Case History: Advanced Gas Turbine Asset and Performance Management at Endesa
The gas turbine industry must focus on several key factors that will make its future technology successful in the electric power generation market. These factors are summarized in the list below and in Figure 1:

- Competitive economic performance (i.e., higher efficiency and optimized life-cycle cost).
- Reliable operation under a duty cycle (repeated gas turbine startups and shutdowns).
- Increased dependability of current and future plants (reliability, availability, maintenance, and durability, or RAM-D).
- Ability to meet regulatory emissions levels and achieve high thermal efficiencies.
- Reliable fuel-switching capability and fuel flexibility.

Gas turbines will be one of the most important horizontal technologies and will play an essential role in meeting these requirements. Gas turbine technology is considered horizontal due to its capacity to be widely applied across many different types of power plant configurations while running with different fuels (coal gas, natural gas, hydrogen, liquid fuels, etc.). This is in contrast to so-called “vertical” technologies, such as coal processing, that are obviously only suitable for specific types of plant configurations and fuels. The Spanish electricity utility Endesa (www.endesa.es) is participating in the promotion of initiatives to improve gas turbine technology; in particular, the European Turbine Network (www.eu-gasturbine.org), which is dedicated to the application of highly efficient and environmentally friendly technologies.

The Role of Asset Management at Endesa

Of primary concern to Endesa is the development of gas turbine asset and performance management systems. Armed with such systems, many improvements can be made to the practice of managing power generation assets that are simply not possible otherwise. The ultimate goal is to manage our gas turbine assets by knowing their condition (known as condition-based maintenance or CBM) and their performance (known as performance monitoring), rather than relying on calendar intervals. This entails a combination of both online and offline techniques. Figure 2 shows the conceptual levels that comprise such systems.

Gas turbine units are typically equipped with minimal sensors. While the supplied instrumentation is adequate to ensure safe operation and to monitor basic performance and emission requirements, there is generally not a sufficient complement of sensors for optimizing performance, assessing risk associated with extension...
KEY DEFINITIONS

**Condition-Based Maintenance (CBM)**
“The preventive maintenance initiated as a result of knowledge of the condition of an item from routine or continuous monitoring” (Seddon, 1984).

**Performance Monitoring**
Performance Monitoring is a technology that uses measured and calculated thermodynamic properties to assess the condition of a machine or system. The advantages of performance monitoring systems as a part of preventive/predictive maintenance programs are the economic impact on the turnover of the power plant.

**Life-Cycle Cost (LCC)**
Life-Cycle Cost is the total cost of ownership to the customer for acquisition, operation, maintenance, and disposal of a product over its lifespan.

**Dependability**
Dependability is a collective term used only for non-quantitative descriptions of the following:

- **Reliability (R).** This answers the question “How often does it fail?” and can be expressed in terms of time as Mean Time Between Failure (MTBF).
- **Availability (A).** This answers the question “Can it be used when you want it?” and is a measure of an ability to satisfy demand.
- **Maintainability (M).** This answers the question “How easy is it to fix?” and is expressed in terms of time as Mean Time To Repair (MTTR).

of maintenance intervals, monitoring component degradation, providing early warning of faults, and monitoring hot section environment and failure mechanisms. However, by augmenting the basic instrumentation on the gas turbine with additional sensors and systems, most of these objectives can be achieved.

Endesa’s philosophy on gas turbines is therefore to provide the machine train with all the instrumentation needed for appropriate mechanical condition and performance monitoring. The specifics of our approach for monitoring the gas turbines in our fleet based on the levels depicted in Figure 2 are discussed next.

**Level 1: Sensing**
Basically, gas turbines are equipped with proximity probes and seismic transducers all along the train with different purposes depending on the location.

- X-Y radial proximity probes are installed on each of the fluid-film bearings for radial vibration analysis.
- Radial proximity probes are installed on each shaft in the machine train to provide a once-per-turn Keyphasor* pulse for phase angle calculation, speed indication, and transient speed tracking.
- Axial proximity probes are installed only on the thrust bearing in the compressor side of the machine for detection of the axial position and axial vibration of the shaft. They are primarily used for detecting thrust bearing wear or abnormalities. They are also useful for detecting instability during operation, as many aerodynamic instabilities manifest themselves as axial vibration.
- Radial seismic transducers are installed on each of the two radial bearings in the gas turbine, allowing casing motion to be observed.
- Bearing metal temperature sensors are installed on each bearing.
Level 2: Control, Supervision, and Protection

All vibration sensors installed on our gas turbines are connected to GE’s Bently Nevada® 3500 Series machinery protection systems for protection and monitoring purposes. These systems are able to trip the unit if high vibration occurs during any operation mode. To allow display, annunciation, and trending of the basic data provided by these protection and monitoring systems in our Distributed Control System (DCS), digital communication interfaces using industry-standard protocols are provided.

