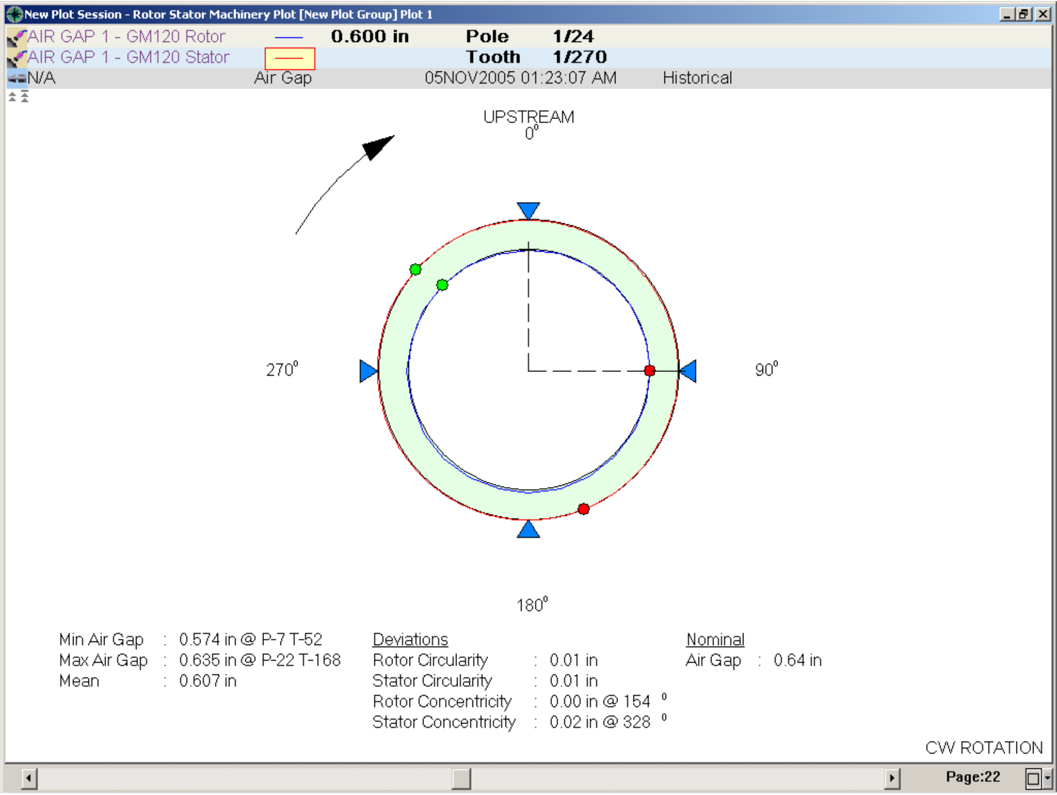

Figure D - Graph showing combined rotor and stator shape utilizing online air gap monitoring

Stator mounted sensors are most common because they provide an adequate amount of information and are easily installed. The negative aspect is that it takes many sensors in order to provide a good indication of stator shape.

Rotor

For larger generators the stator is often more flexible and complex in construction due to size and thermal issues. For these large machines a better indication of the stator shape is needed. The method for providing this is the combination of a minimum of one stator mounted air gap sensor and one rotor mounted air gap sensor. The premise of the measurement is the same, the sensor mounted to the stator scans the rotor profile for the rotation of the rotor while the sensor mounted to the rotor scans the stator profile. There are multiple benefits to this measurement including lower number of installed sensors and much greater resolution of the stator shape [7]. As opposed to getting an indication of the stator gap at 4, 8, 12, or 16 points (where the stator sensors are located) you can easily directly measure the gap at 1° intervals along the stator as the rotor turns.

The sensor power and signal in most cases can be transferred on and off the rotor using commercially available instrumentation slip rings.

Rotor mounted sensors provide similar measurements to stator mounted sensors: max, min, and average air gap readings but rather than pole numbers it gives the location of the minimum and maximum in terms of degrees from any machine reference you choose.

