THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

98-GT-129

INTEGRATED CONDITION MONITORING SYSTEM STRATEGY AT CEMIG

BREAK

Michael M. Hastings
Brüel & Kjaer CMS A/S
Naerum
Denmark

Wander Luiz de Oliveira
Raimundo Jorge Ivo Metzker
CEMIG
Belo Horizonte
Brazil

ABSTRACT

The condition monitoring section at the Brazilian power utility CEMIG is implementing an effective condition-based maintenance strategy that ensures the over 40 power plants spread out over a large area operate with minimal downtime and at a minimal maintenance cost. The condition monitoring system needed to fulfil CEMIG's needs for the larger plants did not exist, so it was decided to integrate several monitoring systems for this purpose. A computerized, permanently installed vibration monitoring system is planned to be integrated to other systems dedicated to specific periodic machine condition monitoring applications (e.g. air gap monitoring, oil analysis, magnetic flux monitoring, partial discharge analysis). This integrated monitoring approach results in a distributed system with a single system technique for alarm handling, and a user interface and database for analysis, diagnosis and fault correlation. The vibration monitoring system will also be extended for importing process data from the existing distributed supervisory and control system for monitoring calculated performance parameters such as efficiency and head. Testing is also under way for investigating the possibility of more effectively monitoring cavitation without purchasing a separate stand-alone system. Several of the larger plants at CEMIG will eventually be remotely monitored this way, but this paper focuses primarily on the monitoring system, strategy and current operating experience at the Nova Ponte hydroelectric power station. Even before integrating the other monitoring systems, the installed condition monitoring section played a large role in ensuring the plant operates safely, cost effectively and with maximum availability. Although the monitoring system is installed at a hydro-electric power station, some examples are briefly given on how the same integrated monitoring system approach could equally be advantageous in detecting and/or diagnosing certain faults within gas turbines and compressors.

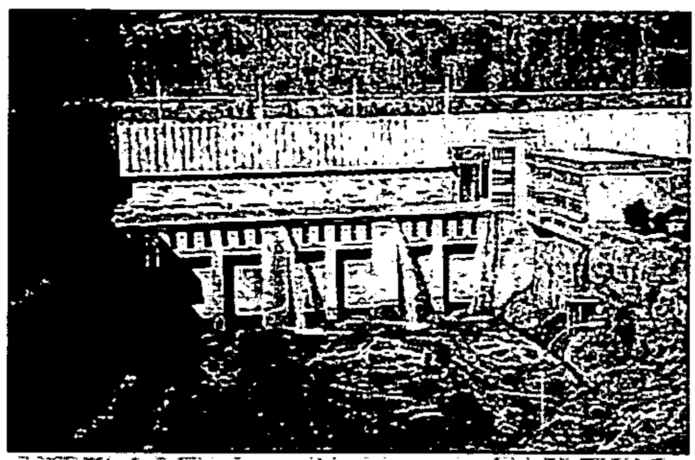

Fig.1 CEMIG's 510 MW hydroelectric power station at Nova Ponte, Brazil

CEMIG POWER UTILITY

CEMIG (Companhia Energética de Minas Gerais) is one of Brazil's largest and most important electrical utilities with regards to its strategic location, the size of the market it supplies, its environmental programs, and its technical competence. It is a dynamic company and has been heavily investing in expanding its energy capacity in order to keep pace with the economic growth of the region, while ensuring the best possible service to its consumers.

CEMIG, a state-controlled power utility, holds an important strategic location since it connects the southern and southeastern regions of Brazil into one single net grid. For an area that is so dependent on hydropower, it is sometimes necessary to import energy where and when it is needed because of the local seasonal rains and droughts.

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Stockholm, Sweden — June 2–June 5, 1998

Automation and Control

CEMIG supplies power to 98% of the state of Minas Gerais, which covers an area of 560,000 km2 (approximately the size of France). Within this vastness there are 40 power stations scattered around, some of which are 840 km from the head office in Belo Horizonte. Moreover, 97% of CEMIG's power is hydroelectric, which is sensitive to varying rains. To meet the challenge of operating so many remote power plants efficiently and under such varying power-producing conditions, CEMIG launched a huge modernization and automation project to establish a single System Operations Centre to serve as the heart and nerve centre of CEMIG's electricity network.

Plans are under way to make the larger power stations fully automated and the smaller ones semi-automated (i.e. automatic shut down).

The System Operations Centre is based on an energy management system and a distributed supervisory and control system (DSCS) that CEMIG technicians have designed, developed and implemented (see Fig.2). CEMIG also designed the interface to connect the older stations with the new master station. The DSCS entered into service in 1996, and is capable of handling the most advanced control and management applications for electric power systems.

This system plays an important role in the monitoring strategy, as described later.

Fig.2 The System Operation Centre is based on the DEC VMS operating system and uses client-server technology with SQL (Structured Query Language), and a relational database which communicates over a fiber optic FDDI and Ethernet local area network

Maintenance Support Activities

To facilitate performing maintenance tasks on numerous machines spread out over a large area, CEMIG is setting up Regional Maintenance Centres. These will play an important role as the larger hydroelectric power plants become automated.

