Performance Monitoring For Gas Turbines

Introduction

Managing an asset requires numerous technologies designed to assess health. While most gas turbines in the field are fitted with some type of mechanical condition monitoring system (see companion article on page 48 in this issue of ORBIT), it is less common to see the inclusion of thermodynamic performance monitoring systems. However, performance monitoring is no less critical for those seeking to get the most from their machinery and processes. As will be seen, the financial benefits for those that employ performance monitoring are both consistent and compelling.

This article discusses the reasons for monitoring performance on both gas turbines and the machines that they drive, the fundamentals of how a performance monitoring system works, and the types of information the system can provide. It presents the business case for monitoring performance along with several examples of how actual customers are obtaining value from their performance monitoring systems. It also describes the various performance monitoring solutions available from GE Energy,

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the applications that they target, and how they can be used individually or in conjunction with one another as part of a larger System 1 implementation.

Gas Turbine Thermodynamics

Gas turbines convert fuel energy into mechanical power or – by connecting to electric generators – electric power. The underlying thermodynamic cycle, known as the Brayton Cycle, involves the compression of a gaseous medium (typically air), the addition of fuel energy through combustion or heat exchange, and expansion of the hot, compressed gas through a turbine to convert the thermal energy into shaft power. In contrast to an ideal thermodynamic cycle, a real gas turbine cannot perform these processes free of friction and losses. This results in the simplified overall balance equation for a gas turbine as follows:

Shaft Power = Fuel Energy − Power Required for Compression − Exhaust Energy − Mechanical Losses

MODERN GAS TURBINES MUST WORK AT PROCESS **CONDITIONS THAT PUSH** THE MECHANICAL AND THERMAL **STRESS** OF GAS PATH COMPONENTS TO **THEIR LIMITS.**

The profitability of this process is directly related to the difference between the cost of fuel and the value of the machine's output (e.g., electricity, if the turbine is driving an electric generator). However, operators have only limited (if any) control over their cost of fuel and the selling price of the machine's output. This leaves only the *efficiency* of the machine's conversion process (i.e., the consumption of fuel per unit of generated output) as something the operator can directly influence. The importance of maximizing efficiency is thus evident.

Factors Affecting Performance

Gas turbines operate efficiently if the energy conversion process is operated at the following thermodynamically favorable conditions:

1. **high pressure and temperature at the turbine inlet;**
2. **minimal losses during compression and expansion.**

While conversion losses can be minimized through optimal aerodynamic design of the compressor and turbine expander, the high pressures (ratios of 20:1 or greater) and turbine inlet temperatures (2500°F and above) desirable for efficiency come at a price: reduced durability of the gas path components. Effectively, to achieve the thermal efficiencies delivered by modern gas turbines, they must work at process conditions that push the mechanical and thermal stress of the materials used in the machine's gas path components to their limits. The technologies developed to increase process efficiency while mitigating the risk of parts failure include air or steam cooling, and the use of special materials such as high performance alloys, single-crystal materials, thermal barrier coatings, and others. Adding to these complexities are the effects that ambient conditions and load have on the operating characteristics of gas turbines. This results in considerable engineering challenges for those who design, manufacture, and refurbish today's gas turbines.

Ambient conditions affect a gas turbine at both the compressor inlet and the turbine outlet. At the compressor inlet, the higher the temperature and the lower the pressure, the less mass flow that can be generated through the turbine. Humidity also plays a role. Higher specific humidity increases the specific volume of the inlet air flow, so that the mass flow through the turbine is reduced resulting in less power output and increased heat rate. At the turbine outlet, ambient conditions also play a role. The higher the pressure (either exhausting into a stack, or a heat recovery steam generator in combined cycle plants) the less energy that can be converted to shaft power.

