Case Studies of Problems Diagnosed Using On-Line Machine Monitoring on Hydro-Generating Machines

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ABSTRACT

On-line monitoring systems are valuable tools that provide information to help power producers get the most out of their generators in the safest and most economical fashion. Such systems can detect early signs of anomalies, allow planning of timely corrective actions, and ultimately prevent generator failure. Proven technologies designed for monitoring air gap, vibration, partial discharge, and temperature are available to assess hydroelectric machines under any operating and transient conditions.

Rotor-stator air gap can be significantly affected by a host of factors, i.e. mechanical, thermal, and electro-magnetic. Monitoring the air gap reveals a great deal about the structural condition and dynamic behaviour of a hydro-generator. Combining data from air gap and other parameters through an integrated machine monitoring system allows comprehensive analysis of machine condition and behaviour. This information is valuable for effective operation and maintenance.

The field experience case studies in this paper show examples where such combination of air gap data and other generator parameters has helped the power producers to better manage their generating assets.

Introduction

For years, dynamic measurements taken on hydroelectric machines mainly consisted of vibration, temperature, pressure and level parameters, in addition to the main electrical parameters like power, voltage and current for real-time protection and controls. The advent of micro-processing and personal computers in the ’70s favoured the development of on-line monitoring technologies in the early ’80s, for air gap, partial discharge, shaft current, cavitation, etc. Then emerged machine monitoring systems that could integrate various stand-alone monitoring/measuring technologies. They provide easy to understand information on machine condition through dedicated software.

This paper presents cases based on two such technologies used on more than 800 hydro-generators of all sizes and types: the Air Gap Monitoring System (AGMS®) and the ZOOM® machine condition monitoring system. Both systems rely on the capacitive† measuring technology that provides the high precision and repeatability, essential to proper analysis and diagnostic of hydro-generators.
The benefits of these two systems have been documented over the past two decades and are referenced below:

- Reduce the risk of equipment damage, improve maintenance and outage planning, lower maintenance costs, and increase productivity. This translated into multi-million dollars in savings and additional revenues since 1989.
  R.H. Saunders GS, OPG, Canada [1]
- Avoid a catastrophic rotor failure within months of commissioning while the vibration instrumentation failed to provide any early indication. Air gap data allowed for immediate design modifications to be implemented on all five units.
  Igarapava HEPP, CEMIG, Brazil [2,3]
- Provide valuable information on pre-refurbishment condition to define scope of works and plan generator rehabilitation.
  Grand Coulee Dam, USBR [4,5] and Rock Island, Chelan County PUD, United States.
- Verify tolerances on new or refurbished machines and force manufacturer to undertake remedial work under warranty.
  Arrow Lakes, Columbia Power Corp., Canada

Typical Factors Affecting the Air Gap of a Hydro-generator

The air gap is affected by a host of factors that act on rotating or static components: mechanical, thermal, electro-magnetic and hydraulic. Any radial movement of the rotor, the shaft, the stator and its foundation will impact the air gap. Consequently, it will have an effect on the dynamic behavior and overall condition of the hydro-generator (Fig. 1).

It is often possible to determine what is responsible for a particular air gap variation when studying air gap measurements recorded simultaneously or under various operating conditions. By correlating with other parameters, the diagnostic possibilities are greatly enhanced and identifying the cause of a given problem becomes simple.

VibroSystM’s theory is that, for large and slow rotating machines such as hydro-generators, air gap often measures the anomaly directly or indirectly, thus indicating the exact cause of a problem, whereas vibration typically measures its effects. Although both parameters are complementary, experience demonstrates that air gap monitoring is most important when analyzing the behavior of hydro-generators.

Mechanical Tolerances Guidelines for Hydroelectric Generators

The guidelines used by VibroSystM are based on 20 years experience with dynamic air gap measurements and data interpretation, as well as on the guidelines established by the Canadian Electrical Association (CEA) [6] and Hydro-Québec [7]. The CEA guidelines were initiated in the early ’80s upon request from Canadian utilities and equipment manufacturers as a baseline for negotiations. They were set for manual static measurements. However, VibroSystM’s guidelines have been adapted for automated and computerized dynamic...
measurements obtained with VibroSystM monitoring equipment [8]. The guidelines serve as a reference for machines of different types, sizes and designs.

The values are conservative by design because a) manufacturers safety factor margins are often unknown and b) air gap sensors may not be installed at true critical gap locations. Assembly tolerances are set for new or refurbished generators at commissioning and up to five years in operation. Acceptable tolerances apply to generators in service for five to fifteen years. Critical tolerances indicate generators requiring immediate actions. The values are expressed in percentage (%) of the nominal air gap.

