Best Practice Catalog

Machine Condition Monitoring

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1.0 Scope and Purpose

Condition monitoring of hydroelectric power generating units is essential to protect against sudden failure. Fault development can occur very quickly. Many hydro units are located in remote areas making regular inspection difficult. They are required to have a monitoring system that continuously checks machine condition, remotely indicates the onset of a fault, and provides the possibility of preventative automatic shutdown.

Hydroelectric turbine-generators are subject to forces and operating conditions unique to their operation and configuration. They typically operate at low rotational speeds. Their physical mass and slow rotational speeds give rise to large vibration amplitudes and low vibration frequencies. This requires a monitoring system with special low frequency response capabilities.

1.1 Hydropower Taxonomy Position

Hydropower Facility → Powerhouse → Instrument and Controls → I&C for Condition Monitoring

1.1.1 Condition Monitoring Transducers and Measurements

Performance and reliability related components are primarily centered on the turbine and generator. The primary components are proximity probes (used for vibration and air gap), temperature probes, speed indication, and partial discharge analysis.

A high level of monitoring and diagnostic analysis is available using software that monitors the probes and can react immediately to serious faults and also warn on slowly developing system anomalies which may require maintenance at some time in the future. These slow developing anomalies, such as a breakdown in stator insulation, can be diagnosed with expert systems and a technical condition management system. A proactive maintenance system will include a larger number of probes, flow meters, partial discharge analysis, and other possible instrumentation as opposed to a simple system that trips a unit from only high vibration or high temperature.

Eddy current transducers (proximity probes) are the choice for vibration transducers and monitoring. Eddy current transducers are the only transducers that provide shaft relative (relative to the bearing) vibration measurement. "Relative and absolute shaft vibration measurements are carried out on hydraulic machine sets using non-contacting transducers. Shaft-riding probes with seismic transducers cannot generally be used due to the very low frequency range of the measuring equipment required for low-speed hydraulic machinery. For relative measurements, transducers should be mounted directly on the bearing shell or the bearing pad. If the transducers are installed on the bearing support structure or bearing housing, as is common for vertical machines, care shall be taken that the relative motion between the bearing shell or pad and the transducer itself is small compared with the shaft motion [11]."

Several methods are usually available for the installation of eddy current transducers, including internal, internal/external, and external mounting. Before selecting the appropriate method of mounting, special consideration needs to be given to several important aspects of installation that will determine the success of monitoring.

Eddy current transducers work on the proximity theory of operation. An eddy current system consists of a matched component system which includes a probe, an extension cable, and an oscillator/demodulator. A high frequency RF (radio frequency) signal is generated by the oscillator/demodulator, sent through the extension cable, and radiated from the probe tip. Eddy currents are generated in the surface of the shaft. The oscillator/demodulator demodulates the signal and provides a modulated DC voltage where the DC portion is directly proportional to gap (distance) and the AC portion is directly proportional to vibration. In this way, an eddy current transducer can be used for both radial vibration and distance measurements such as thrust position and shaft position [2].

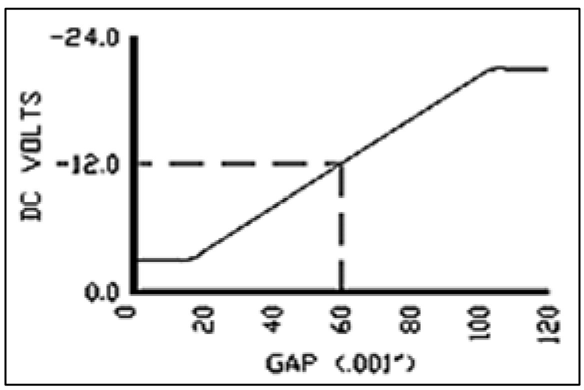


Figure 1: Typical Eddy Current Transducer Curve

- Guide Bearing Vibration Probe (Seismic Transducer): By measuring vibration at the generator and turbine guide bearings, various sources of unbalance, shear pin failure, bearing problems, and wicket gate problems can be determined [1].

- Gap: Gap indicates the distance between the probe tip and the shaft. It is determined by filtering out the dynamic signal (AC portion of the waveform) and looking only at the DC portion of the waveform. This is shown in Figure 1.

