Combined Cycle Modeling for Fuel Flow Predictions

Leif Svensen, P.E.
Santee Cooper

Bill Toombs
Santee Cooper

Gene Minner
Scientech, Inc.

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Introduction

Santee Cooper is a state owned utility in South Carolina with a current generating capacity totaling 3,543 MW net. This paper is on a new unit under construction in Anderson County known as Rainey Station. This generating station will have an output of 800 MW net burning entirely natural gas for fuel. Rainey Station consists of two simple cycle gas turbines generating 300 MW net and one combined cycle unit generating 500 MW net.

This station will have some unique fuel purchasing needs. Each day the station personnel will receive a predicted dispatch sheet of hourly generation requirements. From this dispatch sheet, they will determine the amount of fuel purchased for the next day. The station is sent the dispatch data at 10:00 am each day. Station personnel will then have one hour to decide on the amount of this fuel purchase. This fuel purchase has to be accurate enough so the station completes the burn of fuel at the end of the 24th hour. In addition, Rainey station personnel will need a program that tracks fuel consumption. The need for this is to insure the fuel is burned at the rate predicted and to reschedule the output if required. This program will track fuel burned and predict loads the unit will output to complete the total burn of fuel by the end of the 24th hour. The penalities are if you run out of fuel the price is off the spot market and if you over buy you pay for fuel you did not use. The personnel at Rainey station will also need to predict fuel requirements on a weekly and monthly basis. Above all, the process has to be simple and robust to avoid the plant personnel having to debug problems.

It was determined that the Rainey station PEPSE models would be a good way to predict performance. We had a model of the station already to use so it was modified to meet the needs of this program. Next is an explanation of the modeling process.

Modeling

Rainey Station was modeled in PEPSE two years ago to match the full load output heat balance. Last year the model was used to predict the effects of output due to changing ambient air temperature. This analysis was to consider if inlet air refrigeration was beneficial and cost effective to summertime generation requirements. To meet the needs of this current project the model will now need to have capability over the load range and temperature range.

In reviewing the combine cycle gas turbine (CCGT) at Rainey Station it was decided that schedules would be required for the gas turbines (GTs). To simplify the development of the schedules it was decided to model a simple cycle gas turbine (GT) in PEPSE. This single GT is a two-component model because of this simplicity the model runs fast with low iteration counts. We used this single GT to develop the schedules to meet the design specifications of the GT over the load range. This also leaves us a model for fuel flow predictions for the other simple cycle GTs onsite. For the schedules, we used the GT global correction variables. These variable names are GTPOGW for output power, GTTETG for exit gas temperature, GTFLOG for exit gas flow, GTHRG for heat rate. To obtain these factors we ran the model with the base vendor turbine for our system and used the built-in PEPSE GT curves to obtained the results. These results were compared with the results manually calculated from the vendor curves. Using a ratio of the difference at each inlet air temperature, global correction factors were developed. This develops a complicated x,y,z schedule. The schedule inputs are ambient air temperature (GTTTA) and combustion turbine load ratio (GTLOAD) and outputs the appropriate global multiplier. Actual variables could also be used in the schedules, but we decided on using the global corrections at the time because we were not sure if these variables are available for scheduling.

After the schedules were checked out in the simple cycle GT they were manually added to the CCGT model. Currently we do not know of any procedure that allows the copying of schedules from one model to the next. These were then tested again and initially the results did not match the simple GT. The reason for this will be detailed later under the section on problems and opportunities.

The initial fuel flow prediction goal was to have PEPSE run from an Excel spreadsheet and resupply the spreadsheet with the fuel flows predicted. This was going to be completed by using controls to obtain the required generation. Plant output and local predicted temperature are input from the spreadsheet and fuel flow was output to the Excel spreadsheet. We created a control card controlling GTLOAD to obtain GKGROS. Using this control was a hurdle since at outputs less than 67 percent the initial condensate estimate needed to be modified. Without modifying the condensate flow the Rainey Station model does not converge. Because of run time constraints and error free operation requirements this mode for using the model was discontinued.

