Online Monitoring of Gas Turbine Power Plants

Hans-Gerd Brummel, Dennis H. LeMieux, Matthias Voigt*, Paul J. Zombo

Siemens Power Generation (PG)
* Siemens Corporate Research (SCR)

USA / Germany

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1. Introduction

In recent years significant changes in the business relationships between customers and original equipment manufacturers (OEMs) could be observed in the power industry, which led to new forms of cooperation between those partners. Remote online monitoring is one important outcome of this development.

An analysis gives various reasons for these changes:

Since the early nineties a strong trend towards gas turbine application for power generation could be noticed. Decreasing gas prices in connection with high efficiency in combined cycle mode and small staff required made this technology attractive compared to the traditional coal based power generation.

In the late nineties advanced gas turbines became available with more than 250 MW electrical output and 38 % simple cycle / 58 % combined cycle efficiency. This impressive development could only be realized by applying the most advanced technologies and materials available.

As always, you do not get things for free. The more complex the machines got, the higher the turbine inlet temperature was pushed, the more exotic cooling techniques and materials had to be applied, resulting in an increased risk for abnormal behavior with the threat of non-availability on the horizon.
In traditional business relationships, OEMs sold gas turbines to utilities, and—after a fixed guarantee period—the customer had to carry all the risk and to cover the repair costs for his machine to the full extent.

With the new high performance engines being introduced in the market, customers, in particular independent power producers (IPPs), OEMs and insurance companies were looking for new structures in their relationship. As a consequence, O&M Contracts and Long Term Service Agreements were established that are designed to cover the greater part of the engine lifetime, which under certain contractual conditions include an OEM contribution on repair costs. This made the situation more calculable for the customer, but resulted in additional risk for the OEM, as he eventually had to pay for repairs without knowing how the engine was actually operated.

At the same time as these changes were occurring in power generation, a real boost in information technology took place, allowing the transfer of large masses of data over long distances. As a result the idea of using remote monitoring to mitigate risk for long term gas turbine service contracts was born.

2. Remote Monitoring Strategy

After a basic research phase to select the best technologies available, Siemens Power Generation (PG) decided to establish a pilot remote monitoring center in Orlando, Florida, in late 1999. Since that time, the remote monitoring of Siemens’ advanced gas turbine / combined cycle fleet has been largely extended, primarily focusing on long term maintenance contracts (Long Term Programs - LTPs). Continuous remote online monitoring was officially introduced in February 2002 as “Power Diagnostics® Services” (PDS) to enable both customers and OEM to mitigate risk on a 24/7 basis. In the following chapters the Power Diagnostics® concept, infrastructure, and applied tools will be presented, along with some typical findings which actually prove the concept of risk mitigation, creating a win-win situation for both customers and OEM.
2.1 Power Diagnostics® Services

Power Diagnostics® Services is the Siemens PG remote monitoring and diagnostics strategy targeted to provide early detection of abnormal operating conditions of power plant equipment to help improve plant availability and operations. Multiple data acquisition tools can be used for obtaining daily operational data from customers’ power generating equipment. Advanced diagnostic software helps experienced engineers identifying issues before they reach conventional alarm levels. The diagnostics engineers are supported by specialists from all parts of the company, bringing in the entire knowledge of Siemens PG into remote monitoring. Early detection of faults allows service teams to prepare parts and manpower, under certain conditions it is possible to turn a potential forced outage into a scheduled event (Figure 1).

![Remote Monitoring Structure](image)

Figure 1: Power Diagnostics® Remote Monitoring Infrastructure

Once the data is transmitted to a Power Diagnostics® Center (PDC), it is processed through a series of advanced data analysis tools, and the results are posted for the Siemens Engineers to review on a regular basis. Upon detection of an anomaly, the engineers will prepare a report summarizing the details of the issue, possible causes and suggested actions. This report is then sent to the technical and regional service managers who communicate and discuss the
report and possible courses of action with plant personnel considering the severity of the issue, dispatch of the unit, and the availability of parts and labor.