- Air Gap Magnetic Flux Transducer: This is normally a single-axis magnetic field to analog voltage transducer for magnetic field measurement and provides diagnostic information of generator magnetic fields and shorted pole coils.

- Thrust Bearing Oil Film Thickness: Large vertical hydro units can weigh over 1,000 tons with the unit's entire weight carried by the thrust bearing. An absence or reduction in oil film thickness at the thrust pads results in the rapid breakdown of the bearing babbit which can lead to further rotor/bearing damage if the oil film is not corrected. On hydro units, the thrust bearing shoes are fitted with proximity probes which observe the thrust collar and provide a measurement of oil film thickness. Frequently thrust bearing oil thickness is accomplished by the rotor vertical position measurement.

- Guide Bearing Temperatures: Bearing temperature can indicate problems related to fluid-film bearings, including overload, bearing fatigue, or insufficient lubrication. One RTD (resistance temperature device) or thermocouple sensor is installed per bearing pad.

- Thrust Bearing Temperatures: Bearing temperature can indicate problems related to fluid-film bearings, including overload, bearing fatigue, or insufficient lubrication. One RTD or thermocouple sensor is installed per bearing pad.

- Keyphasor® Signal (*Trademark Bently-Nevada*): A proximity probe observing a once-per-turn notch or protrusion (such as a key or keyway) on the machine's shaft which provides a precise reference signal used for indicating rotational speed, filtering vibration to multiples of running speed (such as 1X, NOT 1X, and NX – see definitions below), providing vibration phase information, and allowing air gap profile data and air gap magnetic flux. The proximity transducer is generally mounted near the upper guide bearing. The shaft's notch or projection should align with an established reference on the rotor such as the generator's #1 pole.

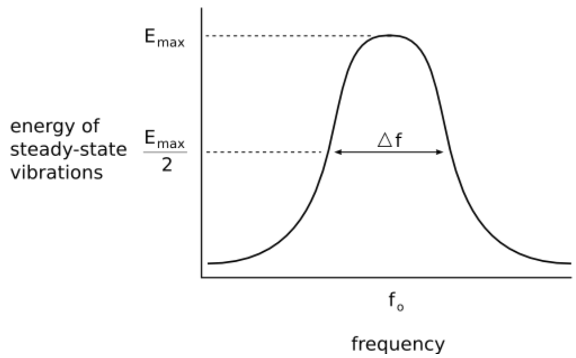
- 1X Amplitude and Phase: This is a measurement of the vibration that is synchronous with rotor speed (1X). A tracking filter with a Q equals 18 (see Figure 2) is used to attenuate all other components. This measurement is valid at speeds between 25 rpm and 1500 rpm which are applicable for most hydro-turbines. This measurement is used to determine acceptance regions and provide data for detecting forced vibrations that may be introduced by bearing wear, unbalance, wicket gate damage, blade damage, generator faults, debris passing through the machine, and other conditions. An amplitude and/or phase change can be indicative of the above conditions [4].

- NOT 1X: This is an overall vibration measurement with the 1X component attenuated. This is a measurement of all vibration components except those occurring at shaft rotation speed. This measurement uses a tracking filter with a Q of 18 to attenuate the 1X component. With the 1X signal attenuated, which is usually the predominant component in hydro-turbines, the remaining signal will be the sub-synchronous vibration due to rough zone conditions and/or super-synchronous vibration. Therefore, the NOT 1X is the primary measurement used for rough zone vibration. Fluid instabilities occur during partial loads and running closer or below the minimum operating level of the turbine. The operating range, where fluid instabilities occur, is considered to be in the rough zone.

In addition to alarm set-points, an option can be implemented on the NOT 1X measurement for enabling or disabling a trip. This may be used to prevent other alarming while the hydro-turbine passes through the rough zone. Alarm delays may also be set to allow time for the hydro-turbine to pass through this zone [4].

- <u>NX (Amplitude and Phase)</u>: This is a measurement of the vibration that is an integer multiple (NX) of the rotor speed. A tracking filter with a Q of 18 is used to attenuate all other components. “N” may be configured to an integer value selected by the operator. Typically, this is used to detect guide vane blockage or shear pin failure, but it may be used for detection of other faults that will cause super-synchronous vibrations. One major cause of super-synchronous vibration is reduced water flow through a wicket gate. This will cause a low-pressure region, and each time a blade or bucket passes through it, an impulse is felt on the rotor causing a super-synchronous vibration equal to the number of blades. The NX measurements are additionally useful for condition management of Kaplan and Pelton turbines. Setting “N” equal to the number of blades will cause the NX amplitude and phase to be detected [4].

