COMMENTS

on

COLLECTING and ANALYZING
TURBINE GENERATOR TEST DATA

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Introduction

Prior to the introduction of versatile modeling tools for steam turbine-generator cycle performance, test data was primarily used to calculate "Corrected" performance. External data (including main steam temperature and pressure, reheat temperature and pressure drop, and circulating water temperature) representing input boundary conditions to the cycle, were used to adjust measured generation and derived heat rate (through correction curves) to yield corrected results. Though the method served a purpose, that of trending unit performance, it failed to reveal where component level improvements could be made, or what they might be worth. Also, error would gradually creep into incremental heat rate curves, in some cases skewing true economic dispatch.

During the early 70's, high oil prices moved regulators to demand higher efficiencies (lower heat rates). Many utilities reacted to the new regulatory imperative with extensive maintenance programs aimed at improved performance. This was probably the greatest impetus for adopting heat balance modeling as a technology for operating units. At the same time, new capacity had to be built to replace generation lost to maintenance outages, and the retirement of older, less efficient units. As interest rates rose, regulators turned to higher availability as a goal, foregoing new capacity, and a new imperative was born. Maintenance programs declined in favor of greater availability.

Today, many states have established goals for both system heat rate and availability as yardsticks for rate cases and allowable rate of return on investment. In turn, the need for accurately interpreting test data for planning maintenance/modification is greater. The objective of this paper is to present a method of modeling, data collection, and analysis for operating units.

The author's first efforts with applying heat balance modeling methods to operating unit data involved several large fossil units. The data analyzed had already been recorded, in many cases months or years before the analysis was performed. Thus, bad data could not be corrected, and missing data important to the model could not be collected. The first two sections of this paper deal with modeling activities before and during a test which insure the collection of accurate and adequate data.

The third and final section presents the application of as-tested equipment characterizations to the as-built model via linear-superposition to yield both incremental heat-rate and load penalties associated with equipment malfunction, and an accurate as-tested unit model. Accurate quantification of the impact of equipment malfunction on load and heat-rate are essential to a variety of maintenance and modification program planning. An accurate full and part-load as-tested model is essential to calculating actual heat rate versus load curves.

Modeling Method

The author's philosophy toward modeling a turbine generator cycle is to keep the model simple: Use serial representations for LP turbines and feedwater heater strings, unless the unit is cross-compound with assymetrical extractions; use single condenser components unless multipressure zones exist; use single pump representations. The purpose is to minimize the amount of data to be manipulated, while producing a more easily interpreted computer output. Mass and energy balances of turbine generator cycle components are basically very simple; but when the number of inputs and outputs double, analysis becomes very difficult, and we fail to see the forest for the trees.

It is good practice to start by attempting to match the turbine vendor's thermal kit heat balances at full and part load. It is important to remember that the major purpose of this exercise is to obtain an accurate representation of the turbine sections over the load range. Accuracy of within 2-3 hundreths of a percent of vendor calculations of generation and heat rate is desirable for modern units with extraction convergence criteria of a few tenths of a percent. For older units, using steam properties other than the 1967 ASME version, an acceptable error range may be twice the amount for generation and heat rate.

Though overall cycle parameters may agree closely, it is important to thoroughly review individual component flow rates and thermodynamic properties for agreement. The most common errors arise from inaccurate Valves Wide Open HP turbine data, steam seal system representations, condensate heat recovery component modeling, and generator loss calculations. Also, clarification should be obtained from the turbine vendor as to whether thermal kit extraction and expansion line thermodynamic data is representative of the locus of extraction point state variables, or some "mean of blade length" condition (Temperatures in the steam path are highest at the blade root and tip due to stagnation and seal bypass; pressure drops through the extraction opening).

For turbine-generators manufactured by the General Electric Company, the published procedures are, of course, recommended. For other manufacturers, the author prefers to derive curves of stage group efficiency versus flow since stage group pressure ratios tend to remain constant over moderate ranges of flow, and excursions from design section inlet temperatures are generally small. An exception to the stage group efficiency selection is the governing stage, where thermal kit governing stage shell data should be used to derive efficiencies at valve points. Pressures throughout the turbine should be calculated by the heat balance program through inputs of design flow, pressure, and enthalpy. The bowl flow coefficients thus derived will be important during test data collection and subsequent analysis.

Once agreement has been reached with thermal kit data for the turbine-generator, it is necessary to consider the as-built configuration and incorporate more detailed representations for full and part-load performance of the condenser, feedwater heaters, feed pump, feedpump turbine, and system pressure drops (primarily reheater and extraction lines). Again, the author's preference is for simplicity; very detailed component modeling can always be done with sub-models specific to the component. The following suggestions are offered:

1) Condensers - Use vendor-supplied bi-variant shell pressure versus heat load and circulating water temperature.

2) Closed Feedwater Heaters - Use TTD and DCA versus feedwater flow curves, as supplied by the vendor, or as derived from the heater geometry and materials specification by utilizing a detailed convection model.