3. Data Acquisition

The process starts with the collection of the data of interest from the plant’s instrumentation & control (I&C) system.

Power Diagnostics® Services uses multiple acquisition tools for obtaining the daily operational data from their customers’ gas turbines, generators and other major plant components. The primary system for data acquisition is WIN_TS™, a PC-based software developed by Siemens PG that is passively connected to the site’s I&C system. This data acquisition system receives data from the plant’s control system along a one-way data highway. There is no interaction with the site’s I&C system, and in particular no threat of interference with the actual engine operation. Figure 2 shows the general data flow configuration from the power plant site to the remote monitoring centers. This configuration is designed to comply with the plant’s and with Siemens PG’s data security procedures.

![Figure 2: Data acquisition, transfer, and processing/evaluation/storage in the Power Diagnostics® Centers. Before the incoming data can enter the PDC, they are checked in the Demilitarized Zone (DMZ), a data storage area protected by firewalls.](image)

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4. Data Evaluation

The Power Diagnostics® approach to remote diagnostics is rather unique in the industry. Siemens does not only have experts that analyze data daily in centers around the world, but also provides the customers with some diagnostic capabilities on-site using WIN_TSTM. This chapter will highlight the potential of diagnostic capabilities and show the value added by Power Diagnostics®.

4.1 On-site Analysis via WIN_TSTM

The WIN_TSTM computer at site provides real-time data analysis capabilities utilizing several tailor-made diagnostic modules that monitor key parameters of engine operation such as the turbine outlet temperature profile, shaft vibrations and bearing conditions, et cetera.

Real-time viewing of these important operational data and the related analysis results is possible via several customized screens. Figure 3 shows an example.

![WIN_TSTM Analysis Modules](image)

**Figure 3:** WIN_TSTM screen for direct online monitoring at the plant
The goal of these WIN_TS™ modules is to catch hardware failures or operational anomalies before they reach the existing control system alarm limits. Early detection of these types of events or conditions can potentially prevent engine trips, forced outages, and additional impacts. The alarm limits in the modules are customized to each unit by analyzing the specific characteristics of the engine in an evaluation period. During this period (designated by the assigned engineer), baseline operating conditions are determined for each of the unit’s modules. After fine tuning of the modules, the actual monitoring period begins, and significant deviations from the determined baseline are to trigger an alarm. If there is a WIN_TS™ alarm that may indicate a serious problem, a Watchdog File is automatically transferred to the PDC. This file is a special data compilation that contains information regarding the alarm, permitting the Siemens engineers to react to the potential problem in a timely manner. If the issue is severe enough, the assigned engineer may contact the site directly. In contrast to other OEM remote monitoring systems, the customer has access to the WIN_TS screens and can use them for his own analyses and evaluations.

4.2 Power Diagnostics® Center Analysis

The majority of the data analysis is carried out at the Power Diagnostics® Centers in Orlando, FL, and Mülheim, Germany. Once the data is transmitted and has successfully passed the security checks in the DMZ, it is processed through a series of advanced neural network models and artificial intelligence software (see right side of Figure 2 and Figure 4). The results are posted for a so-called ‘Platform Team’ to review on a daily basis.

It is Power Diagnostics’ strategy never to rely on one system alone. The analysis and diagnosis process is a mix of automated applications of different software tools and the judgment and expertise of human experts. This expertise comes not only from the PD engineers, but from available specialists within the entire company as well. This assures that the diagnoses -being communicated to the Long Term Programs engineers (liaison to the customers) and the plant operators- have a high level of confidence (more in the following chapters were actual findings and their consequences are presented).