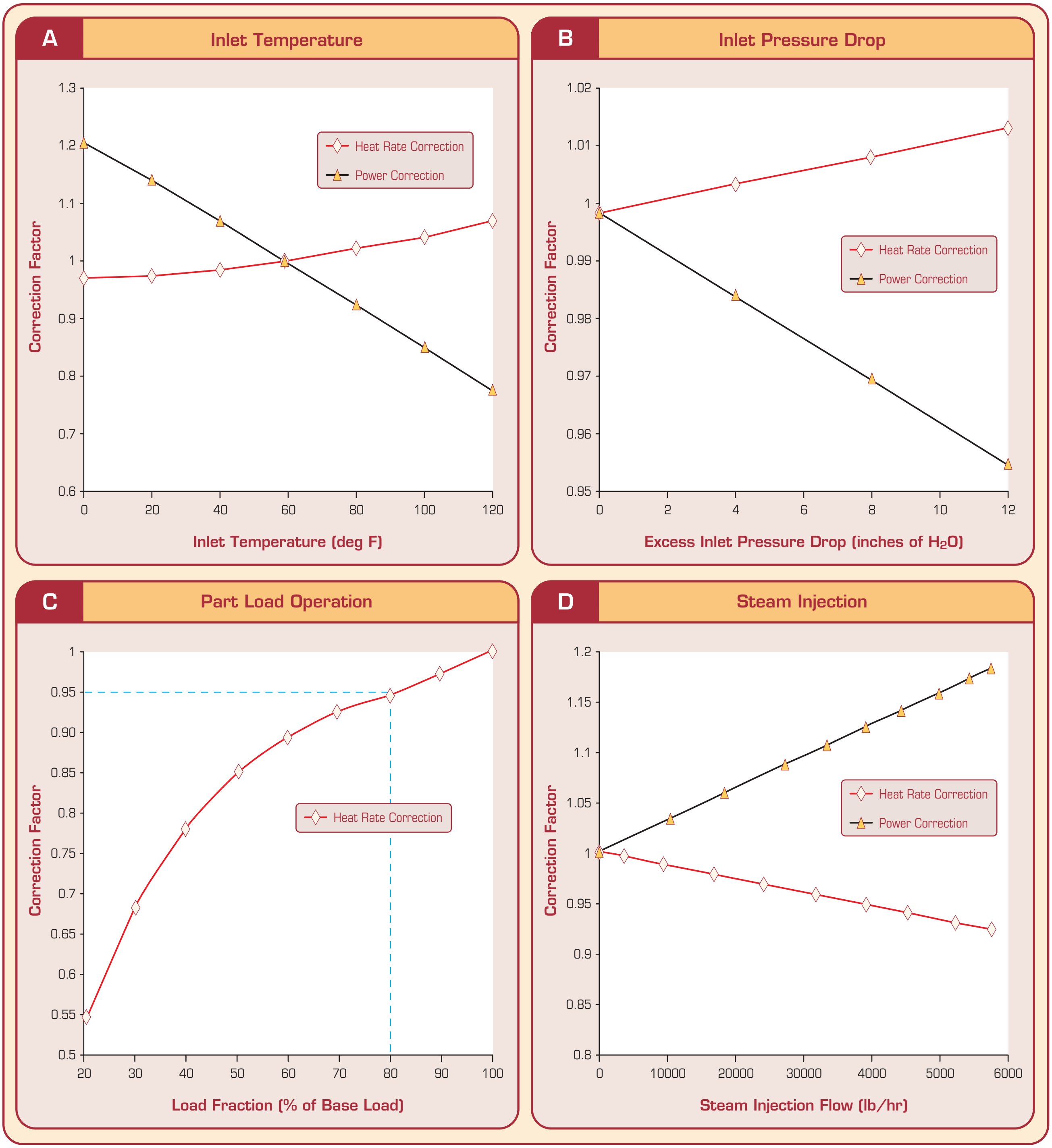
Load is another consideration that affects performance. Gas turbines are aerodynamically designed for optimal performance at base load levels. If the gas turbine is not operated at this load level, the flow triangles in the compressor and turbine expander stages will differ from design assumptions, and more energy will be dissipated.

