MONITORING AND DIAGNOSTICS FOR GAS TURBINES – CASE STUDIES

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ABSTRACT

Monitoring and diagnostics for gas turbines is becoming more widespread. These case studies detail how we have set this up and how we have used it in particular instances.

Deploying monitoring and diagnostics needs to take account of various skill levels in an organization and the paths of communication between them. Using software to assist in the analysis and dissemination of gas turbine information leverages the expertise throughout the organization. Less skill is required to do the initial monitoring, though some turbine knowledge is essential.

Using a distributed architecture adds robustness and allows those at site to use the monitoring and diagnostic software too. The monitoring activities encompass frequency and event based checking as well as producing quarterly and pre-outage summaries.

Monitoring and diagnostic software provides a way of efficiently filtering large amounts of turbine data. The software will not provide all the answers and so must have good tools to allow exploration of the data and verification of faults. Even then, the case studies show that the software is assisting, not replacing, the process of diagnosing problems as part of the effort to increase turbine availability and reliability and to optimize outage activities.
INTRODUCTION

Detecting faults in a timely manner in plant critical equipment is increasingly important. Detection at an early stage can have multiple benefits, including the avoidance of unscheduled outages and possible equipment damage.

The processing of the data to identify incidents and faults can be done manually or computer software can be used to assist in the process. Where skilled manpower resources are in short supply we would like to have as much assistance from computer software as possible for this identification.

Identifying the details of the faults that require repair is a mixture of using the diagnostics provided by the monitoring and diagnostics system, using data exploration tools to get more information and in many cases examining the turbine itself. Various support tools are needed to ensure proper exploration of conclusions such as graphing and diagnostic message management. The ease of use of these tools is one of the key aspects to providing a successful monitoring and diagnostic system (Nicol and Aylett, 2009).

Organizations have a hierarchy of expertise and specialism within them. Depending on the core role of the organization, they may resort to third party help in resolving problems. Information flow within and out with the organization is very important to applying manpower resources effectively.

Various problems will accrue over time and mechanisms need to be in place to track these. Knowing the outstanding problems allows for efficient scheduling for repairs during either planned or unplanned outages. Awareness of the operating condition of the turbine and reacting to this as necessary is important for increasing availability and reliability.

DEPLOYING MONITORING AND DIAGNOSTICS

Skill Sets Needed
Engineering staff resource is scarce. Monitoring and diagnostic contracts are usually part of some larger service agreement.

Our experience has shown that it is easier to train staff with some turbine knowledge to use monitoring and diagnostic software than it is to train computer literate people about turbines. In addition, the best balance is that monitoring turbines on a daily basis should form only part of the workload for any given member of staff. Ideally that person has other work involvements with the site being monitored. Compare this to a dedicated monitoring and diagnostic centre where this is the sole function of the staff.

Getting the information remotely to the monitoring and diagnostic staff and then, if necessary, remotely again to experienced personnel makes for efficient use of staff resources.
Distributing Data

It is necessary to get the turbine data to a point in the organization where the existing infrastructure makes it easily available. For example, we can connect over normal phone links to sites and bring information back to a central server which then makes it available on the internal network and over the internet with appropriate security safeguards as shown in figure 1.

Figure 1 - Example Monitoring and Diagnostics System Architecture

This structure means that many people all through the organization can examine what has happened to the turbine and experts can be called in to help resolve problems when required.

Diagnostics

There are many techniques for capturing knowledge about gas turbines, producing a spectrum of diagnoses from the detection that something is abnormal through to the complete diagnosis of a fault. Note that in some cases it is not possible to distinguish between faults from the sensor input. Often site information is needed to resolve the cause of observed behavior in the monitoring and diagnostic system.

It is important to have concise summaries of diagnostics that can be explored in depth if necessary. We can look at the diagnostics produced in a number of ways and cross relate these to highlight specific areas of interest.
When turbines are being continuously monitored there is a need to know about particular problems that have previously been reported and if plans to rectify the problem have been put in place. This information needs to be available at the time the message is displayed. One way to do this is to attach notes to messages indicating that further information is available.

The presentation of the diagnostics is important as often digital tags will change in the normal running of the turbine. We don’t necessarily want to ignore these as they may be relevant additional information if an abnormality occurs, but in the normal running we want to be able to suppress them. Filtering messages so that they do not appear in a normal diagnostic query allows faster interpretation of the diagnostic list and makes new messages more obvious.