The software tools listed below are the backbone of the data analysis procedure in the Power Diagnostics® Centers Orlando and Mülheim:
- PD Automated Processing System APS
- PowerMonitor
- PD Rulebase GT-AID
- PD Operation Database
- PD WebPage Reporting System

**Figure 4:** Power Diagnostics® Technical Approach

For dealing with a fleet of now more than 200 advanced gas turbines worldwide, it is a must to have a highly effective, automated and fast data processing infrastructure available. As Power Diagnostics® has its own Research and Development organization, the tools are tailor-made for the application in the centers. It is a great advantage that software developers and research engineers work as close as possible with the PD operations engineers who perform the actual data analysis on a daily basis. PD Research & Development cooperates in certain fields with Siemens Central Technology (CT), in particular with its American branch Siemens Corporate Research (SCR) to take advantages of synergies resulting from research work from other branches such as Siemens Medical, another vanguard in remote diagnostics technology.
4.2.1 Automated Processing System APS

This is the overall control system for the analysis process. APS administers the incoming data, transfers it to the analysis tools PowerMonitor and GT-AID and stores raw and processed data as well as the results in the central PD Database.

4.2.2 PowerMonitor

PowerMonitor is a self-learning tool developed in close cooperation with SCR (see Figures 5 and 6). After a short learning period (training mode) the code is able to determine the correlations between operation parameters. In the subsequent monitoring mode the program calculates an expected value for each measured parameter based on the knowledge gained in the training mode. The calculated expected values are compared to the measured values, and deviations trigger an alarm.

![Image of PowerMonitor](https://example.com/image)

Figure 5: PowerMonitor results showing deviation of measured figures from expected (Residuum: Difference measured – expected values).

PowerMonitor is an effective alarming or early warning tool that takes away routine monitoring work from the engineers and let them concentrate on the severe cases. But PowerMonitor only tells you that something is developing; it gives no technical diagnosis. For that purpose the engineers are supported by artificial intelligence software called
GT-AID, a rule-based expert system also developed and maintained by Power Diagnostics® Services’ R&D organization.

Figure 6: PowerMonitor results showing deviation of measured figures from expected (Residuum: Difference measured – expected values).

4.2.3 Power Diagnostics® Rulebase GT-AID

PowerMonitor, described in the previous paragraph, tells you that something is developing; but it gives no technical diagnosis. For that purpose the engineers are supported by an artificial intelligence software called GT-AID, a rule-based expert system also developed and maintained by Power Diagnostics® Services’ R&D organization.

GT-AID is able to draw conclusions in form of technical diagnoses from the constellation of the analyzed data. The software is very versatile and flexible with the result that new insight, transferred into rules, can be simply added to the existing rulebase.

Siemens operations and development engineers work together in writing those technical rules for GT-AID to detect hardware and control system issues and to trend critical parameters over time. The rulebase is also designed to analyze starts, trips and instantaneous load changes and to work out fleet characteristics (see Figure 7).
“Knowledge is power”. To have access to the knowledge that lies within the years of operational data of an entire fleet is one of the advantages only the OEM has. The more data you have, however, the more difficult it is to evaluate and to derive the right conclusion from it. So it is very important to have powerful tools available to select comparable events and analyze them and come up with conclusions. This is realized by a close interaction of the actual database, where all raw data and analysis results are stored, with GT-AID. The internal structure of the GT-AID kernel and the rules make it a very powerful combination to perform fleet comparisons, e.g. start-up analyses.

4.2.5 Power Diagnostics® WebPage Reporting System

In the beginning, data was analyzed using tools such as Microsoft Excel®, and daily diagnostics reports were created by hand. As the number of monitored units grew, this became impractical and led to the automation of many routine tasks. Reports to Siemens LTP
engineers, customers and back offices are now compiled to a great extent without human interference. Much of this information is available on the corporate intranet via the Power Diagnostics® WebPage Reporting System. The structure of the WebPage ensures that only personnel with permission can see the selected results. For example, the LTP engineer of a certain unit can only see the data and results for his plant.

All these tools and systems have one feature in common. They provide unit specific operating characteristics which facilitate early detection of abnormal trends. If the PD engineers are faced with new or unusual issues, they can quickly and easily consult with one of many specific component and design engineers of the company. These specialists can add extensive expertise in the evaluation of operational or hardware issues.