FLUX

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 several dozen turns that is glued to stator teeth. As each rotor pole sweeps by the flux probe, a voltage is induced in the flux probe that is proportional to the flux from the pole that is passing the probe. The voltage is then measured by a rotor flux analyzer. 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 magnetic flux from the pole. The voltage can then be recorded and each peak of the waveform represents the “average” flux across one rotor pole. Any turn short 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.

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. This algorithm was verified in real machines where artificial shorts were induced in a pole and then removed for comparison.

Flux probes used in high speed turbine generators are usually designed in a shape of a cylinder and installed in air gap between stator and rotor. Since the air gap in hydro-generators is much smaller and the rotor construction is different, flux probes used in high speed turbine generators could not be used in hydro-generators.

A new type of the probe [6] has been designed to overcome the disadvantages of existing designs. The new probe compromises of a number of printed circuit layers, printed on a flexible base material. The flexible probe is designed for application on a stator tooth. The very low profile of the installed probe enables its use on hydro-generators with small air gaps. Two types of instruments are available; portable and permanently installed continous instruments. Both instruments are capable of automatic load change detection and have ability to store a number of measurements in internal memeory.

Data collected from Total Flux probe installed in a hydro-generator are shown in the following Figure. The generator was started and the loaded in steps of 5 MW to the rated load of 40 MW.

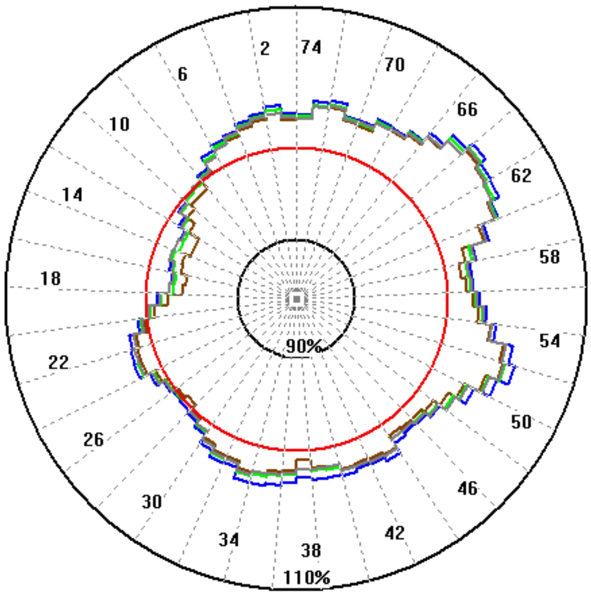

Figure E - Graph showing rotor pole flux compared to average of all poles

The above figure is collection of test results at different loads, where each pole flux is compared to average flux from all poles. Since flux measured on each pole is a function of not only number of active turns, but also of distance from the flux probe, it is possible to detect unequal pole distance from the stator core. To improve diagnostic, other algorithms where each pole result is compared adjacent poles is used and the results are shown in next Figure. The expecation is that pole with a lower number of active turns (i.e. pole with shorts) will have lower flux compared to its neighbours.