Monitoring Activities

There are three different types of monitoring activities

- frequency based checking – typically daily
- event based checking – investigating an incident or specific request
- summarizing – typically quarterly reports

Generally gas turbines are reliable. The control systems usually have redundancy built in and problems develop over time. This means that checking on what has happened on a daily basis is usually enough to spot and track problems as they develop.

Sometimes though, an event occurs that needs immediate attention. For example, after a trip or on a failed start-up.

Over time a number of faults are identified, not all of which can be fixed immediately. It is important to record the history of the turbine and know what outstanding problems exist. Providing summary reports facilitate this.

Ideally, the monitoring and diagnostic system should be available on-site allowing staff there to investigate any incident. Often with monitoring and diagnostic systems, lack of staff resources on-site mean that they rely on remote analysis.

Reports on a per incident basis accumulate over the months. We need to provide a status and history that is easily referenced. Quarterly reports and status reports prior to outages provides summary reports that are easily actionable by the site. Quarterly reports can also show long term trends and performance measurements going back years. Including engineering and site comments in the quarterly reports, often indicates why the observed behavior occurred and what the proposed fix might be, with attendant timescales.
DIAGNOSTIC AND MONITORING SYSTEM CHARACTERISTICS

Download Diagnostics, Not Data

In order to perform a daily check, particularly for remote monitoring, it is preferable to only download and check diagnostic messages and summary data rather than large quantities of raw data. This information can be read quickly to get an overview of any important events or issues that are occurring on the gas turbine, and then only the appropriate data needs to be downloaded.

For remote monitoring this means very small amounts of data needs to be transferred which provides a very rapid way to check an individual turbine or large number of turbines.

History Tracking and Replay

There is a great advantage in keeping all the data permanently, it is possible to go back at anytime and investigate an incident in more detail, possibly with different viewpoints or with additional knowledge gained from further operation or incidents. It is often useful to go back one or more years to look again at specific past incidents to see how a problem built up, or to verify that certain problems are not affecting the turbine currently.

Verify Faults Quickly

The diagnostics will provide a rapid focus as to what has just occurred on the gas turbine. Using further troubleshooting and display tools, it is possible to then verify the concise fault or problem providing confidence for any needed repair actions. When a trip occurs, this provides a means of rapidly identifying the cause of the trip to minimize the downtime.

Maximize Service Intervals

By building up a clear comprehensive picture of the behavior of the gas turbine and the incidents affecting it, it is possible to identify areas that do not need further attention and hence, do not require an immediate shutdown. In addition, by identifying small problems, it is possible to produce a more efficient running gas turbine, and reduce the strain on the gas turbine itself. Monitoring and diagnostics provides information needed to make decisions as to whether shutdowns can be postponed.

Advance Prediction of Faults

By identifying faults and problems at the earliest possible stage and tracking the evolution of these, the monitoring and diagnostic system provides the information needed to anticipate more important faults and allow time to plan for the rectification.
Minimum Monitoring Skill

With a monitoring and diagnostic system the routine monitoring is much simpler and requires less knowledge of the working of the gas turbine. In addition, the diagnostics help an engineer to focus quickly on the key problems, so reducing the time required to identify any behavioral problems of the gas turbine.

Monitor Operator Actions

With a complete history of the behavior and operation of the gas turbine, it is possible to verify whether the operators have run the gas turbine properly and performed actions in sequences as they should.

Minimize Remedial Costs

By identifying problems at an early stage and rapidly troubleshooting the cause, consequential damages and problems can be minimized. The operator can fix minor problems at an early stage, rather than major problems when it is too late.

Optimize Cleaning Cycles

Performance analysis modules help to identify when the gas turbine has lost sufficient efficiency to justify off-line washing. This efficiency monitoring capability can also be used to track the effectiveness of on-line washing.

Faster and More Accurate Commissioning

By using monitoring and diagnostic system during the commissioning process, it is possible to rapidly identify commissioning problems to both get the machine working more quickly and also resolve any latent problems.

Fewer Warranty Claims

The monitoring and diagnostic systems analysis of the behavior of the gas turbine identifies a wide range of problems very rapidly that should be rectified to minimize warranty claims downstream. The information leads to more efficient running of the gas turbine, greatly reducing the risk and liability to future warranty claims.
SHORT EXAMPLES

Sticking Second Stage Nozzles

A chemical plant customer operates a Frame 5 gas turbine in a two-shaft configuration as the prime driver of its key compressors. The machine had a number of enhancements to increase the power output. During maximum power output, the second stage nozzles appeared to stick, and failed to control the speed of the gas turbine within its target. To prevent an over speed trip, the customer was forced to reduce power, limiting the production capacity of the entire plant. The plant continued to operate with this problem for more than one year prior to the installation of a monitoring and diagnostic system.