4.3 Diagnostic Findings Information Distribution Process

Once the data is processed, the results are posted for the Siemens platform team of each unit to review via the PD WebPage. As mentioned above, access to each unit’s data and diagnosis results is strictly controlled. Upon detection of an issue, the PD engineers prepare a report describing the event, possible causes and suggested actions. This report is then sent to the technical and regional service managers, who will discuss the report and possible courses of action with plant personnel considering the severity of the issue, dispatch of the unit, the availability of parts and labor, and the specifics of the contract.

5. Diagnostic Findings and Benefits

There are numerous potential benefits of remote monitoring that are generally shared by the customer and the OEM. By collecting operational data from the site and evaluating it on a daily basis, Siemens can help to reduce the potential for damage to the equipment monitored. As described above, the diagnostic tools set in place are designed to detect already small indications of changes in monitored parameters from expected. These changes are thoroughly analyzed to make fact-based recommendations to the customer. Early fault detection under certain conditions may be able to limit the amount of consequential damage and it can also help reducing the overall repair costs by having the opportunity to plan all necessary actions.
upfront, such as having all manpower and spare parts required available at site when the
game is shut down for repair. In fact, remote monitoring has proven so successful in
reducing the potential of consequential damage that some in the insurance industry are
considering lowering rates to customers with remote monitoring systems installed along with
certain hardware configurations.

Sometimes power generation facilities are urged by the utilities or the government to
postpone outages due to high demand for power, such was the case with the California energy
crisis a few years ago. Under these types of circumstances, remote monitoring services can
afford the customer better information to assess the risk of operation beyond the
recommended service interval. In several cases it was possible after the early detection of an
anomaly to prolong the engine’s operation by close and careful remote monitoring until the
high energy demand was over or even until the next planned outage date was reached.

5.1 Examples of Remote Diagnostics Successes

To prove the benefits of remote monitoring performed by skilled OEM personnel in the
following some typical examples of actual Power Diagnostics® findings will be presented.

5.1.1 Example 1 - Clogged Fuel Nozzle

In the first case Power Diagnostics® Services registered a shift in engine parameters weeks
before a planned maintenance outage. A Siemens gas turbine specialist assessed the severity
of the trend. Possible causes and effects were reported to the Siemens LTP Manager. The
most probable cause was identified as debris in the fuel nozzles and the customer was made
aware of the issue.
Figure 8: Debris in the fuel nozzles, predicted and actually found after opening the engine.

Turbine hardware and operational impacts, such as potential complications during load changes, shutdown or start-up were assessed. The customer and Siemens worked together to monitor the parameters and keep the plant in operation until the next regular outage period. Because Power Diagnostics® Services were able to pinpoint the location of the problem, the clogged nozzles were easily identified (see Figure 8) and the debris removed, thus minimizing the outage. Siemens’ precise assessment of the hardware issue allowed the customer to more fully evaluate the situation and helped them to develop a plan of action that met their operational needs.

5.1.2 Example 2 - Overheated Bearing

An increasing temperature trend on the compressor bearing of an advanced gas turbine with annular combustion chamber was detected by GT-AID™ (Figure 9) well before the I&C system would react (TXP warning at 110 °C, shutdown at 120 °C). Working in close cooperation with the customer, it was decided that the lifting oil pump should be activated and the oil cooler operation adjusted to relieve stress on the shell of the compressor bearing. Continuous monitoring enabled the operation of the gas turbine until a scheduled outage.
Figure 9: Early detection of a bearing issue by remote monitoring well before the I&C system would have alarmed. By counter measures the unit could be operated until a scheduled outage.

5.1.3 Example 3 – Bad Sensor

Sensors going bad are very common events in the diagnostics world. Wrong readings are a dangerous phenomenon, as they can actually result in wrong diagnoses. A lot of effort has been made to clearly identify wrong or unreliable readings using the automated processing tools PowerMonitor and GT-AID. Figure 10 is a PowerMonitor graph clearly identifying a bad sensor. Such dramatic oscillations in the residuals simply could not be caused by a physical effect.

