Application Note

Case study – Predictive maintenance and its contribution to physical asset management at CEMIG

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ABSTRACT

The Brazilian power company CEMIG, with an installed capacity of over 5700 MW, has recognized the importance of machine condition monitoring for many years now. From 1996 to 1999, permanent monitoring systems were installed in 13 of their hydropower generating stations. The primary maintenance and operation objectives for installing these systems were to reduce machine unavailability, reduce maintenance costs and provide a means for optimizing operation procedures for the generators and turbines. There was also a need to make maintenance and operation planning decisions faster, safer and more reliable.

For the larger power stations, various systems are used for automatic, continuous monitoring of vibration, plus other important process parameters such as air gap, magnetic flux, partial discharge analysis, oil analysis, etc. This provides comprehensive monitoring techniques for detecting and trending a wide range of potential failure modes.

The comprehensive monitoring techniques acquired by CEMIG, however, resulted in numerous stand-alone monitoring systems. As a future objective, a monitoring strategy will be evaluated by the condition monitoring group to use these existing systems in a distributed network fashion so data from the various systems can be correlated together to improve the reliability of diagnoses and for making faster, more reliable maintenance decisions. This would include interfacing the DSCS (distributed supervisory and control system) and CMMS (computerized maintenance management system) to these systems for exchanging data. In addition to this, more monitoring techniques are being evaluated to be added such as cavitation and performance monitoring.

This paper focuses on the monitoring strategy and systems used at the various hydroelectric power stations and the results obtained, including some case stories.

Installed capacity	5759 MW
Energy sold	35 868 GWh
Distribution lines	359 304 km[1]
Transmission lines	21 161 km
Consumers	5.7 million
Employees	11 302
Turnover	€$1.8 billion

Figure 1. CEMIG in numbers for 2002. Nova Ponte hydroelectric power station (3 x 170 MW), shown to the left, is one of 13 power stations that are remotely monitored by CEMIG.

BACKGROUND

The Brazilian power company CEMIG has 47 hydroelectric power plants and one thermal power station in the state of Minas Gerais, in the South-eastern part of Brazil. In addition to these power plants, CEMIG, a state-controlled utility under mixed ownership, has also established partnerships with private initiatives

1. Largest in Latin America, and increasing 4% for the last 10 years.

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for investment in other power plants. These will generate an additional 1960 MW within the next six years.

CEMIG's installed generating capacity is 97% hydroelectric – much like the rest of Brazil – so there is always a risk of an energy shortage during dry seasons. Machine downtime during this time obviously aggravates the situation. Over 40% of CEMIG's production is used in the industrial sector (approximately half of that is in the metallurgical industry) so a lack of energy can have a significant chain-reaction effect on the Brazilian industrial economy. Starting from the early 1990's, CEMIG began implementing predictive maintenance programs to meet these challenges.

Improve production capacity, reliability and reduce maintenance costs

The Brazilian energy sector in general has already started to build natural gas infrastructure and other alternate sources of energy to mitigate the hydroelectric dependency, which is critical during the dry seasons. Much more, however, could be done by improving the operation and maintenance of the existing hydroelectric generating units. The need to improve the maintenance strategy for CEMIG was already apparent over 10 years ago. The costs for time-based maintenance of the critical machines were high in view of the following factors:

- **Ageing equipment** – Most of the critical equipment has been in operation for 25-30 years or more, so more attention was needed to keep these machines running.
- **Heavy loads** – The demand for energy has greatly increased during the 1990's with little new capacity being added (as a result of environmental and financial restrictions). This means most of the machines are operating at maximum capacity for longer periods of time. More attention is needed for these machines.
- **Less tolerance for downtime** – During previous times when supply and demand were more balanced in this part of Brazil, units could be shut down for maintenance almost at any time and for long periods of time without interfering with production. Now with most machines running at maximum capacity, this is not possible. This situation becomes even more critical during dry seasons.