Concurrently, the customer attempted to identify the root cause of the problem, but given the data acquisition systems available, was unable to do so.

Using the information acquired by the monitoring and diagnostic system, the customer easily identified the intermittent times when the fault occurred, enabling the engineering staff to investigate the incident in more detail. The staff quickly demonstrated that the sticking of the second stage nozzles was not a mechanical problem, but was due to the hydraulic actuator not being strong enough to override the increased airflow due to the higher power levels. During the next outage, the customer upgraded the hydraulic actuator. Having resolved this problem, the turbine was then able to run effectively at a higher power level.

Unstable Startup

A gas turbine on an oil platform was always started on distillate fuel oil. The engineer on site noticed that the gas turbine was unstable during start-up - a problem that had been ongoing. The engineer notified his maintenance support team who remotely connected to the offshore platform and checked the diagnostic information collected during the start-up. It was quickly determined that the liquid fuel was oscillating between the 0 and 5 MW power levels.

Using the information available via the monitoring and diagnostic system the problem was diagnosed as a sticking bypass valve. This problem was difficult to diagnose on the platform given the operating environment, particularly for the site engineer who would have had to change a number of components and then attempt another restart to see if the problem was solved. In addition, a variety of replacement components are not always available on the platform, which further curtails this type of effort to resolve the problem. If the turbine failed to start due to these oscillations - a very high possibility - then the platform would have lost this power source.
Sticking Fuel Valves

The daily check of the diagnostics detected that both the gas fuel and liquid fuel stop valves were sticking for significant periods of time. The gas fuel stop valve was sticking for 5 seconds and the liquid fuel valves were sticking for 10 seconds. This type of malfunction can cause problems in fuel transfers, including a gas turbine trip when a fuel transfer is attempted and unsuccessful. The site was advised to replace the appropriate fuel valves.

This problem was again detected when, during a fuel transfer to gas fuel, the speed ratio valve did not open until approximately 1 minute after the signal was given by the servo. This caused the fuel transfer to fail and for the system to remain on liquid fuel longer than expected. It was shown that the cause of the problem with the speed ratio valve was the gas fuel stop valve stuck open for approximately 1 minute.

This incident was repeated, whereby the gas fuel stop valve became stuck in the open position, preventing the stop ratio valve from functioning. However the gas control valve continued to open in expectation of a supply of fuel. The gas control valve continued to open to 100%, and then the gas fuel stop valve closed, causing a surge in liquid fuel flow. This quickly led to the exhaust temperature rising to 585ºC, which tripped the unit. The sticking valves were replaced, eliminating the problem.

Sticking Bleed Valves

Platform engineers contacted their maintenance provider and advised that there was a loud 'bang' on run-up of a turbine. A review of the diagnostics indicated that the bleed valves failed to open properly. The loud bang was attributed to compressor surge occurring.

As a result, the bleed valves and limit switches were scheduled for replacement at the next overhaul.

Faulty Fuel Clutch

The customer replaced the flow divider for the liquid fuel and requested that the service provider to monitor the gas turbine on the subsequent start-up. The first three attempts to start the turbine failed.

It was observed that on all three attempts, no fuel flow was achieved through the new flow divider. Through interaction with customer personnel, the customer service provider guided an on-site engineer in determining that the cause was a result of the fuel clutch not engaging due to a faulty relay in the clutch circuit.

This problem was an obscure and uncommon fault, making it likely that the engineer on the platform would not have been able to independently identify it.
Inlet Guide Vane Mechanical Dump

The customer’s gas turbine tripped due to an inlet guide vane problem. The service provider remotely checked the data and determined that the inlet guide vane did not close, but instead continued to open. Checking the recent historical data, it was shown that the inlet guide vanes were very sluggish in their operation.

After the trip, the machine would not start, forcing the customer to contact the service provider to assist in restarting it. The site engineer was directed to replace the inlet guide vanes servo, and then perform different operational approaches to starting the turbine. By remotely monitoring the activities, it was demonstrated that there was a problem with the mechanical dump for the inlet guide vanes.

Faulty Controller Card

The customer phoned and asked for assistance with a problem on the gas turbine. Intermittently large numbers of alarm messages were being generated on the distributed control system. The service provider connected remotely to site, and confirmed through the diagnostics that there was an intermittent fault generating a wide range of diagnostic problems.