At this point, we decided that using controls would not cover the restrictions we applied to the fuel flow prediction program. As we stated earlier, station personnel run the PEPSE model from an Excel spreadsheet and then have the model fill in the data grid. We starting having problems with model stability when using the controls. Along with the stability problem, we had thoughts on the amount of time the model would take to run. At minimum, this model would have to complete 24 stacked cases with 100 to 200 plus iterations per case. Since this approach would not lend itself to "what if" analysis, a "grid" solution was developed. The grid solution increased the possible number of cases to about 200 and this was too many for a quick run time. At this point run time became more of an issue. With a run time of about one-hour this leaves no time left for purchasing fuel.

Another solution was to have a table of the "grid" solution already in place in an Excel spreadsheet that accounts for all the possible load and temperature variations. To do this we actually ran a series of models with each model having a different fixed temperature and varied the GTLOAD parameter from 40 percent to 100 percent. Each of the models were run from an Excel spreadsheet using VBA code with the results were extracted to a table in the spreadsheet. At this point, we were specifying temperature and percent GT output (using the GTLOAD variable) while obtaining heat rate and total output. Fuel flow is a required result but it can be calculated from the heat rate result. Since we wanted to be able to specify temperature and total hourly output to obtain fuel flow we created this relationship from the data obtained from the PEPSE results. This creates a three dimensional table of information for the spreadsheet to use.

This spreadsheet is used in the following way, plant personnel input the required loads and temperatures for the next day in two columns. The spreadsheet then checks if the load is possible at that temperature, if the required ouput is possible then the estimated fuel flow for that hour is placed in a third column. If the load is not possible for that temperature then the spreadsheet uses the maximum load the unit is capable of for the predicted temperature and calculates that fuel flow.

We have now created a program in which PEPSE predicts unit fuel flow. A few enhancements are needed to complete this program. The enhancements will need to estimate the units degradation due to run time and the improvements that happen from water washing. These changes occur as normally during unit operation. In addition, a tracking program is under development to take the current real time fuel consumption and predict the remaining unit generation outputs that will achieve total fuel burnout at the end of the 24th hour.

Modeling is not all straight forward as indicated above. Below we will discuss the troubles, opportunities and things to avoid in the modeling process. Although these occurrences are not that abnormal we seemed to have a few more than expected.

Troubles, Opportunities and Things to Avoid

In modeling, a few problems occurred along the way. We will summarize them here. Complete details can be found in Appendix A. This appendix includes E-mail correspondence on all these circumstances.

Problem/Opportunity #1 (sensitivity studies)

This cropped up when using the sensitivity feature in PEPSE. When using this feature the result of gross plant output (BKGROS) is incorrect. A logic error was calculating the gross output by multiplying it by the case number. This has been corrected for the new GT5 PEPSE version. This problem only affected the system calculated results. All of the individual results for each generator were correct. This problem also occurs in save case modeling.

Problem/Opportunity #2 (non-required information)

We built a simple cycle GT to develop the schedules. When building this GT for full load we used the global corrections on the optional Correction Factor sheet in the GT component. There are two radio buttons: one for the use of standard GT curves and one for aeroderivitive GT curves. We used the aero curves GT model for creating the basis of the correction factors. When we modified the GTs in the combine cycle (CCGT) model this tab was overlooked and the aero button not invoked. Since we were scheduling these now throughout the load range global corrections were not required to be inserted on this page. Therefore, when we ran the CCGT the GT outputs did not match. The problem was found with some detective work.

Avoid this problem by insuring that non-optional tabs are reviewed for each component for correctness. Especially after picking up a job again after a long, break.

Problem/Opportunity #3 (energy imbalances)

The initial thrust of modeling was to ensure the heat recovery steam generator (HRSG) was getting the required gas flows and temperatures. So at this time in the modeling process, only these and generation were setup as schedules. There is a table in the output that indicates what the energy imbalances are. It is important to review this table because negative imbalances indicate that less energy is going into the GT than exhausting it. After this was pointed out to us a set of schedules were created for GT heat rates.

Remember to carefully review the output tables, some that can be very important do not stand out as such.