Compared to the more dramatic findings of the previous examples, this sensor issue does not look very spectacular; it certainly doesn’t have the threat of a multi-million dollar failure. But everyone should keep in mind that continuous diagnostics is not just about finding the big issues. Bad sensors make more than 70% of all detections made, and a sensor which has impact on a protection logic could cause a major issue. Therefore the focus of continuous monitoring lies on persistently evaluating all aspects of the plant and on cooperating with the customer to maintain the sensors and other equipment of the plant on the highest level possible.
6. Future Diagnostic Capabilities

In the previous chapters diagnostics approaches were described, which use the standard instrumentation of the plant. In the following a new monitor will be presented, which is able literally able to see into the core of a gas turbine during operation to survey critical parts.

Five years ago, the Power Diagnostics’ R&D organization teamed up with Siemens Gas Turbine Engineering to develop a device that is a significant step forward in online diagnostics. The proposed infrared (IR) technique gained interest by the US Department of Energy (DOE), which co-sponsored the project from 2001 to 2005.

6.1 Online TBC Blade Monitoring System

As already pointed out in the introduction of this paper, the high process temperature of advanced gas turbines (Figure 11), necessary to achieve the postulated engine efficiencies,
could only be realized by applying combined measures to the most exposed parts as first row turbine vanes and blades (Figure 12) to withstand the heat.

Figure 11: Cutaway of a Siemens SGT6-5000F Gas Turbine (200 MW Class).

6.1.1 Motivation

These measures include the proper choice of heat-resistant alloys, efficient cooling of the vane and blade metal structures, and a thermal insulation layer – referred to as ‘thermal barrier coating’ (TBC) – to protect the metal components from the direct heat impact of the combustion gases. Although considerable effort is put into keeping these components intact, vanes and blades do not last for the entire life of the gas turbine. They have to be replaced during the operational life of the engine, which takes place as scheduled maintenance programs. There are algorithms in place that determine the proper time for an exchange, but it must be emphasized that these calculation methods are estimates, as they do not take into consideration every detail affecting the actual condition of the hot gas path components. Consequently, there is a possibility that individual blades or vanes may fail before the scheduled exchange date.
Of the three measures, which ensure a long component life -material choice, cooling, and thermal barrier coating- the latter is most affected by wear and tear as this is a ceramic layer sprayed on the vanes and blades. TBC is impacted by erosion, debonding effects and spallations, i.e. parts of the thermal insulation layer chip off, leaving the metal surface unprotected (see Figure 13).

A weakened turbine blade, rotating at 3 000 or 3 600 rpm, carries the potential for severe consequential damage. It is extremely difficult to survey those critical components and in particular the condition of thermal barrier coating during operation of the engine, due to the high combustion gas temperature and pressure (more than 1400°C (2600°F) at a system pressure level of 15 bar (220 psia)), and the high rotation velocity of the blades (about 390 m/s (870 mph) tip velocity for row 1 blades).
Figure 13: New and worn row 1 blades: Monitoring of TBC loss is important to avoid unscheduled engine failure or engine damage. It is necessary to replace coated blades due to the limited lifetime of the TBC.

6.1.2 Technical Solution

On the other hand it could be taken advantage from the high process temperature to obtain the required information. It was found that the thermal radiation of the red hot blades provides sufficient energy for an infrared (IR) camera to take images. As there are IR cameras available now, which have an extreme short integration time in the magnitude of only 1 millionth of a second; the other obstacle – the fast blade rotation, which would normally result in a blur on the actual image, could be overcome by literally freezing the movement with this extreme short exposure.

Another important component needed was an overall supervisory system, which should incorporate all functions to operate/control the monitor, in particular the camera and the blade identification and image triggering system.

From the start, the monitor to be developed should be able to be incorporated into Siemens Power Generations’ global remote monitoring infrastructure. The system should be remotely operable and able to automatically evaluate the images taken in terms of detecting defects,
and further to transmit images and evaluation results without human interference to one of the company’s Power Diagnostics® monitoring centers.

After completion of the conceptual phase in 2001, the design of the monitoring system was divided into several individual parts:

- access ports on the engine (multiple view angles for row 1 and row 2 blades);
- optical system;
- camera enclosure including cooling system;
- overall supervisory system.