Monitoring strategy

Optimizing maintenance was the primary concern for CEMIG during the 1990's. After CEMIG benchmarked electric companies in Europe and USA in 1990, an effective predictive maintenance strategy was implemented. It was also decided that machine condition monitoring would play an important role in this strategy.
In an effort to reduce machine downtime and maintenance costs, a monitoring strategy was established that includes the following objectives:

- **Optimize the range of turbine operation** - Ideally a turbine should be flexible enough to operate at all loads and operating conditions to meet energy requirements, but this is normally not possible because of the destructive effects of cavitation and pressure pulsation vortices. A recommended operation range is given by the manufacturer, but there is often a margin of error as a result of the actual installed conditions. Monitoring the machine is therefore important for optimizing the operating range.
- **Detect and identify potential failure modes, and predict the condition of the machine for maintenance planning** – Comprehensive monitoring techniques are needed here to detect developing faults at an early stage of development and diagnostic tools are needed to analyze the fault and trend its progression so maintenance can be cost-effectively planned ahead of time.

  At the time being, no protective monitoring is done on the CEMIG power stations except at the Igarapé thermal power plant and the Neves substation.

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Condition monitoring group

The Operation and Maintenance Engineering Management department for generation – within the Transmission and Generation Division – is responsible for the Predictive Maintenance Section. It is based in the Belo Horizonte headquarters and has Regional Maintenance Centres around the area.

The Predictive Maintenance Section was created in 1998 to implement and coordinate condition-monitoring strategies. There is currently one engineer who manages activities and six technical specialists. As the group's activities are centralized, the logistics of moving personnel and equipment over the large distances can be very expensive. For this reason, nearly everything is done remotely from their headquarters.

Their responsibilities include:

- Establishing the monitoring procedures and training personnel in the Regional Maintenance Centres and individual power plants on how to use and maintain the monitoring equipment
- Optimizing operation regimes for each of the generating units
- Performing diagnoses and analyses on detected machine faults, and make a diagnostic database
- Working with the Maintenance group for planning and optimizing maintenance activities

Size	Plant	Vibr.	Temp.	Oil Anal.[2]	Cavit.[3]	Effic.[3]	PDA	Air Gap	SBV	Mag. Flux	Press.
Large > 66 MW	Jaguara (4x106)	●	●	●			● [2]				●
	Nova Ponte (3x170)	●	● [1]	●	●		● [2]		●	● [4]	●
	Miranda (3x139)	●	● [1]	●			●	●		●	●
	São Simão (6x285)	●		●			● [2]			● [4]	●
	Emborcação (4x298)	●	● [1]	●			● [2]				●
	Volta Grande (4x95)	●	● [1]	●			● [2]				●
Medium 10 – 66 MW	Igarapava (5x42) [6]	● [5]	● [1]	●				●			●
	6 other plants	● [5]		●							
Small <10 MW	34 plants			●							

[1] Data imported from DSCS
[2] Offline monitoring only
[3] Research for cavitation and efficiency monitoring
[4] One unit only
[5] Multiplexed monitoring only
[6] Igarapava, a plant with bulb type turbines, is partly owned by CEMIG as part of a consortium.

Table 1. Monitoring techniques used at CEMIG's hydroelectric power stations.

- Evaluating the performance of the monitoring systems and update and optimize them according to needs
- Establishing partnerships among monitoring system suppliers to find solutions to difficult problems

Monitoring system installation

Already back in 1984 an advanced oil analysis laboratory was set up in CEMIG that significantly helped to improve machine maintenance