- <u>Composite – Gap and NX</u>: The composite measurement combines the gap and NX amplitude to provide a means for detecting and alarming on shear pin failure or other types of conditions that change the flow of water through a wicket gate. In addition to the NX vibration caused by the newly created low-pressure region, the shaft position will also move toward the low-pressure area. The gap measurement will detect the change in shaft position. Composite is simply the NX amplitude multiplied by the percent-change in the gap. These two major indicators of shear pin failure are combined into one convenient measurement to provide extra machine protection [4].



The bandwidth, Δf, of a damped oscillator is shown on a graph of energy versus frequency. The Q factor of the damped oscillator, or filter, is $f_0/\Delta f$. The higher the Q, the narrower and 'sharper' the peak is. Q= $f_0/\Delta f$. In other words, Q is a filter's center frequency divided by its bandwidth and is a measure of how narrowly the filter can pass the desired frequency and attenuate all other frequencies

Figure 2: Definition of Q

- Draft Tube Vibration: Certain operating conditions can give rise to cavitation, an implosion of vapor cavities in the liquid. Cavitation can damage the turbine, erode metal, affect efficiency, and eventually force a shutdown. Cavitation is measured with an accelerometer mounted on the draft tube. By monitoring for draft tube vibration with an accelerometer and filtering appropriately, cavitation can be detected and conditions can be adjusted to avoid operating the unit in this damaging region.

- Runner Cover Vibration: This vibration measurement is helpful in measuring the quality of the sealing system. This vibration can also inform about rotor vertical vibrations due to change of pressure between the upper part of the runner and runner cover.

- Stator Frame Vibration: Vibration of the stator core and frame can cause fretting and damage to the winding insulation. Uneven air gaps can also cause the stator core to vibrate. Low-frequency seismic transducers are mounted on the outer diameter of the stator core and frame. By mounting an appropriate seismic vibration transducer on the stator core and frame, such problems can be detected before serious damage occurs.

- Generator Temperatures: Temperature sensors are installed in locations such as in stator slots, air cooler inlet and outlet, water inlet and outlet, etc., providing important information on stator condition. The system provides alarms and alerts operators when temperatures are outside of acceptable limits. [1]

- Cooling Water Flow and Cooling Water Temperature: Cooling water flow may be an interlock and/or a permissive on some systems. Cooling water temperature tends to be informational only as it varies with ambient conditions. The quantity of cooling water flow, above the interlock minimum, is a minor variable in condition monitoring. This flow measurement is normally an analog device such as a magnetic flow meter or an orifice plate with a differential pressure measurement converted to flow.