The actual design work and manufacturing of the components took place in 2002 and 2003. For the realization of the supervisory system and the development of the automated image evaluation capabilities in particular, Siemens Westinghouse teamed up with Siemens Corporate Research, the US branch of Siemens Corporate Technology.

Most of the individual systems were lab-tested, but it was not until the installation on a real engine that the system in total was able to prove the validity of the concept by demonstrating that sharp images of a large portion of a gas turbine row 1 blade could be obtained under full load operation.

### 6.1.3 First Infrared Images

To validate the concept, the entire system with all subcomponents was installed on a stationary 60-Cycle 200 MW class gas turbine at the Siemens Gas Turbine Test Center in Berlin, Germany. **Figure 14** shows how the monitoring system is arranged in the turbine.

The first images were obtained at low load on January 27, 2004, with the quality being better than expected. Even the cooling holes on the blades with a diameter of a little more than 1 mm could be clearly seen. Some days later a full load test was conducted, with identical image quality.
**Figure 14**: Installation of Blade Monitoring System in the engine.

**Figure 15**: Infrared image taken from a row 1 blade of a 200 MW class gas turbine under full load at the Berlin Test Center. The TBC at the leading edge of the airfoil was artificially removed for blade identification purposes.

*Figure 15* shows an infrared image taken during that full load test. This blade is unique because the TBC on the leading edge was artificially removed to allow blade identification.
and verify the image trigger function of the camera. The TBC removal can be clearly identified on the picture, proving two facts:

1. TBC spallations can be detected with the system.
2. The blade identification and triggering mechanism works. After selection of an individual blade an infrared image of exactly that blade will be taken.

**Figure 16** shows an example taken at Berlin during a later test campaign with experimental thermal barrier coatings, showing clearly spallations at platform of the blades.

![](image)

**Figure 16**: Infrared image of a row 1 blade of a 200 MW class gas turbine at the Berlin Test Center taken at 140 MW load. The Online TBC Monitor proved to be very beneficial during a series of tests with experimental TBC.

### 6.1.4 Next Development Steps – Current Status

The next milestone was reached in December 2004. Three camera systems were installed in a SGT6-5000F gas turbine operated commercially at a 2-in-1 combined cycle power plant located in the United States. Two infrared cameras at different angles provide images of the row 1 blades; the third camera monitors row 2 blades. (**Figure 17**). As in the Berlin test bed
engine operation is limited to only a couple of hours at a time, it is necessary to gain information concerning the long term operation abilities of the new system under full commercial conditions.

**Figure 17:** Cutaway of camera installations for row-1 and row-2, as realized at a commercially operated engine in the US for long term testing of the new system.

The online TBC monitoring system incorporates now automatic image evaluation (advanced pattern recognition) and remote control capabilities. In February 2005 one of the cameras was switched on the first time from the Power Diagnostics® Center Orlando.

This technology is still in its infancy, but it will soon enable design engineers to verify the functionality of new components for the next gas turbine generation in the test facility. With further development the system can be used as an online monitor installed on every engine to actually survey the condition of the TBC, pushing remote monitoring to a new level.
Remote monitoring is rapidly growing in the power generation industry, and Power Diagnostics® Services is doing its part to take care of its customers. PDS provides data acquisition, analysis, storage, and versatile reporting capabilities that are used to help in the early detection of abnormal operating conditions of gas turbines and other power plant equipment. This information, along with associated recommendations, makes it possible to make more informed business decisions about the course of action regarding diagnostics issues. Fact-based decisions can have substantial financial benefits for both the customer and the OEM.

Maintaining good instrumentation health, starting reliability and optimum control settings by continuous monitoring are additional objectives that can help the operators keep plant availability high. Customers can help achieve these objectives through disciplined review, reporting, and follow-up, and addressing small issues before they combine into bigger problems.

Only working hand in hand in an atmosphere of mutual trust can lead to optimum plant conditions and operation.