Some machines are known to run beyond critical levels for a long time, while others have failed at much lower values. Thus, constant monitoring of the air gap to detect the rate of change becomes critical.

These guidelines are for reference only. Further results analysis and other considerations may be recommended before initiating an intervention on the machine. With its Results Interpretation Service (RIS), VibroSystM puts 20 years of expertise in data interpretation at your service to perform hydroelectric machine condition and behavior analysis.

**Case Study 1 – Similarities in Premature Ageing Points to Design or Manufacturing Deficiencies**

This first case outlines manufacturing deficiencies in new hydro-generators. An on-line monitoring system can be a valuable asset to provide early annunciation of an anomaly in order to undertake corrective measures early in the life of the machine.

Arrow Lakes Generating Station is the newest hydroelectric plant owned by Columbia Power Corp. on the Columbia River, about 400 km east of Vancouver, in British Columbia, Canada. The powerplant houses two 92.5-MW Kaplan turbine hydro-generators commissioned in the spring of 2002. Actual generation has been limited to ≈60 MW most of the time since commissioning due to low reservoir levels. It should be noted that the generators with a diameter of 11.43 m / 37.5 ft were designed with a reduced air gap of 12 mm / 472 mils to increase their efficiency.

The new generators presented problems from the start. Unit #1 sustained a rotor-to-stator contact upon initial field flash during commissioning tests. The main cause of the rub was a lower bracket that was too flexible and subsequently had to be stiffened. Following this incident, Columbia Power completed installation of an Air Gap Monitoring System prior to restart, to monitor these valuable assets. The system consists of eight sensors to monitor the top plane air gap, and one sensor on the bottom to check the verticality on both units.

The quality of the new machines was assessed in a series of behavioral tests conducted in September 2002 to establish the initial condition. These tests are based on VibroSystM Results Interpretation Service (RIS).
The test report revealed that all generator dimensional parameters failed the assembly tolerances (Table 2) [8]. Some parameters even exceeded critical tolerances. The stators were out-of-round and off-centered (Fig. 2). This condition worsened when the rotors in both units displaced towards the minimum air gap area upon field excitation. The rotors were also out-of-round – the rim of Unit #2 became loose at 50% nominal RPM – and off-centered. Abnormal and irregular movements of the stator frames on the soleplates were suspected. Minimum air gap was close to critical tolerances and average air gap was at least 10% lower than nominal value at all times.

Table 2 – Evolution of Generator Deviations between 2002 and 2005

<table>
<thead>
<tr>
<th>Parameters</th>
<th>September 2002</th>
<th>February 2004</th>
<th>May 2004</th>
<th>Spring 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit #1</td>
<td>Unit #2</td>
<td>Unit #1</td>
<td>Unit #2</td>
</tr>
<tr>
<td>Stator Roundness</td>
<td>13.2%</td>
<td>18.9%</td>
<td>30.0%</td>
<td>33.7%</td>
</tr>
<tr>
<td>Stator Concentricity</td>
<td>6.0%</td>
<td>5.7%</td>
<td>9.1%</td>
<td>7.4%</td>
</tr>
<tr>
<td>Rotor Roundness</td>
<td>11.5%</td>
<td>7.7%</td>
<td>8.4%</td>
<td>5.7%</td>
</tr>
<tr>
<td>Rotor Concentricity</td>
<td>4.6%</td>
<td>3.2%</td>
<td>2.4%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Max. Air Gap Variation</td>
<td>24.7%</td>
<td>26.6%</td>
<td>38.5%</td>
<td>39.4%</td>
</tr>
<tr>
<td>Minimum Air Gap</td>
<td>71.3%</td>
<td>73.3%</td>
<td>66.7%</td>
<td>68.0%</td>
</tr>
<tr>
<td>Average Air Gap</td>
<td>85.5%</td>
<td>88.7%</td>
<td>85.7%</td>
<td>85.0%</td>
</tr>
</tbody>
</table>

Values expressed in percentage of the 12 mm / 472 mils nominal air gap. For Tolerances, refer to Table 1

Such rotor and stator deformations are considered unacceptable on new generators and can potentially undermine the reliability and efficiency of the machines if immediate corrective actions are not taken.

Based on these findings, Columbia Power requested that the manufacturer undertake corrective actions. Work on Units #1 and #2 took place in the spring of 2003. The rotor rims were rerounded and reshrunk, and rotor key welds were repaired. AGMS results showed the rotor roundness improved by 5 to 6% of nominal gap (Fig. 3).