Other factors influencing gas turbine performance are the fuel heating value (the content of energy per mass unit of fuel), and the injection of steam or water into the combustors to boost power output and/or control NOx emission levels.

Cause and Effect

So far, we have devoted quite a bit of this article to explaining the complexity of gas turbine design and operation. Why did we do this when our goal is to discuss gas turbine performance monitoring? The answer is that assessing the efficiency of a gas turbine and its components requires a solid understanding of the factors that can affect efficiency, and these are not always related to equipment degradation. Indeed, changes in power output and fuel consumption can have very 'natural' causes, and the effects can be as large – or larger – than those arising from equipment degradation.

To illustrate this, Figure 1 shows the typical impact on rated power and heat rate for a hypothetical 40 MW industrial gas turbine that would be caused by changes in inlet temperature, inlet pressure drop, part-load fraction, and steam injection flow.



CHANGES IN POWER OUTPUT AND HEAT RATE FOR A 40 MW GAS TURBINE DUE TO A) INLET TEMPERATURE; B) INLET PRESSURE DROP; C) PARTIAL LOADING; AND, D) STEAM INJECTION FLOW. | FIG. 1

IT IS **IMPORTANT** THAT THE SYSTEM BE ABLE TO **DIFFERENTIATE BETWEEN "NATURAL" CAUSES** AND THOSE FROM ACTUAL EQUIPMENT **PROBLEMS AND DEGRADATION.**

Thus, changes can be due to both so-called "natural" causes (such as load and ambient temperature) as well as actual equipment degradation. Because the goal of a performance monitoring system is to help operators and performance engineers understand the cause/effect relationships when changes occur, it is important that the system be able to differentiate between "natural" causes and those from actual equipment problems and degradation. This can only be determined by comparing measured gas turbine performance against a model of "expected" engine performance reflecting the impacts of all "natural" causes. More details on how this is done are discussed later in this article.

Recoverable and Non-Recoverable Degradation

Another important distinction when monitoring performance is the difference between recoverable and non-recoverable degradation, which we define as follows:

Recoverable Degradation is the performance loss that can be recovered by operational procedures such as keeping the inlet and outlet pressures low, or online and offline water washing of the compressor.

Non-Recoverable Degradation is the performance loss that cannot be recovered without repair or replacement of affected gas turbine components. Examples of non-recoverable degradation include: loss of surface finish on blades, increases in blade tip clearances, packing leakage of both the compressor and turbine, and combustion system component corrosion/erosion leading to flame instabilities or increased thermal stress on the subsequent turbine sections.

Limited instrumentation inside the engine generally means that locating the actual stage where a significant change in performance has occurred will be difficult or impossible; however, the thermodynamic model will generally be able to flag a severe problem early enough to prevent larger damage.

When combined with mechanical condition monitoring, the ability to isolate the location of problems can be improved. For example, tip clearance and packing leakage are clearly related to the rotor dynamics of the turbomachinery, and can often show up as changes in vibration. The combination of thermodynamic performance monitoring and mechanical condition monitoring (such as vibration) can thus allow better diagnostic capabilities for assessing the nature, severity, location, and cause of machinery performance changes.

Why Monitor Performance?