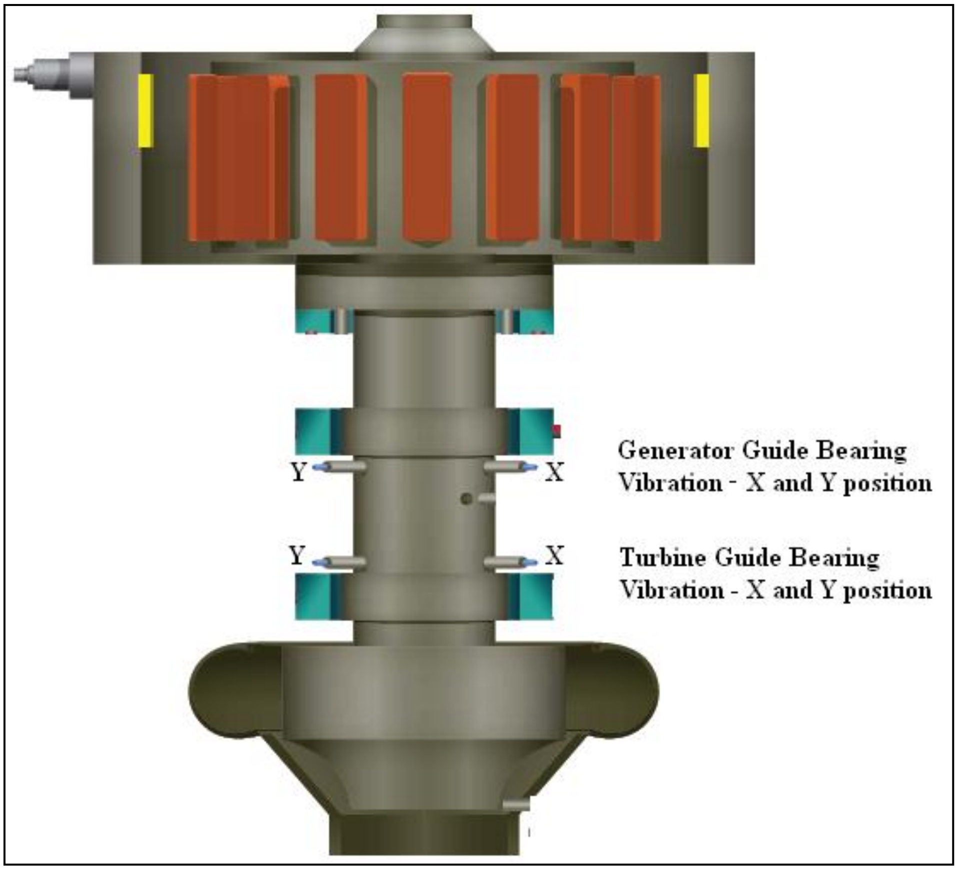


Figure 3: Showing both Turbine and Generator Vibration XY Probes [8]

Radial vibration and position probes are typically located at each bearing in "XY" pairs. The probes in each XY pair are mounted 90° to each other, thus giving a complete view of shaft radial vibration and position at the probe pair location. The bearing vibration probes measure rotor vibration.

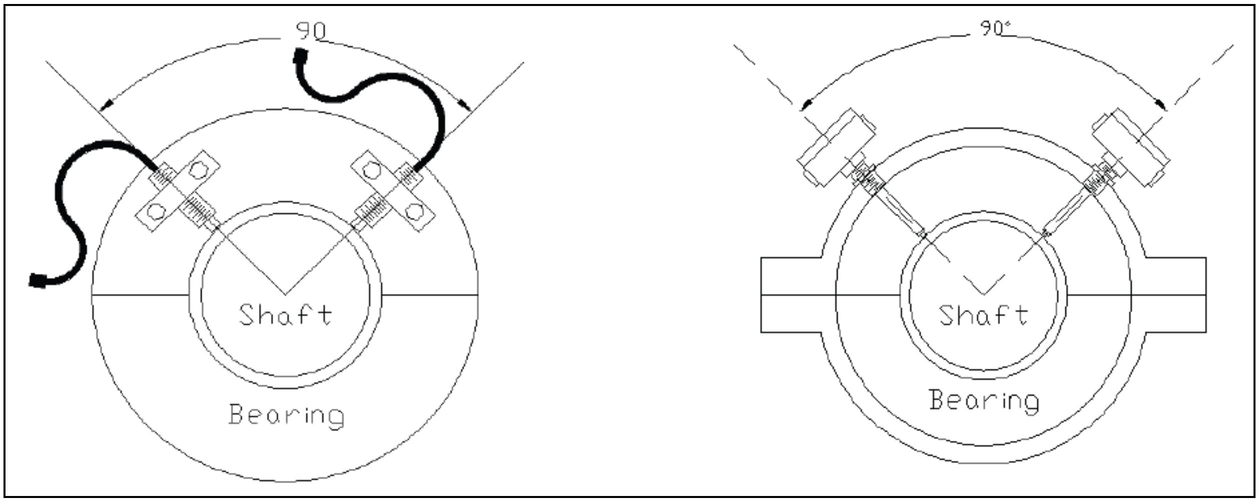


Figure 4: Showing X and Y Probes with Internal or External Mounting [2]

Radial vibration measures the basic dynamic motion (vibration) that is perpendicular, i.e. radial, to the axis of the shaft. The amplitude of radial vibration indicates how "rough or smooth" the machine is running. On critical plant rotating machinery with proximity probes, radial vibration is expressed in units of mils (thousandths of an inch) peak-to-peak displacement.