By using the monitoring and diagnostics to get an overview, they could see the frequency and duration of the intermittent fault, and verify a number of times when the fault was occurring. The only signals to be affected were in the contact input DTBA for the <C> processor, hence the service provider was quickly able to diagnose that the fault was a bad TCDA card causing a large number of alarm fault messages from the Mark V controller at intermittent intervals and facilitate sending a field engineer to site with the correct replacement card to rectify the fault.

Faulty Speed Ratio Valve

The diagnostics indicated that the speed ratio valve was exceeding 42% open for the running conditions and load. In addition, its associated servo was at negative saturation. The information available in showed that at full speed, no load, the servo current was already at -18%, which is outside the specification of the servo. It was also shown that on a 40 megawatt load, the valve would open to 100%, and the inlet pressure was not up to specification.

It was established that the speed ratio valve's servo needed to be checked allowing the site engineers to plan this maintenance.

Calibration of Lube Oil Header Temperature Switches

The gas turbine tripped on a high lube oil temperature. Monitoring and diagnostics were used to remotely verify the fault and determine that the trip should not have occurred. An oil header temperature trip should normally be at 80°C, however, the trip occurred when the temperature
was only 63°C. It was rapidly established using a remote live connection to the site, that the gas turbine could be safely restarted, but that the lube oil header temperature switches needed to be recalibrated.

Sixteen days later the gas turbine tripped again on high lube oil temperature. Diagnostic information was used to rapidly verify that the problem was the same as before, that is, the sensors were incorrectly calibrated and it was an unnecessary trip. Although the site had been told to recalibrate the sensors after the first incident, they had not done so, showing that if they had acted on the data, they would have prevented a trip.

Three months later the gas turbine tripped again on high lube oil temperatures. Diagnostic data was again used to verify that the cause of this was an incorrect calibration of the switches and that the gas turbine could be rapidly restarted. It was determined that an incorrect calibration procedure was being used. The monitoring and diagnostic system was used to rapidly verify the cause of the trip, and confirm it was safe to restart the turbine, as well as to identify that the site was not carrying out a procedure correctly.

**Faulty Vibration Sensor**

The daily check by indicated that one of the bearing sensors had a momentary spike of 16mm per second. The site was advised that this had occurred and the problem was monitored daily.

Three weeks later the same transducer was spiking approximately once per hour with a magnitude of 8mm per second. The site was advised that the sensor was faulty and needed replacement. This early detection of the problem, monitoring its evolution, and advising of a correction, prevented a potential high vibration trip.

**DETAILED EXAMPLE - STEAM FLOW ISSUES**

The steam to fuel ratio was detected as being too low from 5th July and diagnostic messages indicating this were increasing.

Various investigations were carried out that looked at the potential effect of the steam injection nozzles blocking up and restricting the steam flow. These are presented in time order so that it highlights the investigative process.

The differential steam flow was investigated and corresponded to the actual steam flow. This indicated that, there was actually a drop in steam flow or the takeoffs for the flow meters needed some attention.
A snapshot (-45 days) of NOX steam flow, steam/fuel ratio and NOX stack emissions showed the steam flow was down from where it should be and emissions were up indicating that something affecting the required steam/fuel ratio was driving it down.

Steam injection low range differential pressure was steady at 30 from the previous overhaul until around 6th August when it started jumping around and the average then slid to 27 as shown in figure 2. The following graphs all show the maximum, minimum and average of a given tag in a four minute window.

![Figure 2 - Steam injection low range differential pressure beginning to deteriorate](image)

The position indicator of the MK IV NOx steam control valve was examined with the following scenarios

1. near the normal position, the conclusion would be that the flow meter is plugging in its flow element tap valves. This has happened many times before, and it leads to NOx steam operational problems, usually of the type that once it locks out of service operators cannot get it successfully reintroduced until the taps are rodded clear.

2. closed off substantially, then it is being driven that way by some other factor and the flow meter is reporting that fact. The flow is actually reducing in response to the control system
which indicates that the control system is looking at the wrong Gas fuel flow (steam flow and gas fuel flow are directly related).

3. open more than normal then actual steam flow is increasing however indicated steam flow is dropping, this points to the manifold to which the transducers are connected.

Site decided that until the NOx steam values fall off below the point at which the CEMS package on the stack starts reporting concern about making compliance (or they had NOx steam operational problems), they would take no invasive action. It was still peak electrical rate season until October 15.

It was noted that the monitoring and diagnostics allowed the site to plan for this problem as an upcoming event instead of just reacting when it became very serious.