The generators exhibited high magnetic noise level when power exceeded 60 MW and there was evidence of stator vibration. The stator vibration, thermal expansion and movements at field

Fig. 2 - Polar graphs of Unit #1 (left) and Unit #2 (right) Note the deformed rotors (red) and stators (green), as well as center offsets, over circular references (blue).
Fig. 3 - Comparison of polar and rectangular graphs of Unit #1 rotor shape before (left) and after (right) rotor rim rerounding and reshrink in spring 2003. Roundness improved from 12.7% to 7.2%.

Excitation needed further study. In the meantime, stator wedges were inserted between the frame and core to provide a more intimate contact between the two and reduce vibration during operation.

Before addressing the stator problems and other issues, a new set of RIS behavioral tests was conducted in February 2004. The goal was to verify the effectiveness of the rotor corrections and evaluate the evolution of the generator condition since commissioning.

The results indicated an on-going degradation of the stators and a similarity with the premature ageing pattern (Table 2 and Fig. 4). Over the course of two years, the roundness and concentricity of the stators had gradually deteriorated beyond critical tolerances. Their shapes were not uniform and they moved irregularly. The minimum air gap values of 66.7% and 68.0% of the nominal gap on Units #1 and #2 respectively, were a concern (57% upon field flash – cold on both units).

In the second RIS test report, problems with the soleplate keying system and the core-to-frame interface were suspected. Comparison of air gap measurement and frame displacement manual readings using dial indicators outside the stator frame showed significant discrepancies in their behavior.

Fig. 4 - Polar graphs of Unit #1 and Unit #2 in February 2004. The stators have continued to deteriorate dramatically while the rotors have remained stable since rerounded a year before.
The manufacturer's corrective work performed on the rotors in 2003 had mixed results on the two units. However, it may have avoided a rotor-to-stator contact when considering how much the stator roundness had deteriorated on both units. The rotor of Unit #1 had been improved, but was still outside acceptable tolerances at 8.4%. The rim was not sufficiently shrunk and showed signs of cyclic vibration when rotating in the minimum air gap area. The rotor of Unit #2 had been corrected to satisfaction. There was evidence of excessive radial play at the lower guide bearing of both units, which allowed the rotors to displace in the downstream direction upon field application (Fig. 5 and 6). This condition increased the magnetic imbalance, the stress on the rotor and stator components, and the risk of air gap failure. The plant database indicated high temperatures in the combined generator guide and thrust bearing of Unit #2.

The corrective work by the manufacturer in the spring of 2004 focused on the stators. Radial stop blocks were installed to hinder stator expansion/movement in certain sectors and control the deformation. Rotor keys welds were repaired again. Finally, guide bearing segments were opened radially by 0.1 mm on Unit #2 to alleviate the guide bearing heating issue.

The stator vibration study revealed that the primary frequency of the noise was 120 Hz with an elevated contribution at 240 Hz. Although the stator wedge addition helped reduce the noise at high MW, noise at 1/rev. and 2/rev. was still present at lower loads.

The implementation of constraining measures on the stators had a positive effect on the stator shapes and minimum air gap values (Table 2 and Fig. 7). Stator parameters of Unit #1 now comply with assembly tolerances, while Unit #2 still exceeds assembly tolerances.

As a result of the stator vibration study, the manufacturer installed stator winding equalizers in the spring of 2005. The equalizer mitigates the effect of unbalanced magnetic pull by maintaining equal flux in physically opposed segments of the machine. Generators like those in Arrow Lakes, with small air gaps and 2 circuits/phase stator windings, are sensitive to magnetic imbalance from air gap irregularities.

Implementation of the equalizers on the stator windings reduced the noise and vibration levels, as well as improved the stator shape and air gap uniformity (Table 2). The stator roundness, air gap variation and minimum gap of Unit #1 were improved by 1.6 to 1.8%. On Unit #2, which received additional stator adjustments in 2005, the stator roundness and air gap variation were improved.
improved by 3.5 to 3.7%, while the minimum gap was improved by 2.5%. Despite these improvements, Unit #2 deviations still exceed assembly tolerances by far. In addition, rotor torque/drive blocks were refit on both units.

Since the corrective work performed in the spring of 2004 and 2005, the units are showing good stability and the generator roundness and concentricity are slightly improved. This confirms that the modifications by the generator manufacturer have addressed the degradation issue on the rotors and stators for the operating conditions experienced to date, i.e. power output limited to 60 MW.