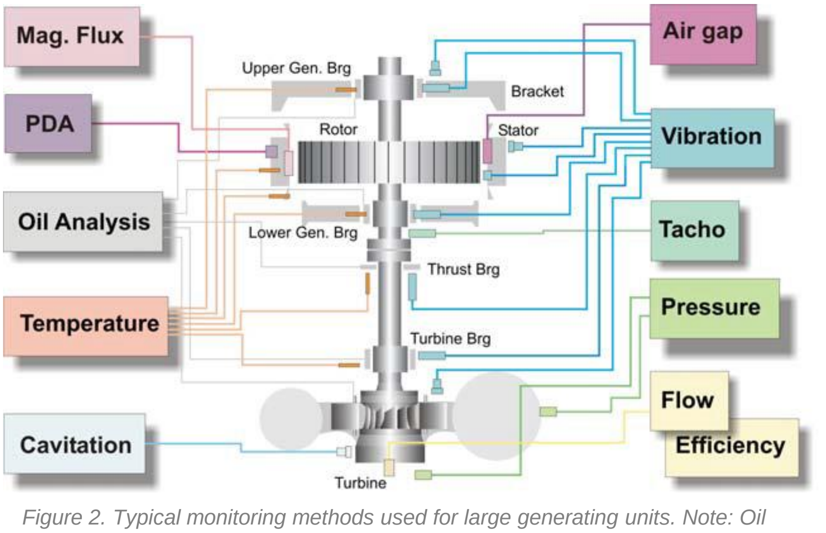

Figure 2. Typical monitoring methods used for large generating units. Note: Oil analysis is done offline. Temperatures and other process parameters (water levels, wicket gate positions, oil pressure, active/reactive power, generator voltage, stator current, exciter current and indication of synchronous and operating states) are imported from the DSCS. Auxiliary equipment monitoring is not shown.

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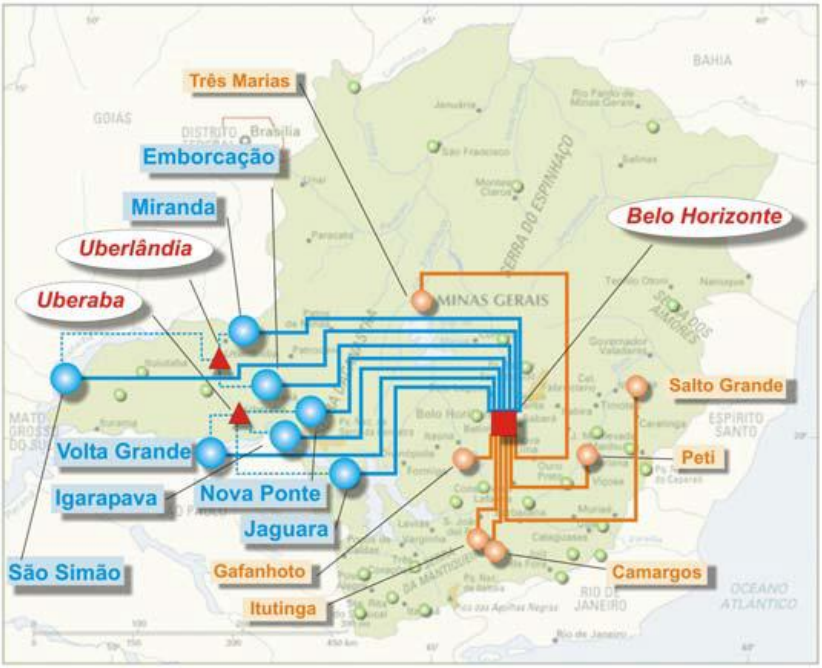

Figure 3. Remote monitoring of CEMIG's hydroelectric power stations. Large power stations (>66 MW) are shown in blue, medium sized (10-66 MW) are shown in orange. The Central Diagnostic Office is shown as a square, and the regional maintenance centres are shown as triangles.

and availability. Portable vibration monitoring equipment was being successfully used at the time, but the generating units had to be shut down to install the sensors, and shut down again to uninstall them.

The big break came in 1994 when a permanent, continuous on-line vibration monitoring system was installed at the Jaguara hydroelectric power station, which was followed in rapid succession by other permanently installed monitoring systems as shown in Table 1. In 2000, portable "offline" monitoring instruments were implemented to regularly monitor auxiliary machines such as pumps, motors, compressors, fans, diesel generators, etc.

Monitoring system configuration

The specific monitoring solution used for each of CEMIG's hydro generating units is an economic consideration based on the downtime criticality of each machine and the prices and level of technology that monitoring systems offer today. In any case vibration, oil analysis and pressure measurements remain the most important monitoring techniques and are used on all medium and large-sized hydropower generating units. Depending on the specific dynamics of the machine for its given operation regimes, other monitoring techniques are also used on the large power stations, as shown in Table 1 and Figure 2.

There are many benefits of using a wide range of monitoring techniques. As mentioned in the previous section, an important task for the condition-monitoring group is to build up a diagnostic database since there is little such information available for hydroelectric generating stations. The numerous measurement techniques make it possible to research the data to find new fault symptoms for more reliable diagnosis. Because many of the monitoring techniques are interrelated, they can be correlated to corroborate with each other to improve the reliability and speed of making maintenance decisions.