3) Feedwater Pumps and Feedpump Turbines - Use efficiency and discharge pressure versus flow as specified by the vendor or derived from vendor information.

4) System Pressure Drops - Consider the as-built piping information with friction factors to derive percent pressure drop versus flow rate.

Some exceptions to these recommendations will be discussed under Pre-Test Model Calibration.

Another useful model to prepare is an interactive-graphics expansion line model (Figure 1), which is a real-time visual aid in validating turbine performance data. It is also useful in developing turbine stage group efficiency data over the load range.

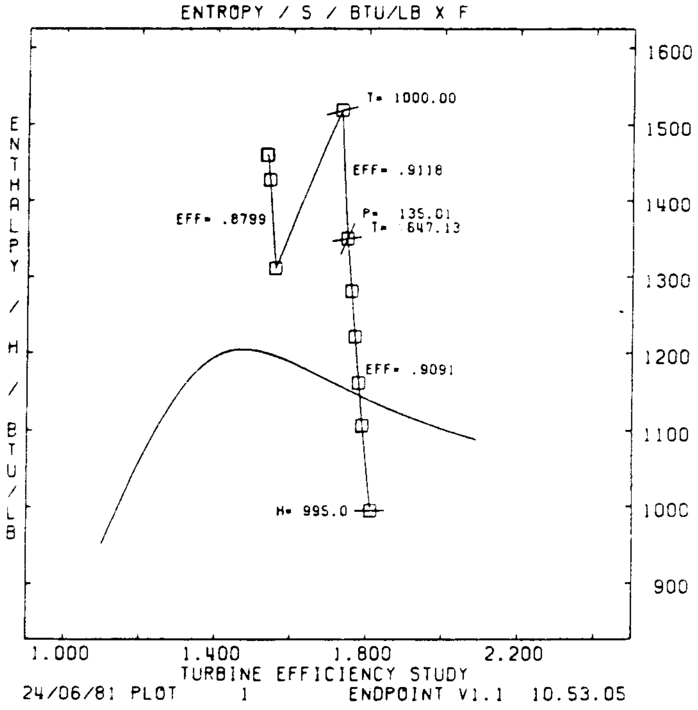

Figure 1: Developing turbine design information

A turbine-generator model assembled in this manner should be capable of accurately predicting as-built cycle state variables and overall performance at any load and for any set of External

Data imposed on the model. The objective to be achieved is that of predicting the test results prior to actually collecting the data.

Data Collection

Pre-test analysis in calibrating a model of a unit is very useful as a means of eliminating instrumentation error, and as a guide in test planning. A first step often employed is to examine a few hours of sample data taken from the control room. External data, as defined in the introduction, is input to the model and the heat balance output is examined for agreement with load and temperatures and pressures throughout the cycle. Significant differences should be checked with calibrated gauges and unresolved discrepancies should be considered as a part of the test planning function. Control room readouts should be adjusted accordingly.

If it can be established during this process that equipment is not performing according to design specification, than characteristic curves or efficiency corrections should be shifted/applied to reflect anticipated performance. Again, the objectives of the model are to validate test data in real time, and to possibly eliminate the need for redundant or extra instrumentation where equipment performance is well known. This step may be repeated when test instrumentation has been installed, but prior to the actual test.

Another very useful aid to accurate data collection is a computer-based data reduction program. The program should be capable of bulk data reduction, and also of accepting single raw data inputs and translating them. Thus, it is possible to "eye ball average" a sheet of data and produce a single heat balance model parameter such as a temperature or pressure.

The most crucial quantity to be derived from the test data is feedwater (and thus throttle) flow rate. The author often thinks of this quantity as "negotiable" in that a number of other measurements and calculated variables can be used to "adjust" main steam flow within the established error range (usually ± 2%) to arrive at the most reasonable value to be used in analysis. This quantity is particularly crucial to nuclear units where flow rate impacts the operating envelope limit on reactor thermal output.

Data useful to validating or adjusting the main steam flow rate are:

1. First Stage Pressure
2. Bowl flow coefficients for all turbine stages*
3. Condenser condensate flow
4. Measured Generation

* W/((P/V)**0.5) at the entrance of a stage group.

First Stage Pressure curves versus main steam flow are often available from the unit thermal kit. This curve should be adjusted for actual Main Steam Temperature and Pressure to achieve the greatest accuracy. This parameter should not be considered as a strong indicator in that manufacturing variations from design drawings of as much as ± 5% or more in flow area at the first stage are common. Also, operating service environment can result in deposits, errosion, or damage further devalidating the First Stage Pressure measurement as an indicator of flow rate. Actually, once flow rate accuracy has been resolved, measured first stage pressure variations from design values can often signal damage to the stage.

Interpretation of first stage pressure is aided greatly by any historical data that is available, particularly that taken during initial performance testing or after turbine overhaul.

It is revealing to compare stage group bowl flow coefficients derived from test data with those derived from the thermal kit data. The turbine may be thought of as a series of orifices, or flow meters, and the stage group flow coefficient represents the orifice flow area. The author's method of presentation is to take the ratio of as-tested flow coefficient to as-designed flow coefficient, and to plot bar charts as shown in figure 2.

