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Cogeneration process modelling in a paper factory

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Abstract

The aim of the study is to model and to simulate the thermal and electrical efficiencies of the cogeneration plant of a paper mill. The final purpose is the benefits optimization by adjusting production to the amount of energy to be sold. It is necessary to know it because the sale price goes down when the actual production of electrical energy does not match the scheduled power.

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Keywords: Modeling; cogeneration; paper industry; optimization; gas turbine.

1. Introduction

The papermaking process under study in this article employs recycled paper as main raw material. The plant has an annual output of 400,000 tons of paper per year. Paper production requires steam in its final stages and this is provided by the power plant. Simultaneously, generation plant produces electricity using the generated steam. Part is used and the surplus is sold to the electric company. Both electricity and steam are obtained from a cogeneration plant that uses natural gas as fuel.

A mathematical model of the power plant was performed, obtaining functions that allow the calculation of its power and performance, with emphasis on its relationship with the manufacturing process, and without going into detail of the production of electricity. The nominal parameters, given by the turbines manufacturers, have been adapted to the actual operating conditions. The generated electrical power can be estimated in a precise way, not

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only the production that will be getting, and possible problems of the power plant can be diagnosed to avoid a lack of power or efficiency, ANSI/ASME (1974).

The methodology to accomplish this work was the definition of several production scenarios and the identification of the most critical variables of the cogeneration system. So, it was possible to reach a totally accurate method of power generation estimation.

To develop a cogeneration process model, which was checked and validated, work was done with diagrams of different operating points of the constituent elements of the power plant. The work analyzes the environmental variables, fuel, and variations in nominal machine parameters and also studies the sensitivity to them. The nominal parameters, given by the turbines manufacturers, have been adapted to the actual operating conditions. This allows estimating the energy production and diagnosing any problems that there may be in the power plant.

Mechanical and energetic performances were analyzed considering, not only the parameters that has influence, but also measurement errors that introduce uncertainty in the actual plant status. In order to materialize the proposed modeling, an Excel-based software tool was developed by programming macros coded in Visual Basic by Serrano (2013). Later, the model was adjusted using the measured data of the power plant. Finally, the adjusted model predicts accurately the turbine performance.

2. Power plant

The power plant main elements are:

- The steam turbine
- The heat recovery boiler
- The steam turbine electrical generator
- The gas turbine and its electrical generator

The developed tool focused on the behaviour of the main components, which are the steam turbine and gas turbine. There were two main issues in the power plan for which it was necessary to approach the modelling: the first is the proper daily planning of electric power to be generated with the machine. The final purpose is the benefits optimization by adjusting production by the amount of energy to be sold. The company sells the not consumed electric energy and must give advance notice, on a daily basis, of the amount of electricity sent to the network. It is necessary to know it because the sale price goes down when the actual production of electrical energy does not match the scheduled power.

2.1. Steam turbine

The steam turbine is a Siemens ST3 and has a nominal capacity of 9.5 MW. To model the turbine, the real working conditions were taken into account. That means the inlet conditions remain constants. So, the inlet pressure and temperature were fixed and parametric curves were built depending on backpressure. This variation of the backpressure is associated with the steam leaving the steam turbine. The steam is required at different temperatures depending on the need of the paper production line and the way to change this temperature and thereby the steam flow is to change the backpressure.

The manufacturer provided several correction curves for the turbine operation according to the working conditions. These curves were parameterized obtaining, for various working conditions, two groups of graphics of power, some depending on the outlet temperature of the turbine, and other as a function of the variation of vapor pressure at the output, ANSI/ASME (1996).

2.2. Gas turbine

The gas turbine is a General Electric PG6581 model that uses natural gas as fuel and has a nominal electrical power of 37 MW, with a combustion system of low NOx emissions. The air and natural gas enter into the gas turbine where combustion takes place. This combustion generates electricity and hot gases that are sent to the heat recovery boiler. The manufacturer of gas turbine undertook an operational check at the time of installation. The results of those tests, as well as turbine graphs in standard operation, have been used in the modeling. These plots were adjusted to obtain individual relations functions in each of the states for the gas turbine. Outflow functions were obtained depending on four variables:

- Inlet temperature
- Inlet pressure to the turbine
- Pressure drop
- Relative humidity

Likewise, eight functions were generated linking Power and Heat Rate based on:

- Compressor inlet temperature
- Atmospheric pressure
- Relative humidity
- Performance loss function of aging (based on the thermal efficiency curve)
- Output pressure
- Fuel composition
- Temperature of fuel.

The outlet temperature was adjusted by two equations as a function of compressor inlet temperature and relative humidity. So we can estimate the true and correct outlet temperature if there are deviations causes.

3. Calculation method

It has been determined which process variables was necessary to study for each element modeled to include its influence on the variable treated. Those are presented in this section.