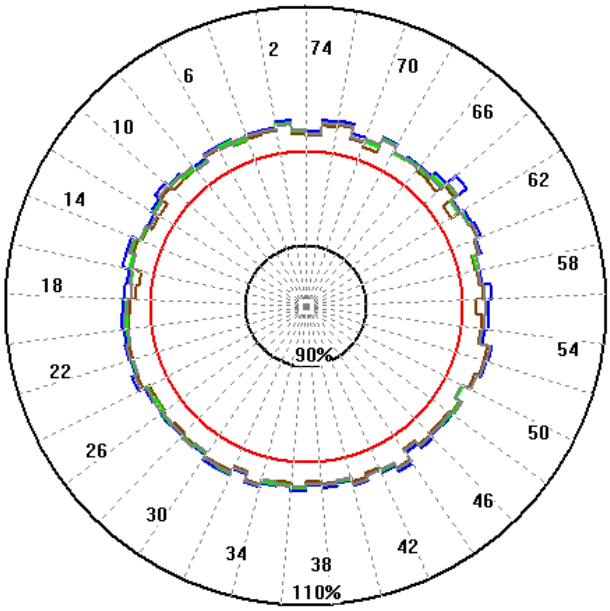

Figure F - Graph showing rotor pole flux compared to adjacent pole

HYDROX

As described above, current technology advances in condition monitoring are employing an increasing number of on-line sensors to automatically monitor the status and performance of the complex systems required for power generation. Proper use of this information can assist in saving operating and maintenance expenses, in addition to reducing unscheduled outages and catastrophic failures. However, the large volume of available data from these complex monitors and sensors can overwhelm personnel and require extensive interpretation. Correctly handling this information requires expertise in machine design and operating limits, sophisticated on-line monitoring instrumentation, and alarm processing and interpretation. The knowledge necessary to perform these tasks generally resides in a group of experts which may include the manufacturer of the electrical equipment, the manufacturer of the test or monitoring instrumentation, plant maintenance engineers, plant operations engineers, and various other specialists on particular aspects of the generator. Thus, although the necessary knowledge for proper operation and maintenance of hydraulic generators is generally available, it typically resides in a wide array of individuals and organizations. Once this information is collected and represented in a diagnostic monitoring system, a broad base of knowledge can be brought to bear to help non-experts investigate a particular equipment problem. The advantages of such a system include:

- Making expertise available to general workers even when a human expert is unavailable. Because expertise is often a scarce quantity, decisions must often be made when a human expert is unavailable. For example the decision to shut down a hydro-generator may often have to be made quickly by an operator in the middle of the night when no human generator experts can be reached.
- Improve the efficiency and consistency of an expert. Experts in one field may overlook the source of a problem that lays outside of their particular area of expertise. An smart monitoring system can focus even an expert user and ensure consistent results.
- Improve the quality of performance of non-experts. A monitoring and diagnostic system can often take the place of a human expert in guiding a less experienced individual through a particular problem. Thus a less experienced staff can still maintain high standards of quality.
- Train less experienced personnel. Because a computer system can be interrogated as to why a particular conclusion was made, less experienced users can gain knowledge about the approach experts use to solve problems.

HydroX™ is a knowledge-based expert system program for on-line monitoring of hydro-generators that employs the advanced monitoring technoligies described above. An ideal time to install such sensors/monitors necessary to support a system like HydroX is during a plant refurbishment / upgrade. At the St. Lawrence Power Project, the New York Power Authority (NYPA) was undertaking a plant life extension project on 16 units and this project provided the platform for evaluating the HydroX monitors and diagnostic rules. During each unit's upgrade, additional sensors were installed to support the expert system and interfaces to the plant control and monitoring systems were created. Using the data acquisition portion of HydroX, data was collected from these systems over time on several units making it possible to identify machine specific behavior and characteristics. The generalized rule-set developed during the HydroX knowledge base development was then customized thru “tuning” algorithms developed to account for specific generator behaviors due to subtle differences in manufacture or external factors such as seasonal changes in ambient conditions.

In HydroX, the prediction of “expected” value for sensors is made based on mathematical models of machine parameters that are then tuned for the specific unit. Part of the expert systems function is to use these predicted values which are compared to the actual measured values and deviations are analyzed by the rules to compute a diagnosis. For example the predictions of thrust bearing pad temperatures are made based on the thrust bearing oil temperature and the MW load on the machine. This basic equation is then customized to account for heating/cooling time constants of the machine with load, and to the actual readings obtained at full load for each sensor which vary due to sensor location and other physical properties.