Level 3: Mechanical Condition Monitoring

The machinery protection systems described in Level 2 are used for gas turbines and other auxiliary equipment in our plants. These are normally connected to the DCS so that the operator can view basic machinery data and protection system statuses in a common environment with other plant process and operational data. They are also connected to a centralized computer running special condition monitoring software. We use GE’s System 1® software where all the detailed vibration data (dynamic and static) is processed and stored. Process data from our PI System® data historian software is imported to the System 1 database, allowing correlation of process and operating data with condition data.

Diagnostic users are able to connect to the System 1 server as clients with different purposes. Examples of diagnostic uses include remote analysis of machinery behavior, collecting machine baseline data for future comparison, and establishing software alarm levels that are more sensitive to subtle changes in machine condition, beyond what may be achievable in the underlying machinery protection system of Level 2.

Remote client/server connectivity is also supported. Endesa maintains a centralized monitoring center in Madrid that can connect to any of the System 1 servers at its various facilities. This allows a centralized team to perform remote machinery diagnostics using archived and real-time data, to optimize and configure System 1 settings as required, and to maintain the software.

Level 4: Performance and Health Assessment

Assessment of the machine condition is done with dynamic and static vibration data at different load and speed conditions. Transient data (i.e., data collected at preset speed change intervals during start up or shut down) is also captured using appropriate Bently Nevada hardware compatible with our 3500 racks, and this data is the most valuable information that can be shown on any centrifugal machine. As described in Level 3, additional process static data (temperature, load, etc.) is imported from our PI data historian server to the System 1 server for correlation with the aforementioned vibration data.

Access to time synchronized process and condition data on a single platform allows easier and more effective diagnostics of machinery malfunctions on gas turbines such as unbalance, misalignment, rub, fluid instabilities, etc.

Level 5: Prognostics

The primary function of the prognostics level is to project the current health and performance state of equipment into the future, taking into account estimates of future usage profiles. The prognostics level may report health and performance status at a future time or may estimate the remaining useful life of an asset given its projected usage profile. Assessments of future health or remaining useful life may also include a diagnosis of the projected fault condition. Prognostics therefore allow us to predict the onset of hot gas path component failure to match its use or to enhance maintenance support. Prognostic capabilities expand support options and allow for cost-effective planning and management.
Level 6: Decision Support*

This optional component of System 1 software can automatically analyze its collected data and transform this into Actionable Information* advisories for optimization or diagnostics. Vibration and process information is processed through specific rules created for each type of machine (compressors, turbines, pumps, etc.) and the malfunctions applicable to each. The case history in the article details a machinery malfunction that was correctly diagnosed by our installed Decision Support module of System 1 software.

Level 7: Human Interface

As has been discussed regarding Level 2, basic condition monitoring data such as protection system statuses, values, and alarms are introduced directly into the DCS via a digital communications link. This allows operators to access the data most relevant to them within a common display environment. Specialists, however, typically utilize the System 1 software user interface instead, either locally or remotely, as the additional data collected and diagnostic capabilities make this the most convenient environment for them rather than the DCS. Thus, the human interface employed by a particular group of users is a function of their role within the plant. When advanced capabilities of the condition monitoring software is provided, such as the Decision Support advisories of Level 6, these advisories can be integrated into the DCS environment so that both basic protection system alarms and more sophisticated software “expert system” alarms are provided in a single manner for operators. In contrast, machinery specialists will normally interact with such alarms using the System 1 software interface itself, rather than the DCS.

Next, we examine a practical application of these systems by way of a case history where a fluid instability was diagnosed in one of our gas turbines.

Case History

Figure 3 shows the arrangement of a large 8-bearing combination gas turbine/steam turbine/generator train. All eight radial bearings are fitted with X-Y proximity probes and the two gas turbine bearings are fitted with casing transducers as denoted by BB4 and BB2 in the figure. Vibration levels as measured by proximity probes on all eight bearings as of September 2003 were under 3 mils (75 microns) and within acceptable limits.

By mid-2005, however, operators began to see significant increases in average vibration levels, particularly at the #3 bearing, with transient excursions up to 6 mils (150 microns). The installed Decision Support capabilities of System 1 software utilized a Bently Nevada RulePak module for gas turbines, and this software was indicating a fluid-induced instability. The plant’s rotating equipment engineers utilized the manual analysis capabilities of their online monitoring system to further validate the automated diagnostic results provided by the Decision Support software module, increasing everyone's confidence in the diagnosis.