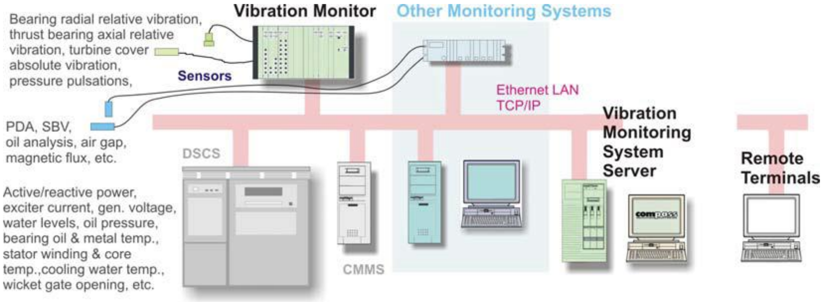

Figure 4. The current monitoring system configuration for a typical installation. Ideally information should be exchanged between the vibration monitoring system (shown in green), the other monitoring systems (shown in blue) and the DSCS and CMMS (shown in grey).

Remote monitoring

Each vibration monitoring system and many of the other monitoring technique systems are remotely accessed by condition monitoring group's central diagnostic centre in Belo Horizonte and by the nearest regional maintenance centre, as shown in Figure 3. The comprehensive monitoring techniques provides sufficient information for most diagnosis and analysis to be done remotely at headquarters, without moving equipment or people to the site.

Managing the existing monitoring systems

One of the consequences of using so many different monitoring techniques is that they are provided by different monitoring system suppliers, many of which are stand-alone systems (see Figure 4). There is much monitoring information provided by the monitoring systems, especially for the larger hydroelectric power stations, but it resides in different databases and currently cannot be correlated and compared together in a single screen. Studies will eventually be done to determine the feasibility of interconnecting the various systems in an integrated, distributed network.

As the various systems later become interfaced, multi-parameter correlations within a single plot can be displayed, such as bearing temperature and vibration, time-integrated cavitation and efficiency drop, pressure pulsations and efficiency, etc. The monitoring group is also planning on extending the amount

Monitoring Method	Faults Detected
Vibration • Accelerometers (for turbine cover, spider bracket, stator • Capacitive eddy current displacement sensors (for bearings) • Capacitive sensor (for stator bar vibrations)	• Misalignment • Unbalance • Bearing wear • Axial movement of shaft • Shaft rub • Short circuited poles • Loose stator bar s • Pulsation pressure vortices
Pressure	• Pulsation pressure vortices • Power fluctuations
Air gap • Capacitive sensor	• Unbalance • Misalignment • Rotor/stator eccentricity and concentricity • Individual rotor pole displacement
Magnetic flux • Inductive sensor	• Magnetic field unbalance such as short circuited poles (which reduces generator efficiency and increase stress on bearings)
Partial discharge analysis (PDA) • Capacitive bus couplers	• Degradation of stator winding insulation
Oil analysis • Off-line samples	• Bearing wear • Heat exchanger wear • Refrigeration system filters • Wicket gate servo valves • Bearing rub • Condition of oil
Performance (under research) • Flow • Head • Wicket gate opening • Pressure	• Efficiency optimization • Optimize the operation regimes of the turbine at part loads • Optimize shutdowns to repair eroded runners due to cavitation erosion
Cavitation (under research)	• Cavitation erosion
Temperature • RTDs	• Misalignment of bearings • Unbalance • Overheating of stator • Bearing rub

Table 2. Monitoring techniques currently used by CEMIG.

of process data imported from the DSCS and establishing a user interface to SAP/R3 computerized maintenance management system (CMMS) for making work orders and accessing the maintenance and diagnostic databases.

Fault detection and diagnosis techniques

Some of CEMIG's measurement techniques can be used for singly for identifying potential failure modes and others can be correlated with various measurements to corroborate fault detection (see Table).
In addition to these measurement techniques, the possibility is being investigated in using calculated measurement techniques. These use other measurements and constants as variables within a user-defined formula for calculating efficiency (using flow as measured by ultra-sonic techniques), performing data reduction and data correlations and calculating statistics, etc.
It is important to say, however, that vibration monitoring still remains the most effective method for detecting incipient machine faults, diagnosis and analysis of the faults, and trending the faults for prognosis and maintenance planning.