Radial position provides information about the average position of the shaft within the bearing clearance. Fluid-film bearings, whether sleeve or tilting pad, have clearances between the shaft and bearing which permits the shaft to ride at different positions within the clearance. The average position is a primary indicator of proper machine alignment and bearing loading both of which are key to managing vibration to acceptable levels.

The Keyphasor® probe provides the timing marker required to measure the phase angle of vibration. Accurate phase angle is necessary for in-situ rotor balancing and is extremely important for analysis of machinery malfunctions as well as magnetic flux measurement.

1.2 Summary of Best Practices

Best practices for machine condition monitoring can have a significant impact on plant efficiency and generation. A condition monitoring system can predict a pending failure and avoid machine stressors, detect deterioration earlier, reduce the length and frequency of outages, provide root cause analysis, and improve availability and overall efficiency. The system can be used as a predictive maintenance tool to reduce unplanned outages. The system can be used as a standalone condition monitoring and analysis system or it can be integrated with the plant's automatic control system.

1.3 Best Practice Cross-references

- I&C - Automation
- Mechanical - Lubrication System
- Electrical - Generator
- Mechanical – Governor
- Mechanical – Raw Water System

2.0 Technology Design Summary

2.1 Technological Evolution and Design Technology

Vibration analysis was typically performed by a mechanic or the operator by observing a dial indicator. This is still the only method in older facilities. Recent developments in vibration sensor, data acquisition, and analysis technologies, however, are making vibration analysis cheaper, easier, and more widely available.

Air gap and vibration data is now being incorporated into model-based diagnostics. Models create virtual sensors where physical sensors are not able to be installed. An example is where real data from physical sensors mounted on the bearings at the shaft ends is used to create a virtual sensor for mid-span vibration.

Detailed analysis is now available in near real time for stator insulation failure, stator grounding issues, and stator vibration. These problems were previously only determined by expensive shutdowns and testing when the unit was disabled. Even when the unit is down, it can be very difficult to identify stator problems. The testing is expensive and time consuming. Partial discharge measurements are used exclusively to identify problems with stator insulation. Measuring magnetic flux to uncover a non-uniform magnetic field during rotor rotation between the rotor and stator is becoming more common. The flux transducer is usually connected to the stator.

2.2 State of the Art Technology

State of the art cannot be discussed without mentioning the hardware required. Having all the sensors mounted, as listed below, and tied to a supervisory system that has model-based software, is the state of the art.

State of the art turbine measurements (See Figure 5):

- 2-axis guide bearing vibration
- Guide bearing temperature
- Guide bearing housing seismic
- Draft tube vibration (may include head cover vibration)
- Rotational speed
- Seal ring position/blade clearance
- Cooling water flow
- Wicket gate position