Figure 3 – Machine train diagram for 8-bearing gas turbine/generator.
A trend of NOT 1X data (Figure 4) collected between April and June 2005 showed a steady increase. Changes in NOT 1X data are usually quite significant as the majority of vibration in most machines is due to residual imbalance and occurs at rotative speed (1X). Substantial vibration occurring at other frequencies—particularly when it is increasing over time—merits detailed investigation. Examination of waterfall plots (half-spectrum trends) as shown in Figure 5 indicated that the NOT 1X vibration was predominantly occurring at 1/2X (the unit runs at 50 Hz, and the subsynchronous component occurred at 25 Hz). This was most pronounced at bearing #3 and to a lesser extent at bearing #4. Startup data was then examined, and the shaft average centerline plots showed abnormally high (unstable) positions assumed by bearing #3 within its clearance during both transient and steady-state conditions.

Startup data from orbit plots (Figure 6) was likewise examined and interior loops were clearly evident on bearing #3. Slight temporary rubbing was occasionally observed in addition to the instability. The full spectrum plots (Figure 7) for these orbits were examined and showed that the vibration precession was in the forward direction. All of this data validated the advisory provided by the Decision Support system that a fluid-induced instability indeed existed in bearing #3.
ALL OF THIS DATA VALIDATED THE ADVISORY PROVIDED BY THE DECISION SUPPORT SYSTEM THAT A FLUID-INDUCED INSTABILITY INDEED EXISTED IN BEARING #3.
Operating and Maintenance Decisions

Although continuing to run the machine was undesirable, it was preferable to a forced outage. Because the plant had good data and was able to validate the malfunction to their satisfaction, they elected to continue running the unit for another year until a planned outage was scheduled. During that time, critical parameters were monitored such as bearing metal temperatures and vibration data for evidence of more serious problems that would warrant taking the unit down sooner. Figure 8 was collected during September 2005 and shows trend plots of the type of data monitored closely during this time. It shows the intermittent, cyclic nature of the instability.

Using this data, and working together with the turbine OEM, an oil wedge instability was diagnosed and the root cause was traced to increased thermal growth in the gas turbine and decreased thermal growth in the steam turbine as verified by alignment checks. Combined, this hot misalignment was unloading bearing #3, resulting in a fluid instability.

During the scheduled turnaround of this unit, the following corrective actions were taken based on continuing engineering review and fleet experience:

- Alignment conditions were corrected to OEM specifications.
- Retrofit of a 4-pad load-between-pad design was made to bearing #3. This bearing had acceptable lateral dynamics/steam force margins and demonstrated a better margin of stability at light loading conditions. Disassembly during the retrofit confirmed that rubbing had occurred on bearings #2 and #3 (Figure 9).

Conclusions

As a result of the installed condition monitoring system, Endesa realized the following advantages:

**Early warning**
A machinery malfunction was detected at an early stage—more than one year ahead of the next planned outage.
Figure 8 – September 2005 steady-state trend plots from horizontal probe (top) and vertical probe (bottom) on bearing #3. Note the cyclic nature of the high vibration, consistent with the initiation and cessation of a fluid instability.
Accurate Problem Identification
A warning on the Decision Support system allowed us to focus the vibration analysis on a specific failure mode—fluid instability.

Forced Outage Avoidance
By understanding the phenomenon, we were able to continue running the unit, understanding the nature and severity of the problem, while closely monitoring its degradation until the next planned outage. A forced outage was avoided and this avoidance would not have been possible without a condition monitoring system.

Smoother, Faster Turnaround
Advanced information regarding the problem allowed us to more effectively plan the outage. We knew where the problems would be and what the problems would be prior to opening the machine. This allowed for a smoother, faster outage than would have been possible without condition monitoring data to help guide our activities. As a result, we were able to conduct the outage within the originally scheduled time frame and return the unit to service on time. Valuable downtime was avoided.

Summary
Future advanced thermal power plants will need to be highly complex in order to fulfill the requirements of a global society that is increasingly sensitive to environmental issues. Gas turbines have emerged as a core technology in thermal power generation, supporting many different plant configurations. Consequently, many operators are placing increasing emphasis on the optimization of gas turbine life-cycle costs, with particular attention to gas turbine dependability and performance.

Endesa is a strong proponent of online monitoring systems for gas turbines, and they represent an integral part of our operating strategy. As has been shown in this article, such systems provide tangible value, validating our belief that gas turbine asset and performance management plays an extremely important role in enhancing the competitiveness of power generation operators.