Problem/Opportunity #4 (evaporators)

At this point, we were getting a working model that converged and was giving results. However, we would also get results with warnings. Below is the warning that was occurring quite frequently.

```
*** WARNING FROM HXCONV ROUTINE ***
    FOR CONVECTIVE STAGE COMPONENT WITH ID = 165,
    IN THE APPLICATION AS A HRSG ELEMENT, THE CALCU-
    LATION TO PREDICT HEAT TRANSFER BASED ON UA HAS
    NOT CONVERGED ON A VALUE OF LMTD IN 20 ATTEMPTS
    (WITHIN SPECIFIED TOLERANCE, TERROR, WORD 4-R,
    CARD 012000). CHECK INPUT.
    CALCULATIONS ARE CONTINUING USING THE RESULTS FROM
    THE LAST ATTEMPT.
 *** END OF WARNING ***
```

```
*** WARNING FROM HXCONV ROUTINE ***
   FOR CONVECTIVE STAGE COMPONENT WITH ID = 166,
   IN THE APPLICATION AS A HRSG ELEMENT, THE CALCU-
   LATION TO PREDICT HEAT TRANSFER BASED ON UA HAS
   NOT CONVERGED ON A VALUE OF LMTD IN 20 ATTEMPTS
   (WITHIN SPECIFIED TOLERANCE, TERROR, WORD 4-R,
   CARD 012000). CHECK INPUT.
   CALCULATIONS ARE CONTINUING USING THE RESULTS FROM
   THE LAST ATTEMPT.
*** END OF WARNING ***
```

The reason for this as quoted from Appendix A is "When the msg is printed this way, it is done at the final overall PEPSE iteration". Inside of the T28 component there is an iteration process, with a limit of 20 times, to calculate the heat transfer. So, I conclude that the internal heat transfer calculation is not converged at the end of the run. A check can be made on how bad it is by a hand calculation using the definition of LMTD, together with the UA that PEPSE prints out to compare with the heat transfer that PEPSE prints. You may find that the answer is good enough, and if so, you could make the warning go away by loosening TERROR SLIGHTLY.

The pertinent equations are:

$Q = U * A * \text{LMTD}$

$\text{LMTD} = (\text{Delta T1} - \text{Delta T2}) / \text{Ln}(\text{Delta T1} / \text{Delta T2})$

where for counter flow:

$\text{Delta T1} = \text{Thi} - \text{Tco}$
$\text{Delta T2} = \text{Tho} - \text{Tci}$

And for parallel flow:

$\text{Delta T1} = \text{Thi} - \text{Tci}$
$\text{Delta T2} = \text{Tho} - \text{Tco}$

In these formulas, h means hot, c means cold, I means in, and o means out."

After reviewing the above information, we used these calculations to check the output results. It was found that a great many of them had internal imbalances less than 1.6 percent. We then increased the convergence variable TERROR from the default of .000005 to .00000508. This change removed many warnings but a lot still remained. These remaining internal component imbalances were greater than 3 to 50 percent. It was found in the PEPSE software that when the initial values were far from expected the software went into a "repair" mode. For the most part this auto fix worked okay but in some cases it did not. A better way for this auto fix was developed and will be in the new PEPSE version GT5.

Problem/Opportunity #5 (low operating temperature)

Most CCGTs and simple cycle GTs will run at or below 32 °F even in the warm sunny South Carolina winters. When modeling at these temperatures one must put in "dry air" and to do so one must insert a humidity of Zero. In PEPSE in the default value for this card is 60 percent relative humidity because of this when a zero is input the program thinks it is the default value and uses the 60 percent relative humidity. This really makes for some unsettling outputs. The "work around" for this is to put in an infinitesimal amount of humidity like 1.0E-06.

If having a problem with PEPSE inputting a number that is incorrect it is important to check the default values and how they are triggered. A "work around" is possible in most cases.

Problem/Opportunity #6 (controls)

Two items are to note here. The first one is that when running the controls a Lahey FORTRAN error was occurring. The error that was occurring is rare and intermittent. The plus side is that the Lahey failure has nothing to due with the program calculations, but it still stopped running the case and sent the model to a failure result. The reason for having no impact on the calculations is that the programming, which causes this problem, was developed to improve the look of the output printout.

The second item is that at station outputs that are less than 300 MWg the controls do not converge, even after 600 iterations. The initial condition of the input component creates this problem. In this case, the input in question is the condensate flow. If condensate flow is far from the answer PEPSE has problems trying to converge. The repair is to use an initial guess that is closer to the expected result. When changing these initial flow conditions we had some inconsistencies in the results and decided to abort using the controls to create the prediction. The inconsistencies were in the ability to have a single flow for each GT load range that would work 100 percent of the time without having to modify this prediction by the user. This is one of the reasons why the method of creating the fuel use report was modified.