CEMIG also has an extensive maintenance database to simplify the tasks. The maintenance department keeps a record of the entire maintenance history of all the machines, which is accessible to all plants. Recurring faults are easily identified using this system. A "Fault Rate" index is also calculated for every plant in order to provide data to engineering studies to increase machine availability.

But the key to how successful a predictive maintenance strategy can be achieved depends on how much is known on the condition of the machines. Therefore the condition monitoring strategy, system and personnel play a significant role in making the maintenance department and CEMIG operate successfully.

CONDITION MONITORING STRATEGY

The monitoring strategy adopted for the three largest hydroelectric power stations is primarily predictive, based on the concept of using a permanently installed system for automatic data acquisition, conditioning, alarm handling and storage. The plant auxiliaries such as water pumps and air compressors (for synchronous-running and switch-gear operation) will be monitored using a portable data collector, but this data is stored in the permanent system's database.

Currently, much of the maintenance on the hydro-generating units is still time-based, but this is gradually being replaced by a condition-based maintenance strategy with the monitoring system. Scheduled overhaul downtime is being reduced as inspections are no longer done on those machine components which are being condition monitored. This minimizes maintenance expenses, reduces the risk of "tampering" with properly functioning machine components and introducing re-assembly errors, and maximizes machine availability.

The monitoring strategy done on the hydro-generator units at the larger hydroelectric power stations consists of:

- Monitoring the turbines for optimizing operation ranges
- Detecting potential failure modes at an early stage of development
- Monitoring the turbines for determining the general machine condition for maintenance purposes
- Analyzing, diagnosing and trending of detected faults for maintenance prognosis

Operation Ranges

The automatic operation ranges used by Production are established by the condition monitoring engineers and are generally based on turbine runner vibration and pressure pulsations. Pressure pulsations reduce efficiency and can also create dangerous levels of vibration.

Although the loads and heads in which the runner is allowed to operate to avoid these effects (as well as cavitation) are given by the manufacturer, there is often some margin of error from the actual installed conditions. It is therefore the responsibility of the monitoring section to test for these conditions and advise Production what the actual limits are.

These tests, incidentally, can span a period of several years to account for different head conditions, i.e. heavy rains and droughts.

The monitoring section also tests and defines operation procedures for reducing the effects of vortex turbulence, such as air injection.

Potential Failure Mode Detection

The other primary monitoring function is potential failure mode (PFM) detection. The goal here is not to monitor the process, but to automatically detect incipient machine faults at an early stage of development that will eventually lead to machine failure. In addition to this, machine condition monitoring is also used to give an idea on the general condition of the machine. This information, among other things, helps facilitate making maintenance decisions.

Because of the slowly rotating equipment and the generally high reliability of the generating units (i.e. operation after installation and before overhaul), PFM monitoring does not require the same level of monitoring "sophistication" as during the testing periods previously mentioned.

Diagnosis

Lastly, faults which are detected that have large lead times to failure, such as imbalance, misalignment and bearing wear, can be analyzed, diagnosed and trended over a period of time without interrupting production (i.e. predictive monitoring) to facilitate maintenance planning. This is the foundation to predictive monitoring, and its effectiveness is largely dependent on expertise and on the analysis tools available.

NOVA PONTE HYDROELECTRIC POWER STATION

The Nova Ponte plant (Fig.1) is the third largest power plant in CEMIG, and one of the newest, therefore a lot of responsibility rests with the condition monitoring section to ensure that the plant is operating safely with maximum availability.

Selecting a condition monitoring system that can effectively satisfy the requirements at Nova Ponte for fault detection is the primary focus of this paper.

FAULT MONITORING REQUIREMENTS

Vibration monitoring remains the most effective method for detection of incipient machine faults, diagnosis and analysis of the faults, and trending for prognosis and maintenance planning. This applies to both the hydro-generating unit (see Fig.3) and to many of the auxiliaries.

Some of the important vibration measurements made on the shaft/bearing assembly of the hydro-generating unit include:

- Shaft phase and rpm
- Relative vibration of shaft within the bearings
- Centerline position of shaft within the bearings
- Absolute vibrations of the bearings
- Axial position of shaft

Vibration measurements are also extensively used elsewhere, such as in the generator, the suction tube, etc.

Although vibration monitoring can be used for detecting faults on a wide range of machines, it cannot be used for detecting all kinds of machine faults, nor can it be used for distinguishing between certain kinds of faults which are different but have similar symptoms. For this reason, there are several other methods for machine condition monitoring which are invaluable for confirming or complementing the diagnoses provided by vibration monitoring.

Some of the machine condition monitoring methods currently used or contemplated by CEMIG in addition to vibration monitoring are listed below.

Temperature and process parameter monitoring

For machine condition monitoring purposes, process parameters are monitored directly to give an indication on the condition of the individual machine elements as well as used as input to performance calculations (explained further on) or statistical calculations.

As a direct measurement, temperature data is important for monitoring the condition of the bearings (bearing sleeves and lubricating oil) and generator (stator windings, stator center, field windings, and cooling oil).

The process parameters needed include pressure (spiral case and suction tube) upstream and downstream water levels, flow, power, wicket gate opening, valve positions, running hours, stops and starts, etc. Many of the directly monitored process measurements can be correlated directly to the vibration measurements, such as bearing temperature and bearing vibration.