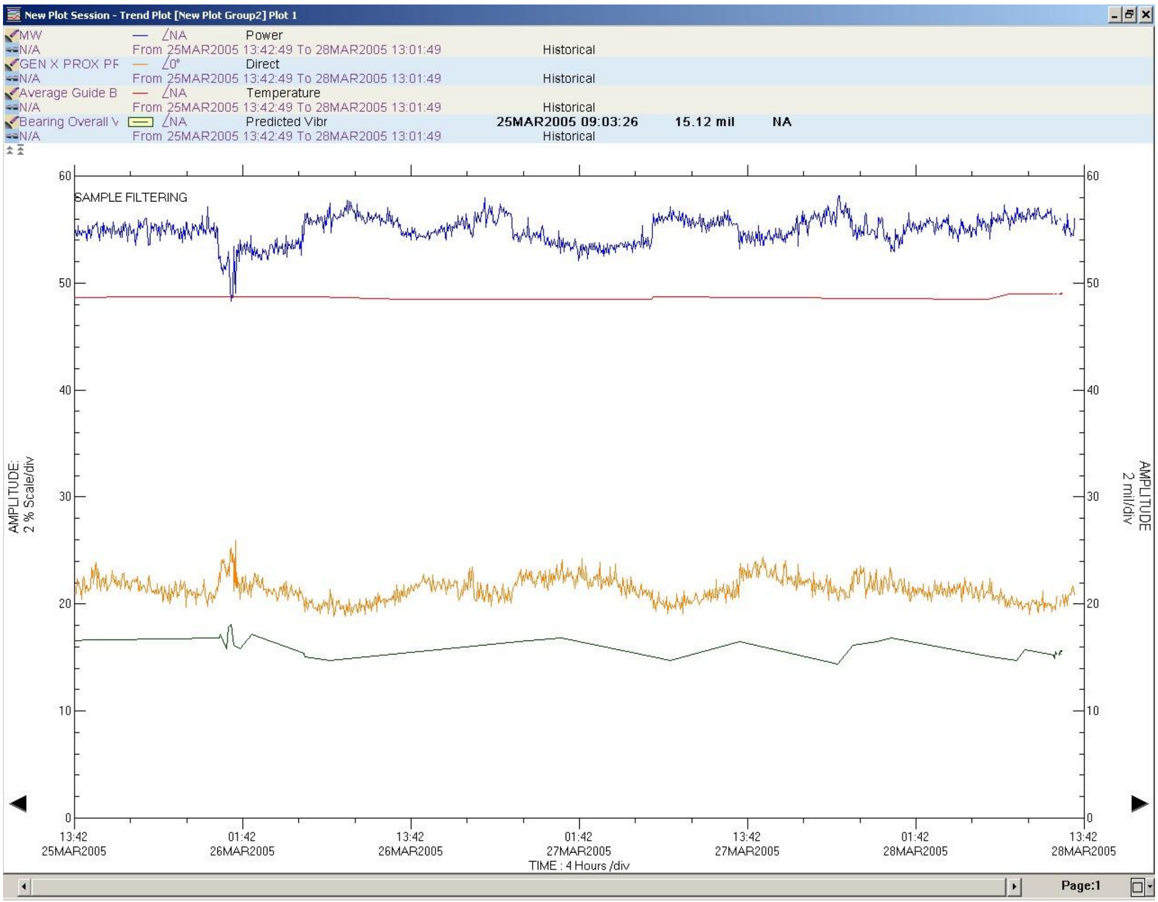

Figure G - Graph showing Comparison of Actual and Predicted bearing Vibration based on Unit load and Bearing Oil Temperature

For many sensors, the alarm thresholds may be significantly different depending on the mode of the machine. An example of this behavior would be air gap measurements, where significantly different nominal air gaps can be expected depending on the machine state. HydroX uses this information to set mode specific thresholds for alarms making the system very sensitive to small changes in each mode.

Current industry trends are to move to more automated plants, with less on-site expertise and operations staff. As described above, HydroX can calculate and trend key features and synthesize summary indications from complex data sets from monitors such as vibration, air-gap, PD, etc. Using these intermediate indicators, along with diagnostic rules, an expert system like HydroX can filter and focus attention to abnormal values, and provide diagnosis of specific faults as well as possible remedies. In addition, trending of such parameters over years can indicate long-term degradation that may otherwise go undetected until damage limits are breached. The layout of sensors and monitors used at the NYPA test site are given in Figure H below.