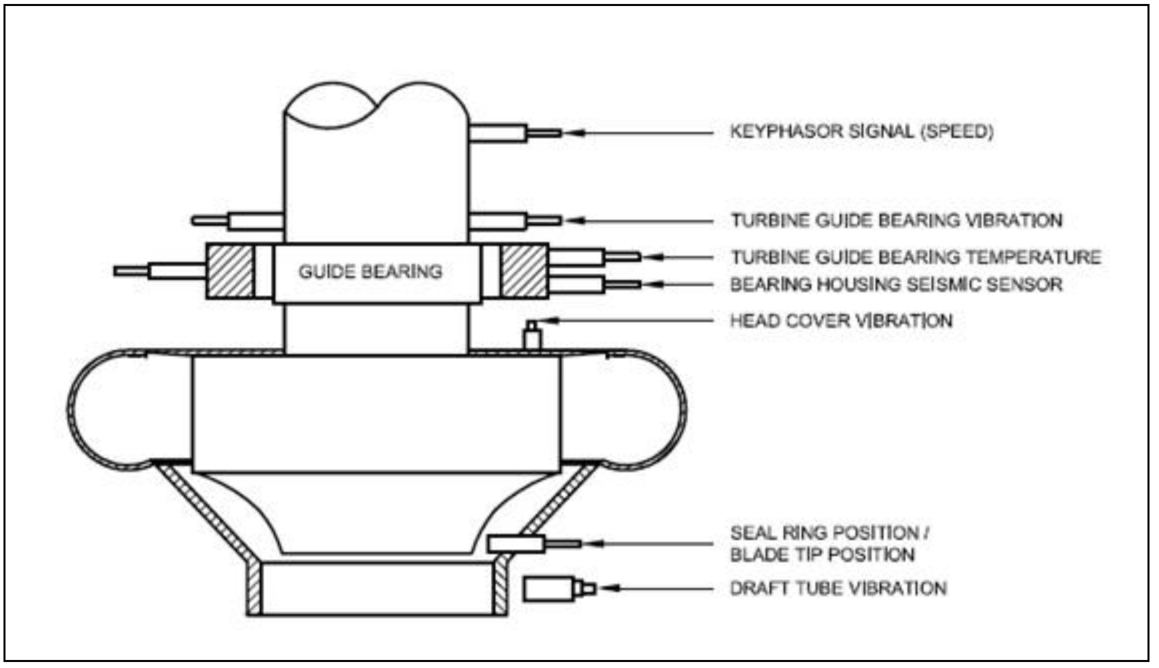


Figure 5: Turbine Measurements [1]

State of the art generator measurements (see Figure 6):

- Air gap
- 2- axis guide bearing vibration
- Guide bearing temperatures
- Thrust bearing oil film thickness
- End winding vibration
- Core vibration
- Stator frame vibration
- Thrust bearing pad temperature
- Generator winding temperatures
- Magnetic flux or partial discharge probes (various types)
- Cooling water flow

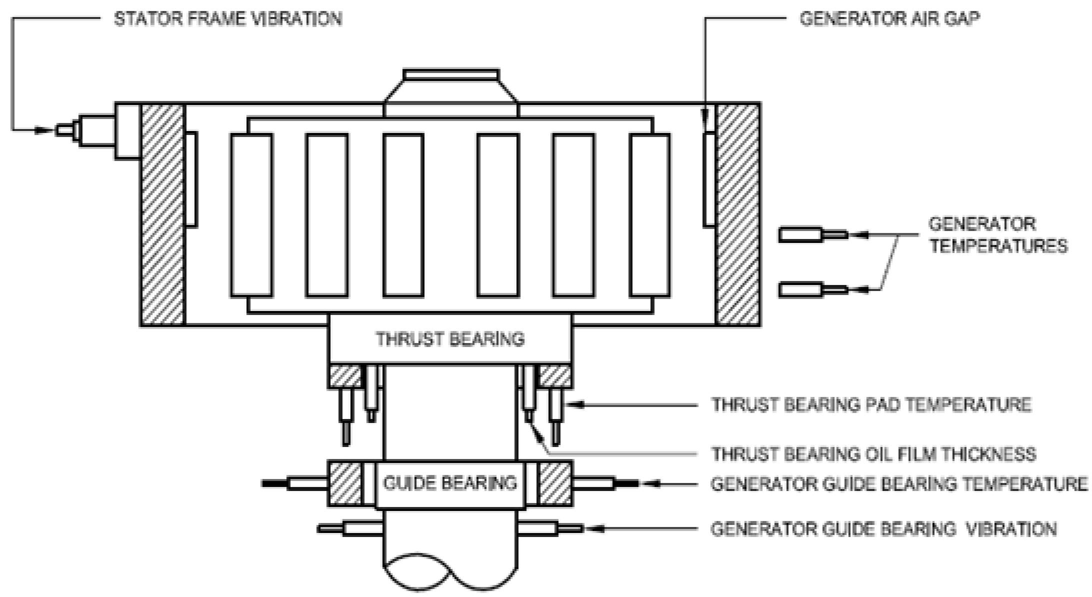


Figure 6: Generator Measurements [1]

3.0 Operation & Maintenance Practices

3.1 Condition Assessment

Assessment criteria:

- What is installed compared to recommended measurements?
- What parameters or variables are available to the (DCS) control system?
- What parameters or variables are available from the (DCS) control system to the condition management system?
- When was it installed? Age of equipment.
- How well was it installed? Proper mounting. Noise protection.
- Long term data for optimization and measure degradation?
- Training of operators? Are they involved in analyzing the data?
- Advanced calculations capability for better outage planning?
- In general, the monitoring and protection system is for the operators. The diagnostic system is for maintenance staff.