Generator monitoring

Aside from vibration and process measurements, there are other specialized monitoring methods which are done on the generator itself. Because this type of monitoring is independent of the prime mover type, it is more or less applicable to many different industrial power applications, e.g. hydro turbine, steam turbine, gas turbine, etc.:

- **Air gap monitoring** – By monitoring the gap between the generator rotor and stator, it is possible to detect conditions such as out-of-roundness, rotor bow, rubs, etc. Also, non-uniform variations in the air gap can create powerful magnetic forces which can damage bearings, etc. This data can easily be correlated with vibrations. It is planned to install air gap monitoring systems only at those plants where the air gap is critical (none have been installed yet)
- **Magnetic flux monitoring** – Gives an indication on the electrical conditions for each pole on the rotor. Small changes here provoke similar changes in the dynamic vibration measurements, therefore it is an ideal measurement for correlation to vibration measurements. For the time being, it is planned to install this system only at the Miranda plant
- **Partial discharge analysis** – Measure of gradual wear in the stator windings. This method has minimal correlation with dynamic data

Oil analysis

In order to keep track of bearing wear, etc., it is important to monitor both the condition of the oil as well as detect the existence of contaminants and metal particles in the oil.

Adaptive monitoring strategy

The hydro-generating units at Nova Ponte do not always operate under the same load conditions, partly due to power demand, partly due to reservoir levels. It is not possible to monitor to limits based on a single reference for all these conditions. One of the important requirements here is monitoring during partial loads. In general, there are five important operating conditions where monitoring will be done:

- Units stopped
- Units running up to speed (or coasting down)
- Synchronous running (no generation)
- "Normal" running (0 to 40 and 111 to 170 MW)
- "Prohibited" running (41 to 110 MW)

Each machine state has its own independent set of references for monitoring to improve monitoring reliability and accuracy. Within these machine states, measurements used for monitoring can be restricted even further to up to three other process conditions, again with individual set of references.

Performance monitoring

The performance monitoring capability has special significance to CEMIG's monitoring strategy since this allows the entire process to be monitored - not just the condition of the individual machine elements. Because the health of a machine and its performance are closely related, a more complete picture is possible on the entire process. Some of the performance parameters to be monitored include efficiency and head.

Performance monitoring parameters, like machine component temperatures, generator electromagnetic properties and oil analysis, is an excellent parameter for correlating with vibration data for accurate fault diagnosis. This correlation applies to gas turbines and compressors as well as to hydro-turbines, as described below:

- **Turbine blade profile changes** – This kind of fault can be more readily diagnosed by correlating balance shaft vibration to efficiency drop. In the case of a Kaplan or Francis hydro turbine, this problem often results from uneven cavitation erosion in the runner blades and wicket gate vanes, thus altering the blade/vane profile. This correlation is also a supplementary method for monitoring the severity of cavitation erosion, as explained in section below on cavitation. In the case of a gas turbine, this fault is due to uneven deposits or erosion on compressor or turbine blades, and can be correlated in a similar fashion
- **Flow turbulence, pulsations, recirculation** – This problem can often be diagnosed by correlating shaft vibration (mechanically, hydraulically or aerodynamically induced) to an efficiency or pressure drop. In the case of both the gas and hydro turbine, there can be several causes for this, such as incorrect flow angle, increase in blade tip clearance, etc.

There are other vibration-performance parameter correlations which are not applicable to hydro turbines but would be beneficial for gas turbines, such as vibrations resulting from uneven combustion caused by a faulty burner, which can be correlated to a burner temperature spread measurements, etc.

Cavitation monitoring

Cavitation occurs when the water pressure within the runner reduces below the water vapor pressure. The small bubbles which are formed by the resultant "boiling" attach themselves to the runner blades (and/or wicket gate) and are swept along its surface. The presence of these bubbles reduces efficiency as the flow stream is altered. The bubbles are eventually swept to an area on the runner blade where there is a pressure recovery, causing the bubbles to "implode". The numerous implosions can cause small quantities of material to be removed from the blade in the process, thus changing the profile of the blades, and reducing the efficiency further. The implosions can also generate high, undesirable vibrations that could reduce the life of bearings and seals.

MONITORING SYSTEM REQUIREMENTS

The various monitoring techniques mentioned above places great demands on the monitoring system itself, not just in terms of the monitoring functionality needed, but also in terms how the system architecture is configured. Some of the important considerations made in selecting a monitoring system are listed below.

On-line/off-line system

Many of the machines in a hydroelectric station are very reliable after they have been properly installed and successfully commissioned. Most faults related to "wear and tear" – even those which are premature - develop slowly and predictively. For this reason, much of the monitoring at various plants have been done with portable instruments (i.e. off-line) at specific intervals of time, such as for air gap monitoring, magnetic flux monitoring, partial discharge analysis and oil analysis. In fact many of the small hydroelectric stations under CEMIG are quite small and are completely cnndition monitored using portable instruments, including vibration monitoring using a portable data collector.