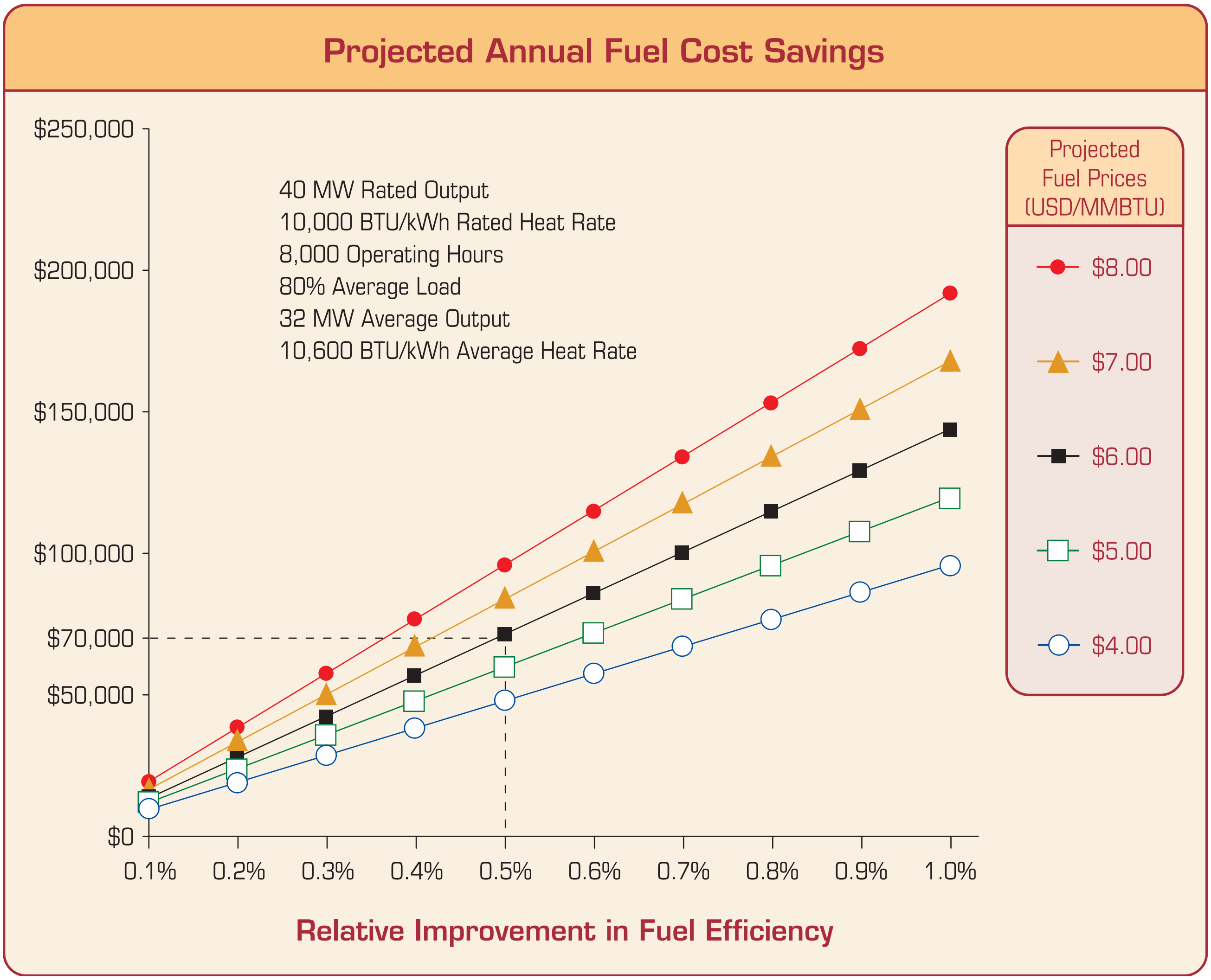
To answer this question, consider a simple, hypothetical example:

# of machines: 1
Machine Type: 40 MW gas turbine
Rated heat rate: 10,000 BTU/kWh
Operating Mode: simple-cycle
Average load level: 80%
Operating hours per year: 8,000

The correction factor for 80% part-load operation is 0.947 (see Figure 1-C). Corrected heat rate thus becomes approximately 10,600 BTU/kWh for the average load of 32 MW. Figure 2 shows the estimated potential savings in fuel costs for this hypothetical machine as a function of relative improvement in efficiency for several different fuel price assumptions.

Referring again to Figure 2, and assuming a fuel price of $6 per MMBTU for the gas turbine in our example, a mere 0.5 % improvement in fuel efficiency can save as much as $ 70,000 per year.