3.2 Operations

Monitoring systems include sensors, transducers, monitoring modules, and software. The systems should be fully integrated with a plant's governor and control system to facilitate shutdown and alarming. Many of the vibration behaviors typical to generator units require specialized filtering and signal conditioning. To minimize inaccurate readings and false warnings, the monitoring system must be designed to operate long-term with the expected mechanical loads in a humid environment. The condition monitoring system should have features to prevent false alarms. Typically, the vibration signals must exceed preset limits for a specified time period before warning is given to reduce false trip signals. The monitoring system should also take into account rough zones that may be experienced due to low loads during start-ups.

Turbines in hydroelectric power plants must be able to withstand stresses as a result of rapid starts, stops, and partial loading. These stresses induce fatigue that accumulates and eventually leads to damage. Wear to the journal bearings, damage to the runner blades from corrosion, cavitation, and/or foreign particles in the water supply are other common problems. In many cases, the damage could be avoided with a condition monitoring system and methodology.

Air gap is a measurement of the distance between rotor and stator in the hydro generator. Monitoring of air gap is important as both the stator and the rotor on large hydro machines can be quite flexible, and their shape and location are affected by operating centrifugal, thermal, and magnetic forces. Off-center or out-of-round conditions will at least reduce operating efficiency and in more severe cases can lead to damage from magnetically induced heating or a rotor-to-stator rub. The rotor flexibility is even more serious in the case of variable speed hydro-turbine generators. Such machines require a stronger rotor dedicated condition monitoring system than a constant speed machine [6].

When a hydro-generator rotor system is balanced and aligned properly, the shaft should spin within the confines of the guide bearings without much force being exerted against these bearings. Clearance of guide bearings can be estimated based on data that is acquired during unit startup. This is because the shaft moves in a random “orbit” throughout the clearance set by the guide bearings for the first few revolutions during unit startup. Therefore, when measuring shaft movement for the first few revolutions (i.e., when the radial forces are not significant because of low speed – e.g. 8 orbits after start-up), guide bearing clearance can be estimated quite accurately using orbit analysis. Usually for vertical machines the accuracy is higher if XY transducers are not connected to a guide bearing cover but are connected to bearing pads. This data can be collected for various temperature conditions of the guide bearings for both cold and hot conditions [5].

Overall reliability and effective operation of a condition monitoring system (including monitoring and protection system) is related to a variety of factors including the following: required range of transducers, location of XY and other transducers, transducer cable routing, and available functionality of the monitoring system.

On many hydro-generators, it is simple to replace a transducer if there is an operational problem. However, for some hydro-generators, transducers have to operate in an enclosed space where quick probe replacement can be problematic. Therefore, for hydro-generators, it is important to consider installing redundant XY-transducers to increase the reliability of the monitoring and protection system. The redundant transducers can be fixed as follows:

- Opposite of the current shaft observing XY-transducers,
- Without significant angular shift when compared to the existing XY-transducers,
- Without significant axial shift when compared to the existing XY-transducers.

The term “shift” means that the distance between the two sets of probe tips has to be greater than the probe separation recommendations in the transducer’s technical documentation. If this condition is not met, then an interaction between both transducers can occur (often called cross-talk), decreasing signal to noise ratio [5].

Partial discharge monitoring or analysis (magnetic flux) is a relatively new development. It requires an advanced software package and a good understanding of the unit being monitored. It can determine in real time a failure of stator insulation, stator grounding problems, or stator vibration. Stator anomalies, such as stator vibration, are frequently difficult to isolate when the unit is down for maintenance.

Vibration monitoring remains the most effective technique for detecting the widest range of machine faults, but a number of other techniques are available for specialized monitoring as seen in the Table 1.