So when does the monitoring have to be done continuously using a permanently installed monitoring system, i.e. on-line? This question, like almost all others concerning maintenance, is based on economy. As the size of the hydro-generating unit increases, the cost for downtime increases dramatically as does the cost for repairing the units, so the need for on-line monitoring increases as well. Generally, at CEMIG, it has been determined that it becomes cost-effective to monitor vibrations, process parameters and performance on-line if the hydro-generator units are 50 MW or larger. The primary reasons for this are:

- **Performance Monitoring** – This becomes more important for the larger units, where monitoring efficiency drops due to turbulent vortices, cavitation, or eroded runner blade profiles can be detected early to help reduce costly repairs. Performance monitoring is done most effectively here on-line
- **Commissioning and Testing** – On-line monitoring is a must here for commissioning large, new machinery since so many different measurement points and parameters for each point have to be simultaneously monitored. A thorough commissioning is important for these kinds of machines since "hidden" design faults which go undetected during commissioning can be expensive to

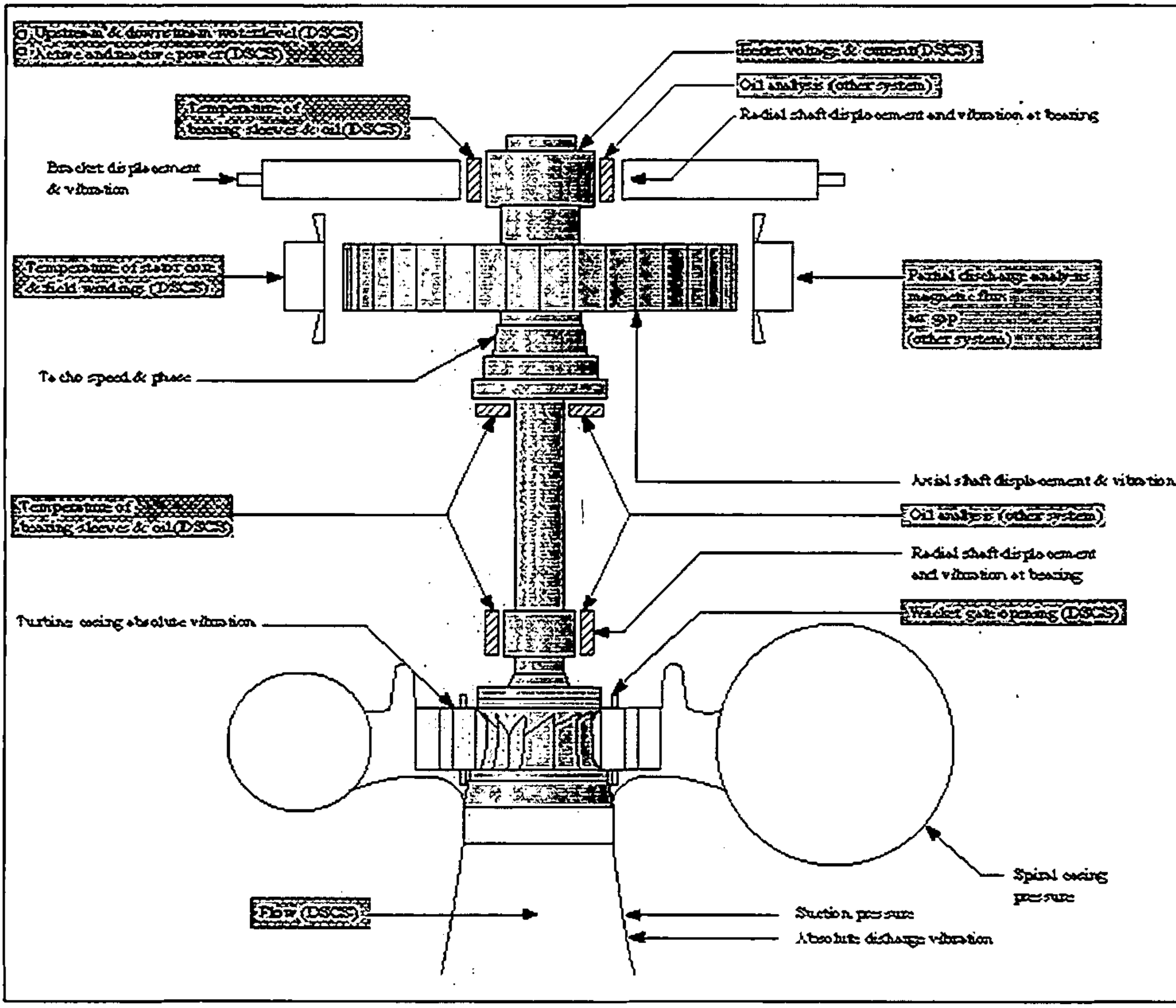

Fig.3 Integrated monitoring strategy on the Nova Ponte Francis turbines

the end-user further down the line. In fact, every time the machine is opened for overhaul, repair, etc., it should be carefully monitored as if it were being commissioned again

- **Operation Optimization** – As mentioned previously, the margin of error for the operating ranges specified by the turbine manufacturer can be too excessive, and at times have to be optimized or re-defined. Vortex turbulence and, more importantly, cavitation are often the biggest factors. Since some of the operating loads are restricted on an hour basis, it is important to continuously monitor these values on-line in order to arrive at a cumulative total based on an integrated period of time

Nevertheless, off-line monitoring remains being important not only for completely monitoring the smaller hydroelectric power stations, but also for monitoring less critical machines of the larger plants, such as the auxiliaries.