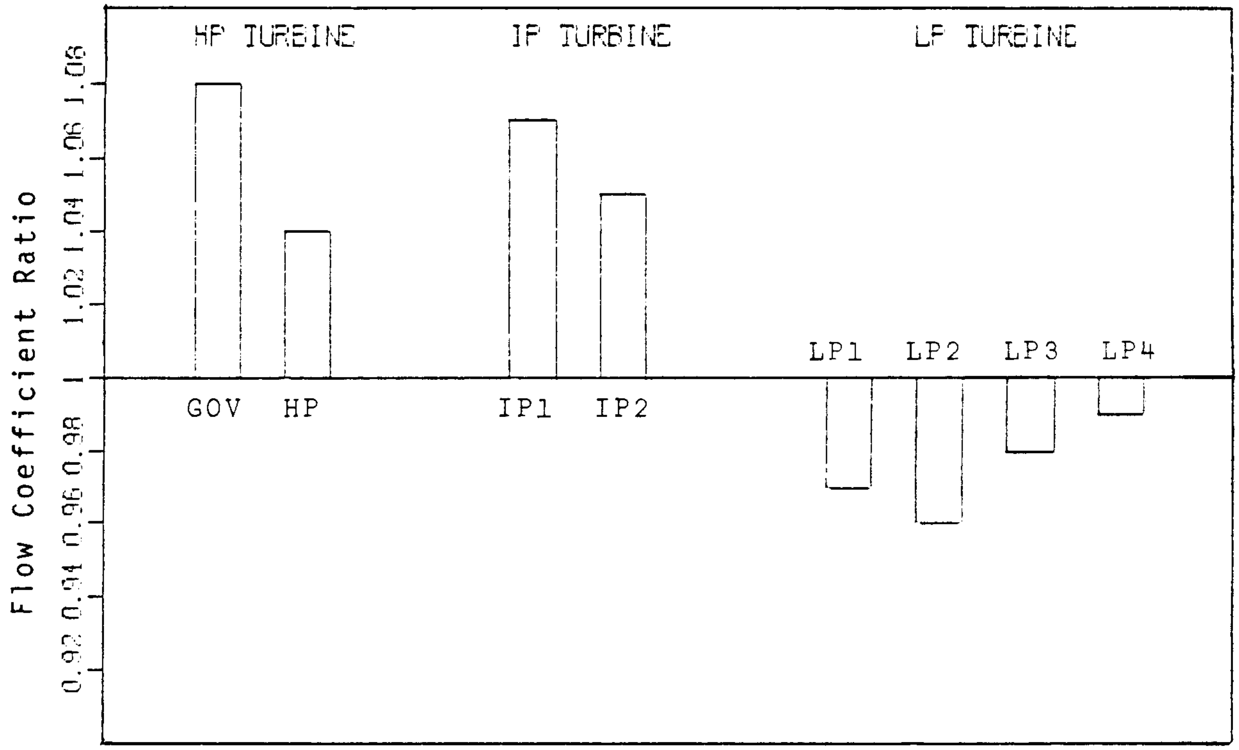

Figure 2: Actual/Design flow coefficient ratios

Consistantly high ratios can be interpreted as too high a value of main steam flow (resulting in high values of stage flow coefficients), and conversly. Abrupt changes between sections, such as that shown in figure 2, should lead the engineer to look for abnormal flow extraction.

Measured condenser condensate flow is an excellent indicator of the accuracy of main steam flow. If the extraction calculations are thought to be accurate and the system is isolated (of make-up flow and blowdown), then agreement between main steam flow and condensate flow should be sought.

Measured generation combined with the expansion line swing method for the moist low pressure turbine stages is another check on main steam flow. An interactive graphics expansion line model (such as that discussed in the modeling section) is useful in this comparison. The result of "swinging" the moist stages expansion line to match measured generation should be a smooth and continuous LP Turbine expansion line which is realistic when compared to the design expansion line under the same entrance conditions.

Post Test Analysis

Averaged values for the external data should be input to the as-built model, and the resulting thermodynamic properties compared with the other test data. Differences must be noted and resolved in terms of component operating characteristics. Correction factors and equipment operating curve shifts must be derived in order to adjust the as-built model to an as-tested condition. Note that the resulting as-tested model is a predictive one, capable of simulating actual unit performance.

To arrive at the final (as-tested) model, and to quantify the impact of any equipment deviations from design values, single heat balance runs should be made, starting from the as-built model with as-tested external data as a benchmark. Modified equipment characteristics/efficiency corrections should be applied singly for each run in a cummulative fashion. Thus, the second run includes two corrections. In this manner, the final run will replicate the as-tested condition, and incremental changes in heat rate and load from run to run are recorded as penalties (improvements) associated with modified equipment performance.

Finally, the as-tested model can be used for a variety of operating studies, including heat rate curves, equipment out of service conditions, and unit modification.