WHEN COMBINED WITH **MECHANICAL CONDITION MONITORING**, THE ABILITY TO ISOLATE THE LOCATION OF PROBLEMS **CAN BE IMPROVED.**



ANNUAL FUEL COST SAVINGS AS A FUNCTION OF EFFICIENCY IMPROVEMENTS AND FUEL PRICES FOR A 40 MW SIMPLE-CYCLE GAS TURBINE. | FIG. 2

Achieving the Savings

How are such savings actually accomplished in practice? There are at least four ways, as summarized below:

1. **By allowing optimal maintenance interval planning for recoverable degradation.**

   The rate at which a compressor fouls or an inlet filter clogs is highly dependent on the site conditions as well as on current weather and climate. Monitoring the rate of degradation and scheduling/conducting maintenance procedures effectively, such as compressor washes or filter cleanings, will ensure that the gas turbine operates most efficiently.

2. **By improving plant output.**

   For production processes as well as capacity sales, a decline in power output due to degradation may have even larger economic impacts than the costs of fuel, depending on the related product sales or power purchase agreements. This decrease in production may be worth as much or more than the additional fuel. This means that performance improvements often have a compound effect, impacting not only fuel costs favorably but by increasing plant output as well.

THE **QUALITY** OF THE INCOMING **MEASUREMENTS** IS VERY **IMPORTANT.**

3. **By reducing unplanned outages.**
   In some cases, performance can degrade to the point that the engine trips or reaches operational limitations that prevent continued operation. A comprehensive performance monitoring system helps mitigate this risk, providing operators with the capability to detect engine problems in time, allowing an outage to be scheduled when economic and production constraints have the smallest impact.
4. **By allowing more efficient outages.**
   Knowing in advance what needs to be maintained or repaired during the next outage enables a maintenance team to minimize the duration of the outage by reducing the risk of "unpleasant surprises" when opening the machinery. Consider our earlier example of the single 40 MW gas turbine: one extra day of outage will mean up to 24 hours x 32 MW = 768 MWh of lost production. Assuming an electricity sales prices of 40 cents per kWh, this translates to lost revenues exceeding $300,000 per day. If the gas turbine is used in a critical mechanical drive application, such as with an unspared blower in a refinery, the downtime can even be even more costly – sometimes, millions of dollars per day.

The Importance of Good Data

The performance monitoring system typically extracts its required data from existing data sources in the plant, such as the turbine control system, mechanical condition monitoring systems, and plant control systems. As described earlier, there are many "natural" causes for performance changes that must be distinguished from actual mechanical degradation of the machinery. Deriving performance parameters from measurements in the turbine control system or plant control system without correcting for ambient and load effects would produce practically useless information. Instead, a performance monitoring system must be capable of not

Case History #1 – Optimizing Fuel Costs

The operations team at a 1000 MW power plant actively uses their EfficiencyMap™ software to optimize daily plant operations. In addition to plant optimization, the EfficiencyMap system is designed to monitor the performance of the plant's evaporative coolers, gas turbines, heat recovery steam generators (HRSG's), steam turbines, condensers, and cooling towers.

Equipment degradation must be accounted for in order to effectively optimize the plant, which consists of two power blocks, each with two gas turbines. The software accounts for this degradation and advises the team on recommended changes to three primary controllable parameters: gas turbine load, evaporative cooler operation, and duct burner fuel flow in the HRSG. In addition, the software calculates the heat rate, heat consumption, and cost savings associated with operational changes.

The EfficiencyMap system at this plant is configured to provide *Opportunity Cost* which calculates the potential cost savings at a given fuel price and current operating conditions. In one recent scenario, the plant was generating approximately 900 MW with 410 MW on Power Block 1 and 490 MW on Power Block 2. The online optimization results recommended that the HRSG duct burners in Power Block 2 should be turned off while the gas turbine loads in Power Block 1 should be increased. The plant engineer directed the operator to make the changes recommended by the EfficiencyMap system. This allowed the plant to capture over 80% of the theoretically possible savings at that particular combination of plant output and ambient conditions, which translated to a nearly 1% fuel savings. These results were later validated by the plant engineer using the measured and heat balance values for plant net heat rate before and after the changes, further increasing the customer's confidence in the system's value as an optimization tool suitable for making real-time operating adjustments.