Monitoring system benefits

The savings of using advanced condition monitoring as an important part of the predictive maintenance strategy is enormous. Machine availability has increased, maintenance costs reduced, and overall production efficiency has improved. Better machine information makes for faster and safer decisions in the maintenance process, and the the technical skills of the maintenance personnel has improved and they have become more intimate with their machinery.

Many machines that were overhauled after 20 000 hours are now 100% CM monitored, so outages can be increased from 30 000 to 40 000 hours. Turn-around time for a generating unit has also been reduced. In the past it took five to six weeks but now it takes a maximum of four weeks, since some of the inspection activities have been eliminated such as for the guide and thrust bearings and measurements of the roundness of the generator. Maintenance time is also reduced because the maintenance activities are focused, with reduced risk of introducing new faults. Earlier fault detection and diagnosis gives more lead time for cost-effective maintenance planning.

Remote monitoring also reduces costs. Tests can be done remotely from the diagnostic center without moving people or equipment. Previously test equipment would have to be mounted and calibrated. A test for a large generating unit would cost €2500 to €4000 with a two days lost production (€33 000 to €49 000). This included moving the equipment and personnel up to 800 km. Today, rotor balancing and operation procedures elaboration of the machines can all be done remotely.

Case stories

Over a period of seven years there have been numerous cases where catastrophic failures and consequential extended downtime has been avoided, but for the sake of brevity, only two case stories are given in this paper.

Case story 1 – the importance of correlating different parameters for reliable diagnosis

Problem: In the past, radial vibrations occasionally exceeded alarm limits in the upper generator

Power Station	Nova Ponte
Began service	1994
Nominal power	3x170
Speed	163 rpm
Flow	190 m^3/s
Nominal head	96 m
Fault detected	Nov. 2000

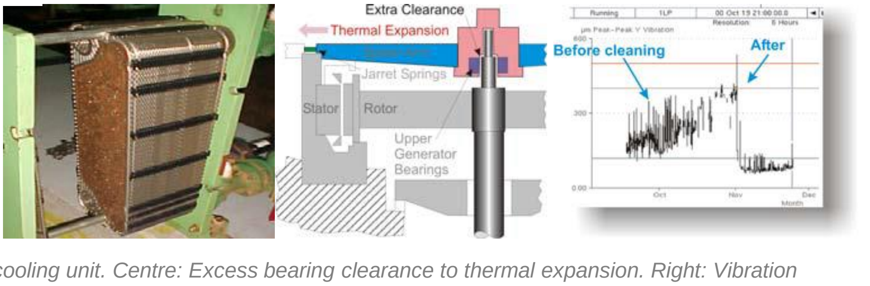

Figure 5. Left picture: Generator air-cooling unit. Centre: Excess bearing clearance to thermal expansion. Right: Vibration trend before and after cleaning the air cooler.

guide bearings for no known reason.

Detection and diagnosis solution: While trying to find the cause for the high vibrations, it was also noticed that the bearing temperatures, although not exceeding the alarm limits, had also increased. As the temperature measurements were made by the DSCS and not the monitoring system, this correlation was not immediately obvious at the time. This gave rise to the theory that the generator air-cooling system could be at fault.

Cause, effects: The generator air coolers use cooling water from the reservoir. This water seasonably becomes dirty with mud, which consequently reduces its cooling capacity. The Jarret shock protection springs at the end of each spider arm of the generator bearing bracket allow for the bracket and bearing housing to thermally expand under the warmer temperatures with minimal hindrance. This results in more clearance between the bearings and the shaft, which causes more vibration.

Remedial action: The air coolers had previously been cleaned only to bearing temperature increases, but now they will be cleaned according to the bearing temperature and/or vibration measurements. To make this correlation easier, the future plans include importing DSCS process data into the same database used by the vibration monitoring system.

Case story 2 –monitoring vortices during both standard and "non-standard" operating ranges

Problem: One day a strong 1.6 Hz signal was detected in the turbine no. 2 draft tube that was significantly higher than normal. The turbine was operating close to its optimal operating point at that time. This was obviously caused by vortex pressure pulsations but normally these are reduced or eliminated by automatically injecting compressed air into the draft tube.