"Single Box" Integrated Monitoring System

Many of the monitoring functions mentioned earlier are traditionally done by dedicated, stand-alone systems. Ideally, all monitoring functions should be combined in a single system. This would give increased monitoring reliability since all data can be correlated to more accurately identify, diagnose and trend faults. Moreover, reliability is further improved and manpower/training requirements are reduced by combining the following monitoring system functionality:

- Data handling (reduction, validation, signal conditioning, time stamping, etc.)
- Alarm handling and relays
- Diagnosis and analysis tools (plots, cursors, trending, etc.) - it is easier and more reliable to perform analysis, diagnosis and trending
- System setup and configuration (single user-interface)
- Data storage (correlation, analysis, backup of data)
- Manpower expertise and training (single-user interface)

There are, however, some disadvantages by combining all monitoring functions into a single box, as is mentioned in the next section.

Distributed Monitoring System

A fully integrated system combining the functionality above in a "single box" is an ideal solution, but not necessarily a practical one, as is described a little further on. Although it is still ideal to incorporate as many functions as possible into a "single box", a more practical solution is a distributed monitoring system. This means data from several standalone monitoring systems dedicated to a specific monitoring method is sent to a server (explained further on) via one or more of the following methods:

- Network protocol such as TCP/IP
- Fieldbus
- Serial communications
- Keyboard (for off-line instruments)

Hardware and software needed for the different methods of monitoring need not sit in the same rack - and need not be from the same supplier. What is needed is a system platform that is based on industry standards and is open to exchanging data with other systems. The raw data from the various interconnected systems would be processed and stored in the server as if the data had originated from there. In fact, all of the benefits of the single box integrated system described above could be achieved by the distributed monitoring solution, except the individual systems can still only be set up and configured locally. But then there are some additional benefits:

- **Combined monitoring functionality** – There is no system on the market that offers all the monitoring and analysis capability required by CEMIG in a "single box"
- **Keeping existing systems** – CEMIG already has some monitoring systems that are more than adequate in detecting specific kinds of potential failure modes. Although somewhat limited in analysis and storage capability, it would be a lost investment if these instruments have to be thrown away in order to make way for a newer system
- **Specific expertise** – It is improbable that a single supplier today has all the technological and application expertise needed to provide multiple methods of condition monitoring to the level required by CEMIG and support them. Companies that make dedicated systems are more likely to do this for their specific applications
- **Tomorrow's technology** – Even if a single supplier could provide all monitoring answers today, what good will this be if a stand-alone system manufacturer develops a new technique for monitoring erosion tomorrow that is far more effective than the today's? An open system will more probably accommodate this new technique than a complete proprietary system
- **Off-line/on-line capability** – Use of data collectors which store data in an on-line system database lends itself to the distributed monitoring solution concept

Although the distributed monitoring system solution offers many benefits over the "single box" solution, there are certain drawbacks as well:

- There are communications hardware, software and manpower requirements to implement a system for transferring data from the other systems "on-line"
- The server itself must be capable of processing and storing data coming from fieldbus, network and keyboard
- It is important to know how the data has been conditioned in the other system before being transferred to the server (averaging, weighting, etc.)

Data Exchange with the DSCS - But No Shared Processing

One of the most important sources of process data for the monitoring system from the power stations is the distributed supervisory and control system (DSCS). The DSCS monitors a lot of data, but the system itself is designed for operations work, not maintenance. Therefore the same data used by the DSCS can also be exported to the monitoring system and used according to CEMIG's condition-based maintenance requirements. This is a cost-effective solution since this avoids duplicating transducer hardware.

It is important, however, that none of the sub-systems in a distributed monitoring system use the DSCS resources for data processing or storage purposes. Even data transfer along common communication lines should be minimized. The DSCS system performs important control functions, and this capability should never be burdened or jeopardized by other systems.

Monitoring System Server

The distributed monitoring system described above requires a a server for steering the entire process, maintaining a unique database and user-interface (for display, data setup, etc.) and providing a common set of monitoring services and data processing for all the "interconnected" systems where needed, such as data validation, data reduction, data processing, alarm handling, diagnostic tools, etc.

INSTALLED MONITORING SYSTEM AT NOVA PONTE

Basic vibration monitoring system capability

The permanently installed vibration monitoring system was installed at Nova Ponte in February 1996 (as shown in Fig.4). Similar systems have been recently ordered for another three plants - namely São Simão, Emborcação and Volta Grande - and for one synchronous compensator at the Neves substation.