Case History #2 – Optimizing When to Perform Maintenance

The ethylene unit in a large refinery was known to have fouling problems on both the process compressor and its prime mover. This prompted the customer to purchase Bently PEFORMANCE™ software for the train.

During a scheduled outage, the compressor was serviced and the performance was found to recover dramatically. The prime mover fouling, however, not only persisted, but continued to grow worse as detected by the software. Another outage was out of the question – the only practical remedy was an online wash. The software, along with our services organization, was drawn upon to help determine the optimal time to conduct a wash.

Savings to the customer were three-fold. First, they were able to correct efficiency losses in the compressor, which translates directly to increased plant throughput and greater profits. Second, the customer would have reasonably assumed that maintenance conducted during the planned outage corrected the efficiency losses in both the prime mover and the compressor. But, because the software was able to conclusively demonstrate the prime mover was still experiencing problems, they were able to address this and avoid continued substantial fuel waste. Third, our service personnel were able to recommend the ideal time to conduct an online wash, finding the time when fuel savings and increased plant throughput would optimally offset the costs of this maintenance.

In the customer's words, "dramatic improvements in production and efficiency" have been realized as a result of their investment in performance monitoring software.

only accepting the necessary data inputs, but of also containing the detailed thermodynamic models that allow "correction" of the raw data for all relevant effects of operation.

In some cases, the necessary data may not be available, or perhaps more commonly, the quality of the measurement may be insufficient for performance monitoring purposes, necessitating the need for additional sensors. The quality of the incoming measurements is very important. Because many performance calculations are derived using mathematical relationships that involve exponents, small inaccuracies in one measured variable can result in very large inaccuracies or uncertainties in a derived result. For this reason, a necessary part of any performance monitoring endeavor must be to review all data inputs for sufficiency during initial system installation and design, and regularly thereafter to ensure that input quality is not degrading over time. Proper pre-processing and range-checking of the data by the online system prior to the performance analysis also helps to detect erroneous sensor readings. Failure to observe this will result in poor accuracy and inconclusive information at best, or at worst, false assumptions and forced outages due to performance problems that are not detected by the system.

How is Performance Monitored?

Basically, the procedure for performance monitoring consists of three steps:

Step 1: Range and Reasonableness of Inputs

Incoming measured data that serve as inputs to the performance calculations are checked for validity, compared to physical limits, and – if necessary – substituted with reasonable default values in order to guarantee proper online operation of the systems.

Step 2: Component Heat Balance

A heat balance around the gas turbine produces additional information on the conditions of the ingoing and outgoing streams and also adds information on certain parameters that cannot be measured directly. It is important to note that the heat balance calculation is not designed to measure performance, but to create detailed information about the current operating point that is consistent with mass and energy balances around the equipment. If the monitoring system covers the entire plant, the redundancy of information between the individual equipment even allows reconciliation of plant measurements and advisories regarding current sensor conditions.

IMPACT CALCULATIONS **HELP** THE OPERATOR OR PERFORMANCE ENGINEER TO **DECIDE** ON THE **URGENCY** OF MAINTENANCE **ACTIONS.**

Step 3: Performance Analysis

Once a consistent set of data on the current operating point has been generated, the performance analysis itself can be conducted, comparing current performance against expected performance calculated from detailed equipment models based on design and test information. In order to make performance data comparable over time, the current performance degradation is corrected to reference conditions, e.g. ISO or acceptance test conditions, so that it is easy for the operator or performance engineer to evaluate trends of equipment performance.

