PERFORMANCE TEST METHODS TO DETERMINE THE BENEFITS OF VARIOUS GAS TURBINE MODERNIZATIONS AND UPGRADES

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ABSTRACT

As gas turbine fleets age and newer technologies become available, there are opportunities to improve gas-turbine based power plant performance by physical modifications to both hardware and software. Mechanical modifications can include, but are not limited to, upgrades to turbine and/or compressor blades and vanes, replacement of seals, and the cleaning, repair, or refurbishment of existing engine components. Controls modifications can include upgrades to the engine logic designed to improve operation and reliability as well as gas turbine and plant performance.

It is a challenge to determine the effects of the modernizations and upgrades by test, usually known as “comparative testing”. This is particularly true when another maintenance activity that affects performance takes place during the outage in which the modification occurs. Other difficulties arise when part load testing of gas turbine or plant performance is desired. This paper details some of the difficulties met in such testing, and the proposed optimized test protocols and agreements to meet these challenges.

INTRODUCTION

The major OEM’s and others are constantly working to develop power plant performance improvements based on gas turbine hardware and software modernizations and upgrades. These modernizations and upgrades generally include examination of both the gas turbine and bottoming cycle (for combined cycles) hardware and controls. While hardware and software upgrades are generally aimed at improved efficiency and power output, they can also reduce overall plant emissions and increase plant reliability and availability in addition to plant performance. Determining the combined cycle benefits from gas turbine based modernizations and upgrades, especially at part loads, can be quite challenging given all the factors that can influence bottoming cycle performance. Comparative testing of gas turbine hardware only modifications, software only modifications, or hardware plus software modifications can be affected by many things including degradation recovery, non-upgrade related maintenance activities, model accuracy, and instrument uncertainty, to name a few.

OBJECTIVE:

The objective of this paper is to provide guidance on acceptable methods to test the improved performance of existing power plants that undergo modernizations and upgrades in order to demonstrate compliance with contractual guarantees.

SCOPE

The methods described herein apply mainly to combined cycle power plants; however, they may also apply to simple cycles. The proposed methods address the need for demonstrating compliance with delta power and heat rate guarantees for a plant when a gas turbine has had upgrades similar to some or all of those described below.

TYPICAL UPGRADES:

Gas Turbine Controls Modernizations and Upgrades
- change to base load firing temperature
- change to base load IGV schedule
- change to base load rotor air cooler (RAC) return air temperature
• change to part load engine control methodology such as Outlet Temperature Corrected (OTC) upgrade
• Gas Turbine Mechanical Modernizations and Upgrades
• replacement of turbine blades and vanes
• replacement of compressor blades and vanes
• replacement of compressor and turbine seals
• cleaning of internal components

Bottoming Cycle Controls and Other Direct Modifications
• set point and operational changes
• any mechanical adjustments, such as cooling tower fan pitch

PERFORMANCE TEST PROTOCOLS:

This paper compares two approaches to demonstrate compliance with guarantees (acceptance tests). The final approach chosen for a given modification or upgrade is very dependent on the type of modification(s). It must also be noted that although the lowest reasonably achievable test uncertainty is important in comparative testing, other considerations need also to be taken into account, (i.e. the time and expense required to achieve what may only be a negligible reduction in the measurement uncertainty). Unless otherwise noted, any gas turbine tests should be conducted strictly in accordance with ASME PTC 22, “Performance Test Code on Gas Turbines”.

Comparative Combined Cycle Overall Plant Performance Tests per ASME PTC 46

ASME PTC 46, “Performance Test Code on Overall Plant Performance”, is the industry standard for the determination of power plant heat rate and power, and it appears to be the most directly applicable to the demonstration of guarantees in a pre-post outage scenario.

Gas Turbine Tests, Pre and Post Outage, with Steam Cycle Improvement Calculation (“GT Test Plus Heat Balance” method)

ASME PTC 22, “Performance Test Code on Gas Turbines”, is the industry standard for the determination of gas turbine power and heat rate. The revision to PTC 22 in printing at the time of this writing will also have details on determination of exhaust flow by calculation.

Changes in the steam turbine cycle (bottoming cycle) due to the gas turbine performance changes are directly calculable by measured changes at the gas turbine test boundary (exhaust gas flow and conditions, RAC flow). Further, changes in steam cycle caused by steam cycle control changes, such as main steam or reheat steam temperature, are generally well known, at least in order of magnitude, and can be fine-tuned by computer heat balance model.