After examination on-site it was found that the NOx steam control valve, (the electric motor driven valve that controls the amount of NOx steam admitted to the combustors) had not moved from the 50% position observed the week before. However, the Mark IV controller was calling for more than 8 #/sec steam flow and was getting about 3.5 #/sec. It was noted that if the situation were to behave like any other control loop, it would be driving the control valve open to make the process conditions satisfy the set point. This was not the case.

The steam flow and steam injection ration continued to fall as of August 29\textsuperscript{th} as shown in figures 3 and 4.

![Figure 3 - Steam Flow Dropping Still](image-url)
Next, the NOx steam supply upstream regulated at 400 PSIG regulated pressure was examined and found to be fairly constant while the attemperation water and 600/400 control valve position ramp had closed, about the same slope as the flow meter trends that the monitoring and diagnostic system had been picking up.

The conclusion of this was that the flow meters were correct, or at least not the controlling factor in this episode. Previous NOx steam problems included the flow meter taps plugging up where the flow ceased to register any changes or drove up or down scale unreasonably. The conclusion was also correlated by the CEMS package on the stack, which showed a NOx emissions increase in almost the exact but opposite curve from the steam flow and 600/400 PRS positions.

The specific gravity meter on the fuel line was considered as it had given problems previously. These included mechanical problems, calibration problems, liquids condensed in the sample line and catching fire. It was thought unlikely this time, since the algorithm in the Mark IV would not be calling for over 8 #/sec steam if it had faulty process information (fuel value, steam flow, dew point, steam temp, dew point).

It was decided to check to see if the signal out to the NOx steam control valve was correct from the Speedtronic Mark IV control system. The Mark IV may have been calling for 8+ #/sec, but something in it could have been preventing it from driving a signal to the control valve to open. Possibly there was a mechanical or electrical problem with the valve itself. It could be stuck, or corroded (again) in its local junction box and not able to move. However, the Pressure
Reducing Station data suggested that it able to move and had choked the steam back over time to the current small value.

The steam flow started dropping to 0 for short periods of time around 12th Sept as shown in figure 5.

![Figure 5 - Steam Flow Dropping to Zero for short periods](image)

Re-examining the electric NOx steam control valve showed it was wide open and the control relays that drive the valve open were both energized with the "full open" limit switch is limiting the valve travel. This differed from the initial observation. The conclusion at this point was that NOx steam nozzles were plugged.

The combustion can door passages were reported on the last outage to be plugged with solid deposits from steam, which was a long-term build-up. Prior to that, plugging was observed in the eight nozzle ports themselves, there was an assumption that the door passages were clear.
since drilling out the nozzles restored steam flow. Vinegar was used to clear the passageways on 3 of the doors last time.

It was decided that the best and quickest method of repair was to pull all the doors and send them to be soaked in mild acid to clear the passageways. This was estimated at a 2 to 3 day outage on the gas turbine and was scheduled for Oct 15.

Advice was taken on the NOx emissions regulations at this point. It was decided to take no action until October 15 (off-peak season) unless the NOx production became an enviro-permit issue that had to be rectified. The repair would definitely involve a NOx steam outage, might cause a turbine trip, and could require a complete gas turbine outage if the steam nozzles and passages in the combustion cans needed to be cleaned out. All these cycle events have their own emissions associated with a round trip down and up, and could result in more NOx release than letting the turbine continue running.

Steam Injection flow continued to trend down with many more instances of the minimum being zero, as shown in figure 6.

![Figure 6 - Steam Injection Flow Drop Outs Increase](image-url)
So far, there had not been any machine availability effects from the situation, although there were a few exhaust points that were high and low compared to the average exhaust temperature. Machine availability problems would trigger an outage.

At this point the NOx out the stack took a step change upward. It was determined to drop some load to get the NOx production numbers down if necessary.

The turbine ran until the scheduled outage in October and the nozzles were cleaned out. The steam flow over the whole period is shown in figure 7.

Figure 7- Steam Flow Over The Whole Time Period

The internal passageways in the combustion can covers were plugged with deposits from the steam or attemperation water system.
CONCLUSION

The process of monitoring and diagnostics for gas turbines requires certain staff skills, staffing structure, software infrastructure, monitoring activities and reporting. Software can be used to enhance the process and there are certain characteristics you would expect to see in a software tool that assists in monitoring and diagnosing problems.

Case study summaries of monitoring and diagnostics in use followed by a more in-depth example show the benefits of monitoring and diagnostics and how it is used as part of the effort to increase turbine availability and reliability and to optimize outage activities.

REFERENCES