Additional features that can be combined with the performance analysis include impact calculations which help personnel to decide on the urgency of maintenance actions. Impacts can be expressed in terms of additional cost per hour, or changes in overall plant heat rate or power. If, for example, the gas turbine is exhausting into a Heat Recovery Steam Generator (HRSG), the impact of gas turbine degradation on the overall plant performance will differ from operation in simple-cycle mode, since part of the energy lost to the gas turbine exhaust can be recovered in the subsequent steam cycle.

Case History #3 – Quantifying Maintenance Savings, Optimizing Load Sharing

A 700MW combined cycle power plant in Asia uses EfficiencyMap™ software in conjunction with a contractual services agreement where our performance engineers regularly review data from the system and provide summary recommendations to the plant. The recommendations in these quarterly reports focus on operating and maintenance actions that the plant can take to optimize performance in light of current business conditions. They also quantify the results of operating and maintenance actions the plant took over the report's time period.

Two recent reports are particularly illustrative, highlighting the cost savings achieved through compressor offline washes and inlet filter replacements, allowing the plant to quantify the financial impact and make better decisions about optimal future maintenance intervals. In the first report, an offline water wash was performed on both GT1 and GT2. EfficiencyMap data showed a profit improvement of $1,100 per day on GT1 and $1,700 per day on GT2 as a result of these washes. This was a combination of the additional revenue from increased power output and better fuel efficiency through reduced heat rate.

In the second quarterly report, the inlet air filters were changed on both units and the EfficiencyMap data was able to quantify the financial impact, as with the offline water washes. In this case, GT1 saw a power output improvement of 1.6MW, translating to $1,200 in incremental revenue per day. GT2 saw an even better improvement of 1.9MW or $1,400 per day. The report also showed that the improvements resulting from filter replacement degraded more quickly in GT1 than in GT2, suggesting a more frequent maintenance interval for GT1 than GT2.

Finally, the reports suggested that the plant begin using an integrated feature of the software: its online optimizer module, allowing them to perform more ideal load sharing. The reports showed that had the plant used this feature, they could have achieved an additional $16,000 per month in fuel savings over the previous six months – simply by more optimally distributing load between the two gas turbines. Based on these compelling numbers, the plant management emphasizes the use of this software module.

Performance Monitoring Solutions from GE Energy

GE Energy offers several complementary performance monitoring products, able to deliver the functionality discussed in this article. They can be used individually or integrated with one another for both plant-wide and machine-centric applications. They can also be customized for specific application requirements. The following list is a brief summary of these offerings:

> **EfficiencyMap™** is a comprehensive stand-alone online performance monitoring system that is designed to cover the entire range of thermal power generation equipment, whether gas turbine-based plants or coal-fired steam plants. Designed for flexibility in end-to-end monitoring of plant heat balance as well as the constituent equipment in the plant's thermodynamic cycle, the system can be configured to address any type of power generation process ranging from pure electricity generation to complex cogeneration such as district heat or seawater desalination plants. EfficiencyMap uses the System 1® platform for its embedded data historian functions and is fully compatible with the Decision Support℠ module of System 1 software, allowing automated data analysis and "intelligent" alarm advisories that include recommended corrective actions.

> **Bently PERFORMANCE™** focuses on individual machine performance, rather than end-to-end plant performance, addressing gas and steam turbines, rotating and reciprocating compressors, and pumps. It is designed as a standard, fully integrated application package for the System 1 condition monitoring platform. Its wide variety of equations of state and special calculation routines for compressor modeling are particularly well-suited for the mechanical drive applications found in the petrochemical and chemical processing industries, including gas and oil pipeline booster stations. Capabilities for analyzing Exhaust Gas Temperature (EGT) have recently been added, allowing improved diagnostics on gas turbine hot gas path components.

[Editor's Note: For more information on EGT plot capabilities, see the companion article on page 88.]

> **Machine Performance** is a completely customizable version of the Bently PERFORMANCE™ calculation templates. It is intended for those who already have their own calculation engine and performance data, but don't need the added burden of developing their own display, database, communication interface, alarming, and other "shell" features of System 1 software. This approach works well for Original Equipment Manufacturers, Engineering and Construction contractors, and others who want to offer a tailored performance monitoring package to their customers while securely embedding the proprietary performance calculations and algorithms unique to their designs.