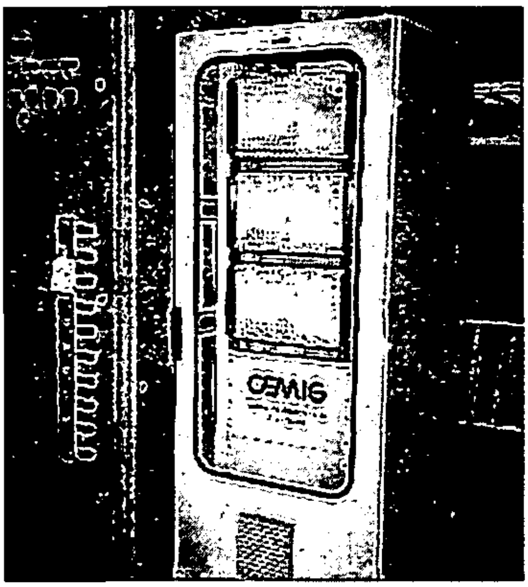

Fig.4 Machine condition monitoring system server

The vibration monitoring system was selected partly because of its versatility, the diagnostic tools used here apply to many different kinds of measurements. The system is also well suited to Nova Ponte because it is a complete, self-contained integrated on-line/off-line predictive/ safety system, and its flexible, modular architecture allows for cost-effective upgrades and expansions to be easily added in the future. It is an open system with many input capabilities that can import and export data over a network, modem or field bus with other systems (as shown in Fig.5, this is explained further on). And the versatile analysis and diagnostic tools that are available in the form of measurements and plots are indispensable.

Another invaluable asset of the system is its automatic, adaptive monitoring capability. This is needed to effectively monitor the hydro-generator under all possible machine states including stopped, transient[1], synchronous running, normal generation running and "prohibited" generation running states.

Because Nova Ponte is to be fully automated, remote monitoring is also an important requirement. The server computer and database at Nova Ponte will be connected by two X-terminal client computers - one at the monitoring section headquarters in Belo Horizonte and one at the Uberlândia Regional Maintenance Centre.

Other reasons for choosing this system include:

- Open-architecture system for importing and exporting data from other systems
- Versatile local and remote communications possibilities via a fieldbus, serial connection or LAN/WAN network
- Automated monitoring capability
- Multi-tasking, multi-user capability
- Automatic user-defined calculations feature where using measurement data as input variables in thermodynamic, statistical and life assessment equations. These post-processed "calculated" measurements are treated like the "normal" measurements, i.e. compared to user-defined alarm limits to detect exceedances, trended to alarms, stored in the database, etc. The calculations feature can also be used for a user-defined data conditioning capability, so data from other systems can be time stamped, averaged, validated, reduced, weighted, post-processed, etc.

Integrated monitoring function capability

Process parameters and Performance monitoring capability

The installed vibration monitoring system is capable of monitoring process data as well as vibration data, but most of the process data will be imported from the DSCS, as is explained further on.

The performance monitoring program has a number of standard built-in performance monitoring functions such as efficiency and pressure head using the imported process data as input. As mentioned earlier, a formula calculation tool box is also offered that allows user-defined measurements to be made for other performance parameters.

The performance monitoring program hasn't been implemented yet.

Cavitation monitoring capability

There are stand-alone systems on the market that can monitor cavitation, but the basic detection and severity monitoring technique used by some of these systems could conceivably be done equally as well using the vibration monitoring capability of the installed integrated monitoring system. In this way, the data can be correlated with other vibration measurements, performance and process data. Therefore testing is currently being done to determine the feasibility of using the vibration monitoring system for detecting of cavitation, monitor its severity and calculating life assessment of cavitation erosion.

The assumption for monitoring cavitation is based on the phenomena that cavitation generates acoustic emission and vibration as it occurs on the runner blades, and the severity of the cavitation is proportional to the relative amplitude of these measurements. Tests are being done using the vibration monitoring system to make blade pass modulation level vibration measurements (BPML). This measurement is based on the filtered time signal of the bubble implosion frequency modulated by the blade passing frequency, which is double rectified, amplitude demodulated into an "envelope", and then converted into a FFT (fast Fourier transform) spectrum. The BPML peak amplitude is assumed to be proportional to the cavitation intensity.

1. Transient machine-state monitoring capability is not particularly suited to hydro turbine monitoring, but lends itself well to compressor and gas turbine monitoring.