An alternate approach to PTC 46 comparative tests is to determine the change in gas turbine performance via a pre-post outage PTC 22 test program, including the change in gas turbine exhaust gas flow and conditions, and to determine the change in the bottoming cycle strictly by plant heat balance model, utilizing the gas turbine exhaust changes, and any bottoming cycle control system or other changes, as the inputs to compare to a base reference case.

There are two advantages to this approach. First, it eliminates the inclusion of any changes in bottoming cycle performance which are not due to the specific modernizations and upgrades of interest performed during the outage in the test results. Secondly, it reduces the complexity and overall cost of the testing.

It is not necessary that the plant heat balance model identically matches the original bottoming cycle heat balance, or the existing power plant performance heat balance but it should be similar in design. The purpose of the model is strictly to determine the change in performance of the bottoming cycle as affected by the measured changes in GT boundary conditions and steam cycle control set point or other changes.

OTHER GOVERNING FACTORS FOR TEST PROTOCOLS:

Part Load Performance

Some gas turbine controls modernizations and upgrades such as the Outlet Temperature Corrected (OTC) control methodology improve plant performance on a percentage basis more at reduced loads than at base load. In addition, many hardware upgrades also benefit part load performance due to improved sealing, improved aerodynamics, and other factors. Therefore, to accurately determine the overall improvement, modifications resulting in part load benefits should consist of several test runs at different load levels (i.e. 60%, 70%, 80%, 90%, and 100% load) with the time weighted average change calculated in order to determine the true benefit of the part load performance improvements.

If economic dispatching is such that there are significant times of the year in which part load operation is typical, then determination of the part load performance improvements provided by modernizations and upgrades such as OTC is critical.

Heat Balance Computer Model for Bottoming Cycle Test Results

In the GT Test Plus Heat Balance test protocol outlined above, the change in gas turbine performance is tested, and the change in the steam cycle performance is determined by heat balance computer model utilizing the delta gas turbine exhaust flow test data, and any steam cycle set point or other changes as inputs. The heat balance model must be agreed to by all parties to an acceptance test, of course.
Steam cycle output change is almost directly linear with exhaust flow change, and is a major affect on the bottoming cycle. The magnitude of the effect of steam cycle changes, although less obvious, can also be easily demonstrated for validation of the heat balance model.

The changes in steam cycle performance may therefore be calculated by using a base reference model of the same configuration as the existing steam cycle, and comparing the results from the pre and post outage corrected gas turbine exhaust changes and the other changes input into the model. The absolute results need not perfectly match actual steam cycle outputs in order to accurately determine the delta improvement from the modernizations and upgrades.

**Degradation**

Two additional factors that affect comparative testing are degradation and degradation recovery (see Figure 1). The amount of degradation a gas turbine has prior to pre-outage testing can vary from site to site for obvious reasons such as operating patterns, air quality, fuel quality, frequency of washes, etc. The amount of degradation recovery not related to the upgrade also varies from site to site and is directly related to the level of degradation the unit has prior to the outage. This variability can be partially mitigated by conducting an offline wash immediately prior to the pre-outage test as well as hand cleaning of the compressor inlet and first stage compressor components. However, there is no easy way to differentiate the remaining non-upgrade-related, or variable recovery, without multiple outages. Conversely, post-outage degradation can be mitigated almost completely by conducting testing as closely as possible to the outage or, if delays are unavoidable, by application of degradation curves similar to those used for new unit performance testing.

If the upgrade is strictly a software upgrade, then it may be possible to test the benefit immediately before and after the software upgrade, thus eliminating degradation concerns.

**DISCUSSION OF TESTING APPROACHES:**

The uncertainty in determination of gas turbine exhaust flow, a major influence of gas turbine modifications on the steam cycle, is approximately 1.5%. If the gas turbine testing protocol combined with a bottoming cycle model is used in lieu of the overall plant testing approach, then the uncertainty of the result of a single overall plant performance test increases from approximately 0.8% to 0.95% (heat rate)\(^1\), and approximately 0.4% to 0.65% (power), if there is no bias uncertainty correlation between the two test phases. However, in a pre-post test scheme, these uncertainties will be reduced or possibly eliminated because the bias component of uncertainties are partially correlated between the two phases (the uncertainty of the change in gas turbine exhaust flow will be less than the uncertainty in gas turbine exhaust flow of a single measuring point due to the bias correlation). Further, unknown uncertainties due to non-upgrade or non-modification changes in steam cycle performance are eliminated with the “GT Test Plus Heat Balance” approach.