The careful interpretation of dynamic air gap data from the various tests clearly showed similarities in the premature ageing behavior of both generators. This deterioration and the extent of remedial work on such young machines are considered abnormal. It can originate from a combination of design, manufacturing and assembly deficiencies. However, remedial work has been successful in stopping the degradation. Ongoing monitoring and inspection will continue to be the key to the safe and efficient operation of these generators over their expected lifetime.

Case Study 2 – Rotational Axis Displacement at Field Excitation

The second case discusses a phenomenon observed on the air gap and shaft vibration parameters during post-refurbishment tests performed on a 58-year-old unit in 2001. The 35 MW unit at Brilliant Dam had just been rewound and the ZOOM machine monitoring system was implemented as part of the refurbishment. Brilliant Dam, also owned by Columbia Power Corp., is located on the Kootenay River, 30 km east of Arrow Lakes.

The polar graph in Figure 8 shows that the stator shape is uniform but offset in the downstream (180°) direction, which explains the high stator roundness value. This offset creates a magnetic imbalance when the field breaker closes.

In Figures 9 and 10, Pole graphs of air gap and X-Y vibration at upper (UGB), lower (LGB) and...
turbine (TGB) guide bearings indicate that the rotor rotational axis is magnetically pulled in the direction of the smallest air gap (upstream/0°). Air gap sensors at 0° (red) and 180° (green) in Figure 9 measure opposite gap variations while sensors at 90° and 270° only measure small changes. Figure 10 shows that proximity probes in the Y (0°) axis on UGB and LGB sense the same movement as the air gap sensors, while no such displacement is noticeable at TGB. The UGB and LGB are in close proximity above and below the rotor, whereas the TGB is significantly below the rotor.

Studying shaft orbits in Figure 11 at UGB (left) during field flashing, we see that the shaft follows an elliptical path in the 0°-180° axis at SNL, then moves upstream upon excitation to adopt a new elliptical path in the 90°-270° axis. The same behavior is observed at LGB level. Meanwhile, shaft behavior at TGB (right) maintains a compact circular path. This is not unusual behavior in units with long shafts like those at Brilliant Dam.

It is clear that the magnetic imbalance from the stator offset attracts the rotor in the direction of the smallest air gap. And from orbit analysis, we conclude that the unit tips over with TGB acting as a pivot. The displacement creates greater mechanical, electrical and thermal stress on the stator components in the smallest air gap area.

Upon field excitation, the rotor is magnetically pulled in the direction of the smallest air gap before excitation, near the 0° sensor in this case. The magnitude of displacement is controlled by the radial play settings of the guide bearing. If the displacement is close to the radial play setting, it is then excessive and can produce a high temperature problem of the bearing segments.

To minimize the rotational axis displacement upon field excitation, realigning the rotor further in the downstream (180°) direction, while preserving shaft alignment and verticality should be considered. From the data collected, this realignment could improve the rotor-stator eccentricity and re-establish air gap and magnetic field balance.
Case Study 3 – Parameter Correlation Reveals Abnormal Shaft and Stator Displacement

The third case demonstrates excessive movements of the shaft and stator components. With the ZOOM system ability to correlate synchronized measurements from various parameters, it was possible to investigate the problem and provide the right information to undertake corrections.

In the summer of 2002, the ZOOM system was installed on four 34 year-old hydroelectric machines as part of a major refurbishment at Mascarenhas de Moraes HEPP [9,10]. The powerplant owned by Furnas Centrais Eletricas is located on the Rio Grande River about 200 km north of Sao Paulo, Brazil. The ZOOM system monitors air gap, shaft vibration and stator core vibration among other parameters. Unusual behavior was recorded during a Start-up/Cold test during the re-commissioning.

Comparison of Pole measurement results on Polar, Orbit and X-Y graphs (Fig. 12-14) for generator guide bearing vibration, air gap, and stator core vibration revealed the following:
• High shaft vibration beyond tolerances at Generator Guide Bearing before and after excitation
• Significant shaft displacement and change of orbit shape at Generator Guide Bearing indicating rubbing against the bearing segments
• Significant air gap reduction at field excitation
• Significant rotor displacement at field excitation in a different angle than where minimum air gap occurs
• Alarmingly high stator core vibration before and at field excitation, exceeding the range on all four accelerometers
• Core vibration still very high and beyond tolerances when machine stabilizes
• Accurate evaluation of rotor rim condition and stator shape rendered difficult due to high rotor axis instability.

Fig. 12 - Polar view of generator air gap at SNL (left, turn 19) and Excited (right, turn 108). The stator clearly moves towards 225° location.

Fig. 13 - The large circular orbit displaces towards the 25° angle and changes to an elongated path in the 90°-270° axis.