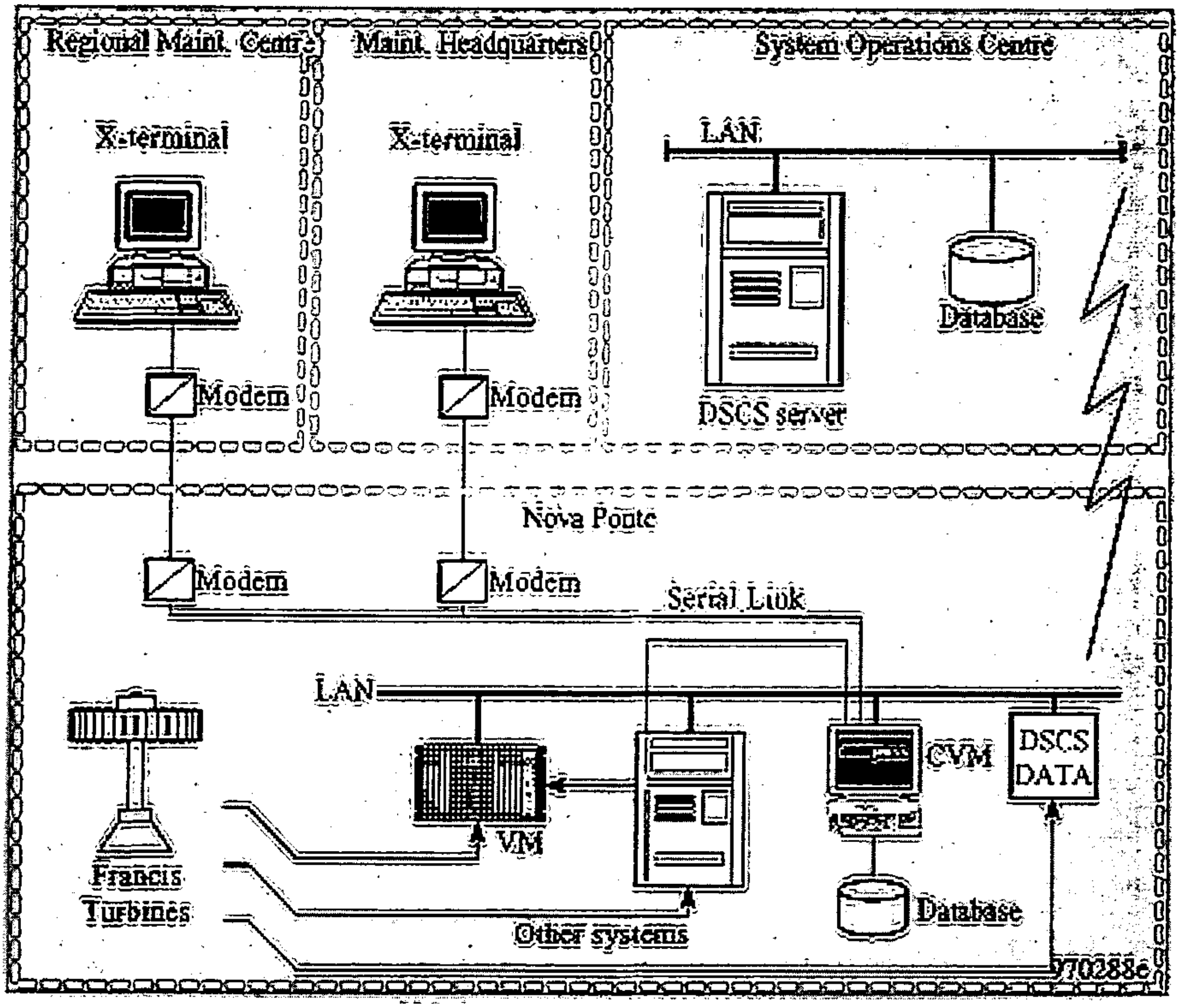

Fig. 5 Machine condition monitoring system connections planned for Nova Ponte ("VM" = Vibration monitoring units, "CVM" = Computer server to the vibration monitoring unit, "X-terminal" = client computers)

Estimation of material loss due to cavitation is based on time-integrating the complex cavitation vibration signal together with other factors, which can be automatically calculated using the system's user-defined measurement calculation toolbox. Testing still is far from being finished, but the initial results look good. It was also noted that the BPML values behaved as a function of load very much like the acoustic emission measurements (AE) taken during the test.

Data imported from the DSCS

The installed integrated monitoring system will use process data from the DSCS in two different ways; machine condition monitoring and performance monitoring.

For the machine condition monitoring portion of the vibration monitoring system, temperature data will be exported from the DSCS for the bearing sleeves, and bearing oil, stator windings, etc. Once imported, these parameters are monitored to limits and stored in the database. They can then be manually correlated to other data during analysis and diagnosis session. The user-defined calculated measurement function of the vibration monitoring system can also be used for automatically correlating the imported data to other measurements as a monitoring function and then compared to alarm limits and then stored as a separate, correlated measurement.

The performance monitoring function of the vibration monitoring system can import process measurements from the DSCS such as temperature, pressure, upstream and downstream water levels, flow, power, wicket gate opening, etc. for calculating thermodynamic efficiency and head, or for statistical or life assessment purposes.

In addition to importing data from the DSCS, the vibration monitoring system can also be used for sending both alarm and measurement data to the DSCS system for informing the operators of alarm situations.

Process data from the DSCS can be exported and imported to the vibration monitoring system via an Ethernet network using a TCP/IP protocol.

Data imported from other systems

As mentioned earlier, other monitoring instruments are or will be implemented at CEMIG, which include a magnetic flux monitoring system, a partial discharge monitoring system and an air gap monitoring system. It is intended to export the data from these instruments to the vibration monitoring system.

CEMIG has developed their own oil analysis software program. The actual analysis is done at a laboratory but the program will be used for storing the analysis results as well as data on the oil type characteristics, equipment that uses the oil, quantity of oil, number of oil changes and filters. For easier correlation with other data, the vibration monitoring system will be used for storing the oil analysis data.

MONITORING EXPERIENCE AT NOVA PONTE

Range Optimization

Most of the monitoring currently done at Nova Ponte is to optimize the operating limits for Production. The installed vibration monitoring system has proven itself particularly good at doing this, and is a much more economical doing this than by testing by other methods, and gives higher quality results. At Nova Ponte, vortex turbulence is present at low loads (110 MW or less), and manifests itself as a radial flow component at the suction end of the Francis turbine. The vortices encountered at Nova Ponte are characterized by high 1/3 sub-harmonic vibration which is easily detected from displacement transducers mounted near the lower guide bearing. Vortices can also be detected by pressure oscillations in the suction.