> **GateCycle™** software is an offline modeling tool – not an online monitoring system – and is used primarily by those who design new thermal power plants and modify existing plants. It provides heat balance modeling and "what if" capabilities for studying the entire plant and the individual equipment components. However, GateCycle software does play a role in our online systems – it is embedded as the calculation engine within EfficiencyMap software.

> **Compressor Wash Advisor** is an optional software module that can be supplied with EfficiencyMap or Bently PERFORMANCE software. The module utilizes online performance information as well as manually entered user inputs on current prices and costs to estimate the optimal time to perform an offline compressor water wash. While an online water wash adds only minor costs to gas turbine operations, an offline water wash

THE **PERFORMANCE MONITORING SYSTEMS** IN THIS ARTICLE HAVE BEEN **SPECIFICALLY DESIGNED** TO ADDRESS **ANY** GAS TURBINE, **REGARDLESS** OF MAKE, MODEL, OR MANUFACTURER.

(also called crank wash) requires a production interruption, and the cost of lost production incurred by this interruption must be added to the cost of detergent and labor required for the wash. However, these additional costs are generally offset by the superior effectiveness of an offline wash compared with an online wash. The key is in determining the optimal time to conduct an offline wash. Utilizing the performance analysis results of the past operation period, the Compressor Wash Advisor extrapolates the current rate of fouling into the future and estimates the economically optimal time for the wash: the time at which the cost of fouled operation exceeds the total cost of the water wash. With this information, the plant can effectively arrange for the most practical time for the water wash (e.g., during low demand periods). Other information provided by the performance monitoring system allows operators to optimally combine the offline wash with additional maintenance actions on inlet filters and other components.

> Online Optimizer is an optional software module that calculates the optimal set points for gas turbine load and other controllable parameters based on current performance of individual gas turbines. The module is compatible with both EfficiencyMap and Bently PERFORMANCE software. For example, plants with more than one gas turbine can use the Online Optimizer module to optimize load sharing between the turbines, making the best out of differences in non-recoverable degradation between multiple units. As every gas turbine has its own specific rating and performance degradation, it is clearly more profitable to distribute the load between the equipment according to their current performance. Another application of the Online Optimizer module is in economically evaluating when and how to use inlet chillers.

OEM Independence

The performance monitoring systems and heat balance modeling software offered by GE Energy and described in this article have been specifically designed to address any gas turbine, regardless of make, model, or manufacturer. Indeed, recent enhancements have extended the applicability of the software as a platform upon which any OEM can base a custom performance monitoring solution, by securely embedding their own machine-specific calculations and performance algorithms. These performance monitoring systems are today installed on a wide variety of gas turbines, driven equipment, and other prime movers from a broad range of machinery OEMs. This "OEM-neutral" posture remains at the core of all condition monitoring software offered by GE Energy, whether used for mechanical or thermodynamic assessment.

Summary

Performance monitoring constitutes a key practice to ensure plant profitability, with considerable cost savings related to maintaining maximum fuel efficiency and availability. As shown in this article, gas turbine performance is strongly affected by "natural" parameters such as ambient environmental and load conditions. As such, only systems that use detailed thermodynamic models of the gas turbine and its components are capable of correctly separating these "natural" effects from actual equipment degradation.

Correct performance information provides the plant with relevant, Actionable Information® on how to best manage recoverable and non-recoverable degradation. Such information can help identify the cause and location of overall performance degradation, quantify its impact on plant operating costs, and allow better optimization of plant equipment given the current level of degradation.

The performance monitoring solutions offered by GE Energy enjoy widespread acceptance in both the power generation and hydrocarbon processing industries, spanning many different machine types and manufacturers, and complementing GE's mechanical condition monitoring solutions. For additional information, use the Reader Service Card in this issue of ORBIT, or send an e-mail to energy.optimization@ge.com.