Fig. 14 - Pole measurement graphs showing behavior of air gap (left), generator guide bearing (center) and stator core vibration (right) during start-up and field excitation.
The data revealed an important difference between displacement values recorded by the probes on the shaft and the sensors in the air gap: Generator Guide Bearing displays a shaft displacement of \( \approx 470 \) µm [18.5 mils] towards the 25° area, while air gap results indicate a displacement of 1.83 mm (1830 µm) [72 mils] towards 25° area as well. This leaves a difference of 1360 µm [53.5 mils], which can be partly explained by the fact that each parameter is measured at different elevations and parts on the machine (guide bearing below rotor vs. upper stator wall). Oddly, the observed displacement is not in the same angle as that of the minimum air gap area (155°) before excitation. This behavior is contrary to typical magnetic imbalance. Therefore, some other factor must be influencing the machine behavior.

Verification of trends over the following 24 hours (Fig. 15) shows that the stator shape quickly returns to its position within the first 3 hours as it heats up while the shaft moves back \( \approx 395 \) µm [15 mils] close to the position before excitation. This indicates that there may be a stator looseness/weakness problem playing an important role in the machine behavior. The orbit now shows a balancing movement of \( \approx 205 \) µm [8 mils] pk-pk in the 135°-315° axis (Fig. 16), and the stator core vibration remains alarmingly high. Both parameters remain abnormally high under all normal operating conditions.

The unit was stopped two months later, and the refurbishment contractor dismantled the machine in an attempt to resolve the main problem and other minor issues. The contractor moved the stator about 1 mm toward upstream to reduce the magnetic imbalance and improve unit behavior. Operation resumed 70 days later. Although this procedure helped decrease the shaft vibration levels when field is applied, the main problem remains. The unit still experiences instability at speed-no-load, significant change of behavior when field is applied, and shaft vibration increase after time. Integrating displacement sensors on the upper part of the stator, behind air gap sensors, to the ZOOM system would help identify the primary cause.

Three other units have been refurbished and all have experienced similar behavior. Two of these units have been shutdown for almost a year until the contractor finds a solution, while the two units with less severe behavior have been kept in operation.

The refurbishment program to extend the life of the units included complete replacement of the stator windings. The insulation was upgraded from class B to F, and the conductor design inside the coils was modified from a four-bar to a one-bar conductor. These changes increased the magnetic pull between the rotor and stator. However, this was done without fully reconsidering the stiffness of the stator assembly and the generator bracket, which could explain the erratic
behavior of the units. The generator bearing flexing allows the shaft to move excessively, which creates a magnetic imbalance that pulls in a loose section of the stator. As the unit warms up, the thermal expansion forces the stator to return to its position, the magnetic imbalance dissipates and the generator bracket brings the shaft back to proper alignment.

In 2005, the contractor added braces to reinforce the generator bracket. The bracket is bolted to the powerhouse concrete foundation and could contribute to the high stator vibration. After this modification, the machine could be balanced and shaft vibration values reduced to levels similar to those prior to refurbishment.

Although the vibration equipment showed a definite movement of the unit in the upstream direction, it is the air gap data that allowed correct identification of the stator behavior. Repairs based on shaft vibration data alone can lead to unnecessary adjustments and modifications to the rotor or bearing components.

In this particular case, both the owner and the contractor highly appreciated the key information the ZOOM system provided to fix and fine-tune the machine. Based on their suggestions, new features were added to the ZOOM software to help diagnose machines with problem similar to those at Mascarenhas de Moraes.

Conclusion

Over the past two decades, on-line monitoring systems have been implemented at many hydro facilities worldwide. As the field examples demonstrated, they can bring a significant contribution to new or refurbished generating equipment. Although it is common practice to implement on-line monitoring technologies during the course of a refurbishment, important data can be recorded and used for analysis, planning and comparison, if the monitoring system is implemented prior to refurbishment.

Both Columbia Power Corp. and Furnas Centrais Eletricas are largely benefiting from their monitoring system to diagnose and correct the problems affecting their machines. In addition, remote monitoring allows engineers at Furnas to keep a close eye on the machines without leaving the Head Office. VibroSystM’s technology and expertise are proven methods to provide valuable information on machine structural condition to optimize operations and maintenance of hydro generating machines.

References


Acknowledgements
The authors thank Ms. Sheila Hagerty from Columbia Power Corp. of Canada, Mr. Flavio I. B. Rolim from Furnas Centrais Eletricas S/A of Brazil, and Réjean Beaudoin from VibroSystM of Canada.

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† Patented technology, Hydro-Québec, Canada
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