Table 1: Condition Monitoring Techniques [9]

	Vibration	Air Gap	Magnetic Flux	Process Values	Cavitation
Mechanical and Bearing					
Unbalance	X				
Misalignment	X				
Rotor rub	X				
Foundation problems	X				
Loose bearings	X				
Oil and lubrication				X	
Stator or rotor bar problems		X			
Generator					
Stator bar/core vibration	X				
Air gap problems		X	X		
Rotor/stator out of roundness		X			
Loose/shorted stator bars or faulty insulation or stator vibration			X		
Turbine					
Turbine runner/blade problems	X				
Wicket gate problems	X				
Turbine blade cavitation	X				X

3.3 Maintenance

Air gap dimension along with rotor and stator shape cannot be effectively measured with the generator out of service because of the combined effects of centrifugal, thermal, and magnetic forces. Early detection of air gap anomalies will facilitate condition-based maintenance by providing the user with important machine data necessary to plan for repairs before scheduled outages. Long term trending of gap and shapes can be correlated with operating conditions and used in operational and rehabilitation planning. Knowing the rotor and stator shapes and minimum air gap dimensions provides the operator with the information needed to remove a machine from service before serious damage (e.g., rotor-to-stator rub) occurs [6].

4.0 Metrics, Monitoring, and Analysis

4.1 Measures of Performance, Condition, and Reliability

Failure modes, that the condition monitoring system helps predict, are listed as follows:

- Wicket gate shear pin failures
- Cavitation
- Blade and shaft cracks
- Bearing rub, fatigue, and overload
- Insufficient bearing lubrication
- Mechanical unbalance or misalignment
- Seal and discharge ring distortion

Insulation breakdown is the ultimate failure in any power generation device. The following faults will lead to the eventual breakdown of insulation.

- Air gap reduction/rub
- Cooling fault
- Winding vibration
- Insulation aging (not directly measureable)

4.2 Analysis of Data

There are numerous software packages available to analyze data from condition monitoring sensors. The high speed data can only be analyzed with computer software that creates charts and calculates variables such as vibration frequencies, changes in air gap, etc. Operators should also be trained to interpret the data and understand how the conditioning monitoring system functions. The operators will then learn to trust the data and use the data for the best local decisions for the plant.

4.3 Integrated Improvements

The best way to gain the benefits of a monitoring system is to take advantage of the economic opportunities offered by various modernization, refurbishment, and new projects to introduce the system and to adapt maintenance practices accordingly. The monitoring system is a major input to a condition-based maintenance program and is a key contributor to capitalizing on high market prices.

The cost of the monitoring system is low compared with the cost of a new power plant. A new plant should automatically be equipped with a monitoring system to minimize maintenance outage periods and to help the unit owner to stay well-informed of the condition of the equipment. [7]

A proper interfacing of a condition management system with a process control system is important for good asset management. A common set up is to have a server with diagnostic software monitoring both the protection system and the control system.

5.0 Information Sources:

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[2] STI Vibration Monitoring, *Eddy Current Transducer Installation*, http://www.stiweb.com/appnotes/PDF%20Files/radial.pdf

[3] Bruel&Kjaer, *Permanent Vibration monitoring on a Hydroelectric Generating Set*, http://www.bksv.com/doc/bo0285.pdf

[4] Orbit, *Exploring the New 3500 Hydro Monitor*, 3rd Quarter 2000, http://www.ge-mcs.com/download/monitoring/3q00cohen.pdf

[5] Orbit, *XY Measurements for Radial Position and Dynamic Motion in Hydro Turbine Generators*, Vol. 30 No. 1, 2010

[6] GE Fact Sheet, *Hydro Generator Air Gap Monitoring*, http://www.gepower.com/o&c/hydro

[7] Hydro World, *Equipment Monitoring: Equipment Condition Monitoring: Sharing Experience*, http://www.hydroworld.com/index/display/article-display/361643/articles/hydro-review/volume-27/issue-2/feature-articles/equipment-monitoring-equipment-condition-monitoring-sharing-experience.html

[8] Orbit, *Condition Monitoring for Hydro Machinery*, 2nd Quarter, 2004

[9] Bruel&KjaerVibro, *Monitoring Solutions*, http://www.bkvibro.com/monitoring-solutions/industries/power-generation/hydroelectric-power-generation/faults-detected.html

[10] *Hydro Life Extension Modernization Guide*, *Volume 7 – Protection and Control*, EPRI, Palo Alto, CA: 2000. TR-112350-V7.

[11] ISO 7919-5:2005 Mechanical vibration -- Evaluation of machine vibration by measurements on rotating shafts -- Part 5: Machine sets in hydraulic power generating and pumping plant.

It should be noted by the user that this document is intended only as a guide. Statements are of a general nature and therefore do not take into account special situations that can differ significantly from those discussed in this document.

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