Air is currently injected at the suction side of the runner to reduce the adverse affects during operation.

Experience with PFM Monitoring

Nova Ponte is a relatively new power plant, so there hasn't been much degradation or wear problems up to now. One problem that has recently been detected is shaft misalignment, possibly caused by asymmetric deformation of the brackets radially supporting the shaft above the generator. Early detection of this condition allowed the condition monitoring engineers to analyze and diagnose the problem so it can be properly corrected at a later time without affecting operation.

This is but one of many potential faults that can occur for this power station. Examples of some of the numerous faults which occurred at CEMIG and can be detected immediately by continuous, on-line monitoring at other power stations include:

- **Motor/generator pole short** – Two of the synchronous compensators at the Neves Substation (20 km from Belo Horizonte) have had continuous problems with poles shorting over the last year or so. A portable data collector has been used up to now, but it is planned to monitor these machines with an on-line system.
- **Thrust bearing failure** – At the São Simão power station, a rubber seal failed that separated the hot and cold oil at the thrust bearing. When the hot and cold oil mixed and came in contact with the thrust bearing, this resulted in thermal distortion of the bearing pads.
- **Wicket gate pin shear** – At the Salto Grande hydroelectric power plant, one of the pins supporting the wicket vane was sheared, thus allowing the vane to move freely and assume a position different from the other vanes. This caused differential hydraulic loading and resulted in a misaligned shaft. This was detected by an increase in amplitude of the blade passing frequency, a reduction in the first harmonic of the shaft running speed, and an increase in bearing temperature.
- **Generator faults** – At the Jaguara power station, out-of-roundness of the stator and deviations in concentricity between the rotor and stator created a magnetic unbalance, which resulted in the rotor being displaced towards the part of the stator where the air gap is less while the unit is excited. This dislocation was verified by proximity probes located in the generator bearing. The shaft dislocation can be verified by any variation in the shaft centerline position. In the case of rotor out-of-roundness, the shaft will vibrate more at running frequency during excitation, and the diameter of the shaft orbit will increase (while still maintaining a circular form).

CONCLUSION

Predictive monitoring of hydro-generator units is not new, but it does present particular challenges because of the low speeds, the large dimensions and weight of the shaft, its vertical position, and other factors. Since the vibration monitoring system has entered service, it has met this challenge and has been extensively used.

Although the monitoring system described in this paper is used in a hydro application, it is believed the integrated monitoring approach can be effectively applied to other critical machines, such as compressors, gas turbines, etc. This is because the vibrations associated with blade profile faults, flow turbulence/recirculation, etc. can be similarly correlated for these machines to performance parameters such as efficiency, head and pressure drop. This applies also to bearing vibrations correlated to oil analysis results, temperature, etc.

The other large hydroelectric power stations, one thermal plant and three synchronous compensators, will be equipped with permanently installed monitoring systems at a later time. Portable monitoring systems will be used for the plant auxiliaries and for monitoring smaller hydroelectric plants. At Nova Ponte, plans are being made to integrate the vibration monitoring system to the other monitoring systems in the near future, but the immediate areas of expansion are in monitoring the turbine efficiency and implementing a cavitation monitoring programme.

Cavitation monitoring is the last obstacle to a complete condition monitoring strategy for the hydro-generator units. Testing is currently being done for detecting cavitation, monitoring its severity and monitoring cavitation erosion life assessment using the vibration monitoring system.

Another area for expansion planned by CEMIG is the addition of an automatic diagnosis capability to the monitoring system. Production can then perform simple diagnostic tasks which can improve their knowledge of the machines they are operating while at the same time reducing the workload of the condition monitoring group so they can concentrate on more complex diagnostic problems. The vibration monitoring system manufacturer provides this possibility, and CEMIG is currently assessing the software for implementation at Nova Ponte.

Partly due to machine monitoring, significant savings has been made in maintenance manpower, material expenditure and machine availability. In the past, overhauls were done at 20,000 hour intervals and required 40 days to complete. Today thanks to the monitoring strategy and the adoption of new maintenance technologies, the overhaul interval has been extended to 30,000 hours and lasts only 20 days. Bearings are only serviced if the bearing vibration, temperature and oil analysis indicate it has to be done. This optimization of maintenance activities has resulted in savings of $2,000,000. Machine availability has increased from 89% in 1991 to 93% in 1997. 95% availability is expected for 1998.

REFERENCES

1 de Oliveira, W. L., 1997, "UHE Nova Ponte Sistema de Monitoramento de Vibrações Situação Atual e Perspectivas de Expansão" – CEMIG report no. 11134-MN/PR3-048

2 Metzker, R. J. I., 1997, "Sistema de Monitoramento Contínuo de Vibração, de Temperatura e Parâmetros de Processo de Centrais Hidrelétricas e Termelétricas e Seus Equipamentos Auxiliares Filosfia de Projeto, Operação e Manutenção" – CEMIG project report

3 Neto, J. P. de B., Barouch, L. A. C., "Quality Management and Technical Insight Make it possible to Meet Surging Energy Demands" – Brüel & Kjær's newsletter PROFILE – Vol. 5, No. 1, August 1997