Further effort is needed to determine precise differences in test uncertainties of both methods. Nevertheless, good justification exists at this point in favor of the gas turbine test approach from a purely technical standpoint due to the reduced complexity and cost, elimination of the effects of changes not caused by the modernizations and upgrades of interest, and improved accuracy by taking advantage of correlated bias uncertainties.

Table 1 summarizes the two different approaches.

**TESTING DEFINITIONS:**

GT base load is defined as operating on the base load exhaust temperature or OTC set point with the inlet guide vanes (IGV) in the full open base load position. GT part load is defined as a percentage of the corrected base load gross power output (as corrected to the measured part load test conditions). A base Load test must be conducted first, then real time corrections can be made in order to determine the target MW level that corresponds to the part load test point.

**GENERAL TEST PROCEDURE FOR “GT TEST PLUS HEAT BALANCE” METHOD:**

For the purpose of calculating plant performance improvements (See Figure 2) due to gas turbine modernizations and upgrades, the overall heat rate improvement is calculated based on the difference in the corrected pre and post outage average heat input between the various plant power output levels and the estimated hours per year the plant operates within those ranges. The estimated hours to use at each load must be part of a contract agreement, and is needed to reflect the economic benefit of the upgrades and modernizations. The overall plant power output improvement is calculated as the difference between the corrected pre and post outage total plant output per section 1.4 below.

1. **Calculating the overall BTU improvement**

1.1 The changes in the corrected gas turbine exhaust conditions are used to calculate the change in the steam cycle output at the base reference conditions by the bottoming cycle model.

1.2 Pre outage GT tests are conducted at various GT load points (i.e. 60%, 70%, 80%, 90%, and 100% of pre-outage base load).

1.3 The GT test results for power, fuel flow, and exhaust conditions (composition, temperature, flow) for each load point are corrected to the base reference conditions. Exhaust

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\(^1\) Assuming existing flow orifice metering run to be used, with a replaced orifice plate.
gas mass flow rates are calculated by applying a mass-energy balance to the gas turbine control volume (see Figure 3). The values of typically unmeasured parameters that are required for heat balance calculations, such as cooling and recirculation flows, mechanical losses, and enclosure heat losses, can be assumed based on OEM gas turbine thermodynamic models. These values typically have a small impact on the calculation, and model predicted values for these parameters yield acceptable results.

1.4 Using the corrected GT results, the total plant output is calculated as the sum of the corrected gas turbine output and, for the purposes of calculation, the reference steam cycle output used to determine the changes per item 1.1.

1.5 A plot is then created of corrected heat input (Q = fuel flow x heating value) vs. corrected gross plant power for the GT load points (see Figure 4).

1.6 Using excel (or other software), the interpolated polynomial is generated that goes through each of the test points.

1.7 Once the modernizations and upgrades have been completed, post outage GT tests are conducted at the same GT load points.

1.8 Steps 1.3 thru 1.6 are then repeated for the post-outage tests.

1.9 The delta BTU savings per year (average and corrected) can then be calculated with the following equations:

\[
BTU\ (pre) = (Q1 + Q2)/2 \times T1-2 + (Q2 + Q3)/2 \times T2-3 + \ldots
\]

\[
BTU\ (post) = (Q1n + Q2n)/2 \times T1-2 + (Q2n + Q3n)/2 \times T2-3 + \ldots
\]

\[
\Delta\text{mmBTU} = [BTU\ (pre) - BTU\ (post)] / 1,000,000
\]

Where:
Q1, Q2, ..., equals the pre-outage heat input in Btu/hr at the mutually agreed to plant power (kW) levels PW1, PW2, ..., as calculated by the pre-outage polynomial equation.
Q1n, Q2n, ..., equals the post-outage heat input in Btu/hr at the mutually agreed to plant power levels PW1, PW2, ..., as calculated by the post-outage polynomial equation.
T1-2, T2-3, ..., corresponds to the mutually agreed to hours the plant operates between PW1 and PW2, PW2 and PW3, ... per year

2. Calculating the overall plant power output improvement

Using the corrected base load GT results, the total plant output for the pre-outage and post-outage tests is calculated as the sum of the corrected gas turbine’s outputs and, for the purposes of calculation, the steam cycle output as determined per item 1.1.