Detection and diagnosis solution: There are two types of vortices that can be encountered: A roping action vortex at low loads (1/3 x to1/5 x turbine speed frequency), and a straight vortex at high loads (1 x turbine speed frequency). Often times, either of these vortex frequencies can also excite structural resonances. In this case the vortex was identified as a high load condition at 1.6 Hz, but it shouldn't have been there at all! By looking at data on the air injector that was imported to the monitoring system, it was immediately obvious the air injector was out of operation.

Cause, Effects: Pressure pulsation vortices reduce the efficiency, and if unchecked, can cause low-cycle fatigue of the runner blades. This is especially true during a hydraulic resonant situation where the magnitudes of the vortex frequency can be greatly amplified.

Remedial action: The turbine was immediately changed to a "safe" operation regime where there were no detected vortices. Although quick action was taken to reduce the effect destructive pressure pulsations, it was still suspected that there could be damage. Plans were made to stop the turbine during the next scheduled stop for inspection. Cracks were found in two of the runner blades! If the condition was not monitored at all, it could have resulted in an expensive catastrophic failure of the turbine with several days downtime at €57 000 per day.

Power Station	São Simão
Began service	1978/79
Nominal power	6x285
Speed	94.7 rpm
Flow	442 m3/s
Nominal head	72 m
Fault detected	Dec. 2001

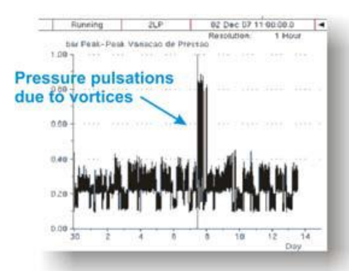

Figure 6. Left picture: One of the two cracks caused by vortex pressure pulsations during a relatively short time. Right: Lowpass plot showing the increased vortex pressure pulsation levels at day 8.

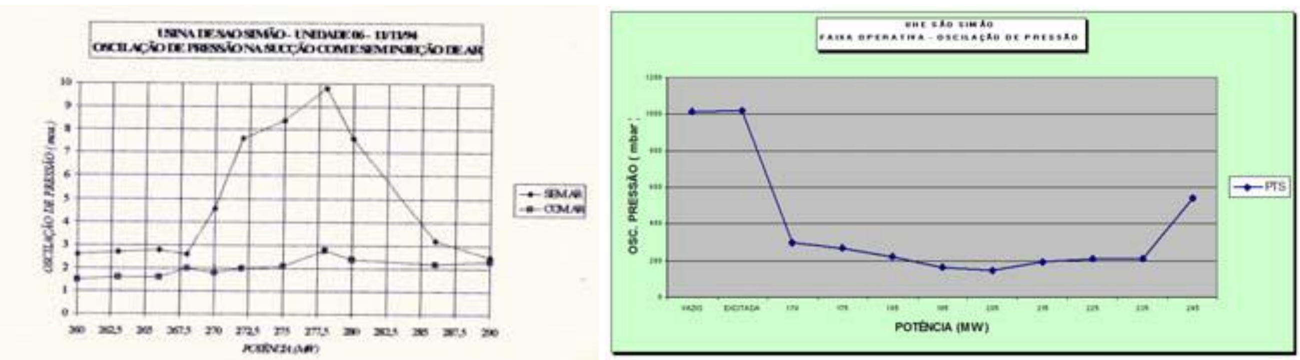

Figure 7. São Simão hydropower station operation regimes. Left picture: Pressure pulsation levels of a high load (268-285 MW) vortex with (top) and without (bottom) injected air control. Right: Low load vortex pressure pulsations levels without injected air.

Other case stories involving pressure pulsation vortices: The automatic air compressors have been programmed to inject air between 268-285 MW where it is known that high-load vortices can occur. One day during operation at 10% of the useful reservoir volume, there were observed pressure pulsations between 235-250 MW, which normally never occur at these loads. Although the pressure pulsation magnitude is less at the lower heads, it was suspected that they were still high enough to cause damage to the runner blades, so the turbines were examined at the next shutdown. Cracks were found in the runner blades. Since then the operational regimes where air is injected to control the vortices was extended to also these loads at low head conditions.

As the reservoir levels throughout Brazil during a two-year period were at their lowest levels in years, it was very important to monitor for vortices and cavitation during this time since there was no operational data available at these low heads. Operational data was collected at that time using the monitoring systems, and new operating ranges were established. Optimal operation ranges are generally more restrictive at lower heads than at the nominal heads.

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