3.1. Steam turbine

The parameters considered in the steam turbine are temperature and pressure of the high pressure region and the pressure and temperature of the low pressure zone. It have been used the relationships between the data in multiple situations to be introduced in the model and in particular, it has been take into account the adjustment for pressure and temperature in the high pressure zone and the deviation that have these parameters with respect to the nominal parameters. It was also considered the backpressure at which the turbine is operating. They have been parameterized graphs to evaluate how this backpressure affects the outcome of the process. With the obtained functions it is possible to find the theoretical power, according to manufacturer specifications, for a set backpressure. The above relations are also dependent on the operation flow, so the calculations were made according to the flow also.

The model also includes the heat losses in the cooling circuit reducing the power generated by the turbine at the time of converting on available electrical power. Given some working conditions, an iterative process of adjusting the values of the functions was performed on the model to calculate the enthalpy and flow. After multiple tests to the model it was found that, in the most complicated cases the values remain adjusted after 4 iterations. Fig. 1, shows the excel program front page for the modelling application to steam turbine.

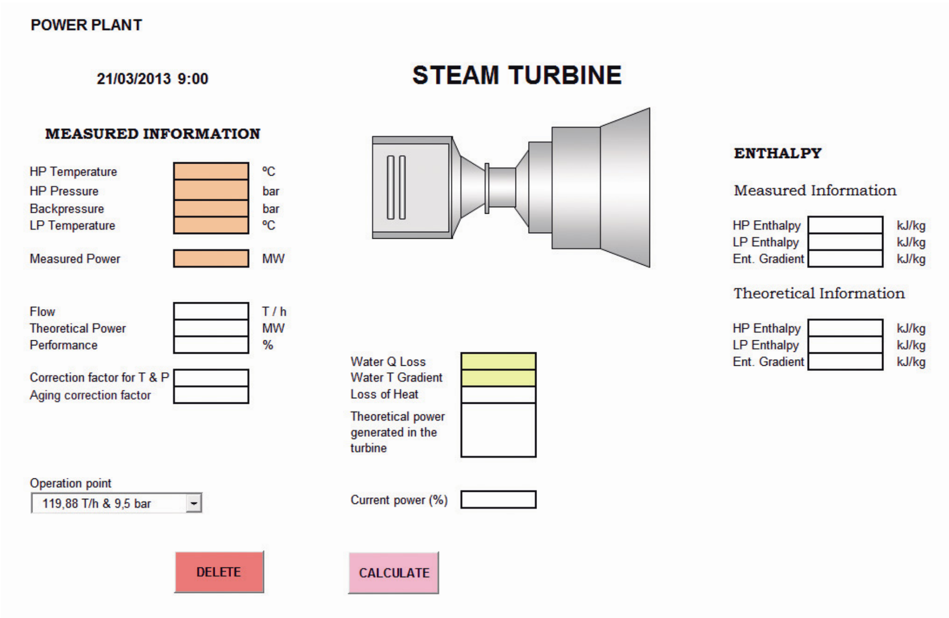

Fig. 1. Modelling application to steam turbine.

3.2. Gas turbine

To obtain a model of the gas turbine power, a similar work than for the steam turbine has been made. From the manufacturer curves, specific charts adapted to the actual control procedures have been built.

Considering the gas turbine probably the most important component of the power plant, the general equation of the power estimation (as well as the used correction factors F_i) shown below:

$$CNP = \frac{NP}{\prod_{i=1}^{9} F_i}$$

Being:

- NP: The nominal power given by the manufacturer's tables predefined conditions
- CNP: The corrected nominal power, which is the nominal power that the manufacturer says it should be obtained after modifying the conditions previously established by the actual operating
- F_1: Factor for compressor inlet temperature
- F_2: Factor for the relative humidity of air entering the compressor, also depending on the inlet temperature
- F_3: Factor for the compressor inlet pressure, also depending on the inlet temperature
- F_4: Factor for varying speed, related to the network frequency
- F_5: Factor for loss of power factor in the electric generator
- F_6: Factor for operating hours accumulated
- F_7: Factor for the pressure of the exhaust gases
- F_8: Factor for fuel composition
- F_9: Factor for fuel supply temperature

Fig. 2, shows the excel program front page for the modelling application to gas turbine.