The base load delta plant power improvement is calculated using the following equation:

\[
\Delta\text{KW} = \text{KWBL}\ (post) - \text{KWBL}\ (pre)
\]

Where:
KWBL (pre) = the calculated pre-outage gross plant power @ corrected GT pre-outage base load conditions
KWBL (post) = the calculated post-outage gross plant power @ corrected GT post outage base load conditions

CONCLUSIONS AND RECOMMENDATIONS:

The “GT Test Plus Heat Balance” method is the recommended test protocol in order to determine the overall plant performance improvement of gas turbine hardware and software modernizations and upgrades and any bottoming cycle control system or other changes, due to the stated advantages.

As an alternative approach, direct back to back on/off testing of the steam turbine performance changes due to gas turbine controls or bottoming cycle control or set point changes can be conducted separately and combined with results from a “GT Test Plus Heat Balance” protocol for gas turbine modifications alone.

If full pre-post testing per PTC 46 is the preferred approach, then considerations need to taken into account to address the complexity and expense associated with such testing.

Further studies of the test uncertainty for each method should be conducted to better understand the cost vs. benefit. It is probable that the uncertainty of the PTC 46 method cannot be determined due to unknown or unquantifiable changes in the bottoming cycle that are not caused by the modernizations and upgrades of interest.

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REFERENCES

2. ASME PTC 22-2005 (Approved Draft, unpublished at the time of writing this paper), The American Society of Mechanical Engineers
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<th>Overall Plant Performance Tests, Pre and Post Outage, per ASME PTC 46</th>
<th>Gas Turbine Tests, Pre and Post Outage, with Steam Cycle Improvement Calculation Post Outage (“GT Test Plus Heat Balance” method)</th>
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| **Advantages** | Captures the results of all the modernizations and upgrades by test data  
Industry accepted test protocol, ASME PTC 46 | Eliminates uncertainties due to unknown steam cycle changes not caused by modernizations and upgrades, thus eliminated unknown bottoming cycle test errors that can be significant  
Eliminates manpower required to develop overall plant correction curves (but does not eliminate the need to develop a heat balance model, although one may already exist which might just need some fine tuning)  
Based on industry accepted test protocol ASME PTC 22, the latest issue which will include determination of exhaust flow. |
| **Disadvantages** | Controls or bottoming cycle changes outside the scope of the upgrade cannot be segregated from the results  
More extensive instrumentation required  
More complex and expensive | Benchmark steam cycle data is eliminated if it is not trended. This can be easily remedied. |

**TABLE 1 – TEST METHODS COMPARED**
FIGURE 1 – TYPICAL GAS TURBINE DEGRADATION TREND

FIGURE 2 – CALCULATING THE PLANT PERFORMANCE IMPROVEMENT

Values for: PW1, PW2, ..., T1-2, T2-3, ....

Delta BTU and Delta Power Improvement

Pre and Post Heat Input vs. Plant Power plotted (Q vs. MW)

Plant Steam Cycle Model

Corrected植物 Power & Heat Input Calculated

Corrected to Reference Conditions

Exhaust Flow Calculated by Heat Balance Around GT

GT Exhaust Conditions

GT Power & GT Fuel Flow

As Tested

Corrected to Reference Conditions

Performance Loss

Variable Degradation Recovery Due to Outage

On-line Water Wash

Off-Line Water Wash

Recoverable Degradation due to Off-Line Water Wash

Performance Improvement due to Upgrade

Operating Hours
FIGURE 3 – GT HEAT BALANCE BOUNDARY USED TO CALCULATE EXHAUST FLOW

Interpolated Polynomials used to Calculate Q1, Q1n, Q2, Q2n, …., Q3, Q3n at PW1, PW2, …., PW4, PW5.

Corrected Plant Performance at Tested GT Load Levels

Before Upgrade

After Upgrade

Plant Power Output Levels

Corrected Gross Plant Power (kW)

Corrected Gross Heat Input (Btu/h)

Interpolated Polynomials used to Calculate Q1, Q1n, Q2, Q2n, …., Q3, Q3n at PW1, PW2, …., PW4, PW5.

Corrected Plant Performance at Tested GT Load Levels

Before Upgrade

After Upgrade

Plant Power Output Levels

Corrected Gross Plant Power (kW)

Corrected Gross Heat Input (Btu/h)

FIGURE 4 - PLOT OF CORRECTED HEAT INPUT VS. CORRECTED GROSS POWER