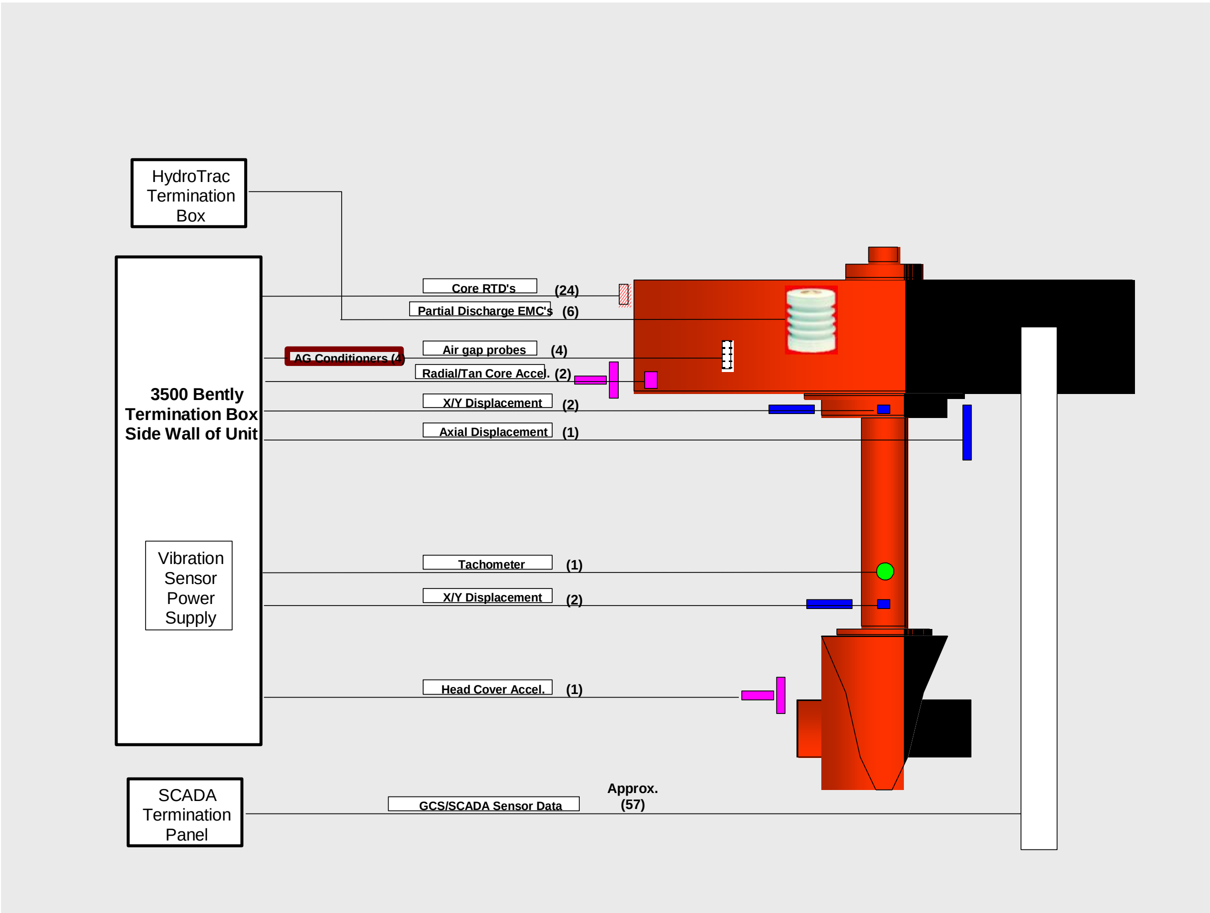

Figure H - HydroX Sensor Set

As each of the 16 units in the plant are refurbished (a 10-year program), the identical sensor set is installed and connected to HydroX for each unit. Once completed, all 16 units will be monitored. Based on the successful deployment on 2 units at St. Lawrence, a commercial Rulepak for HydroX has been created. It is expected, that during future deployments at other sites, interfaces will be developed to sensors and monitors from other vendors.

CONCLUSIONS

As described in this paper, hydro-generator monitoring is employing an increasing number of complex on-line sensors and systems. These monitoring systems provide complex data which often requires considerable expertise in interpretation. Proper use of this information can assist utilities in saving operating and maintenance expenses, in addition to reducing unscheduled outages and catastrophic failures. However, the large volume of available data from these complex monitors and sensors can overwhelm personnel and require extensive interpretation. Correctly handling this information requires expertise in machine design and operating limits, sophisticated on-line monitoring instrumentation, and alarm processing and interpretation. Systems such as HydroX can automate the process of data collection and analysis and provide significant advantages over conventional SCADA alarming systems.

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