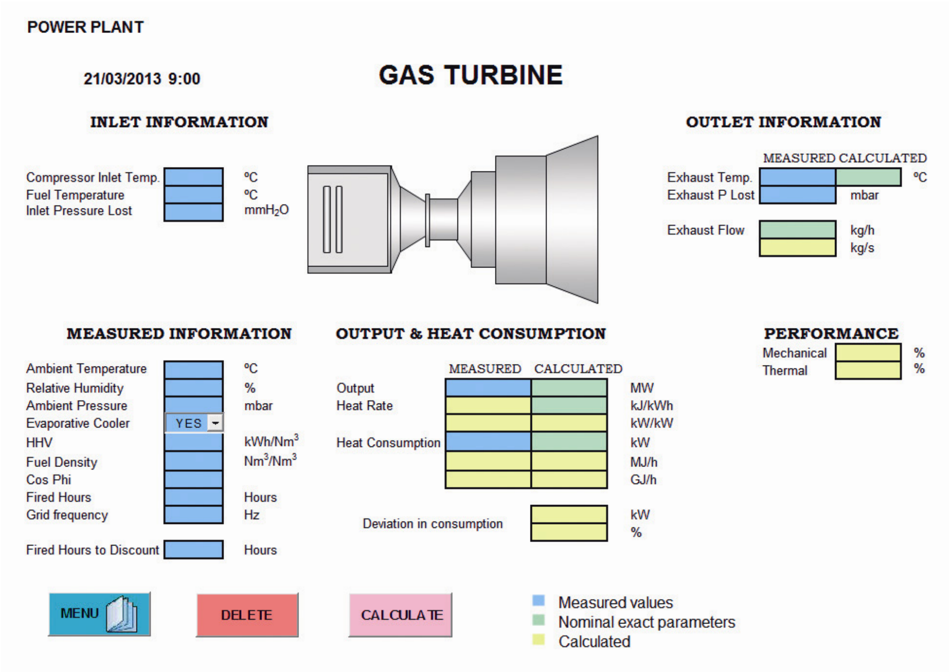

Fig. 2. Modelling application to gas turbine.

Analogously calculations have been made for the heat rate, output temperature and exhaust flow, as well as for the steam turbine, taking into account in each case the factors that might influence him. Similarly that for the power there are two options for correcting the heat rate: To find the value of the real heat rate, either adjusting the parameters to nominal conditions or under defined conditions to check the heat rate can be obtained by modifying the value of the parameters. The second option is the one that best fits to our problem, for the same reason as in the case of the power.

3.3. Variations along operation

The generated model will also allows testing power variation associated with behavioral changes of the different elements. This allows forecasts of change in the values of the power associated with degenerative behavior of the elements of the facility to detect the malfunction of any of them and anticipate their maintenance.

4. Experimental Verification of Results

For one month, the model was tested to make a comprehensive verification of its operation. Initially, they were differences between forecasts and outcomes in the factory. This problem was solved adjusting some parameters. The first observation is that there was a difference in power output. Checked the values of the operating conditions, it was found that the manufacturer's performance curves were adjusted considering a pressure loss in the exhaust of 190 mmH_2O, while the nominal value in the circuit is 204 mmH_2O. This applies in the same way the heat rate. There were also differences in consumption associated with its dependence on the power and heat rate because they were not properly adjusted.

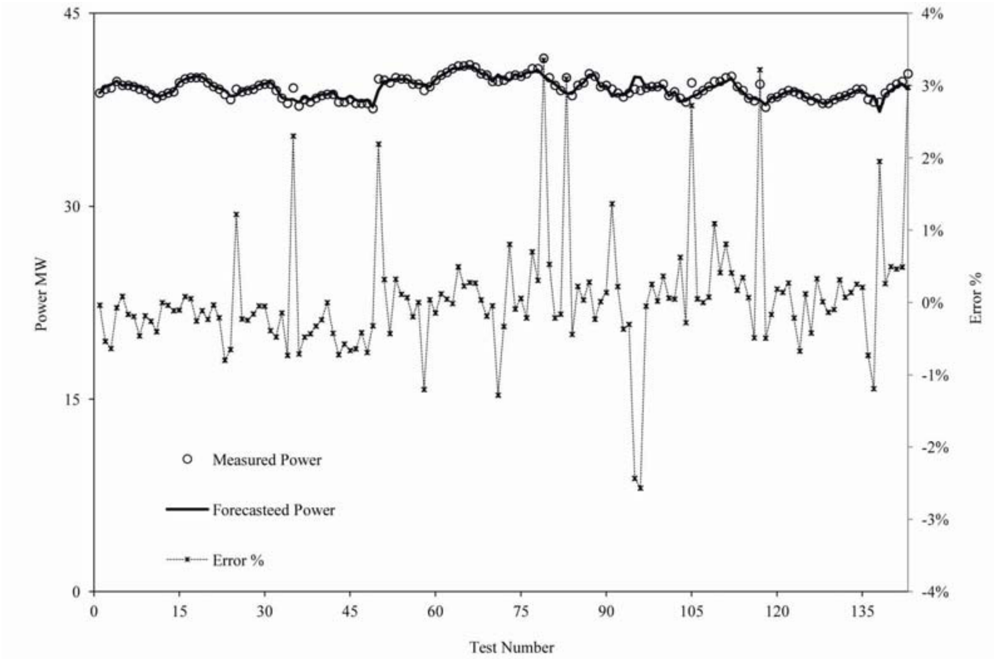

Fig 3. Forecasted and measured electric power and its error.

The early phase of testing also showed superior mechanical performance of 100%. Turbine operation was revised, and the problem was consistent with the behavior during startup tests of the manufacturer. In them, the turbine operated with up to 2% extra performance and, therefore, the values were normalized to that obtained in that test and no respect to the nominal one.

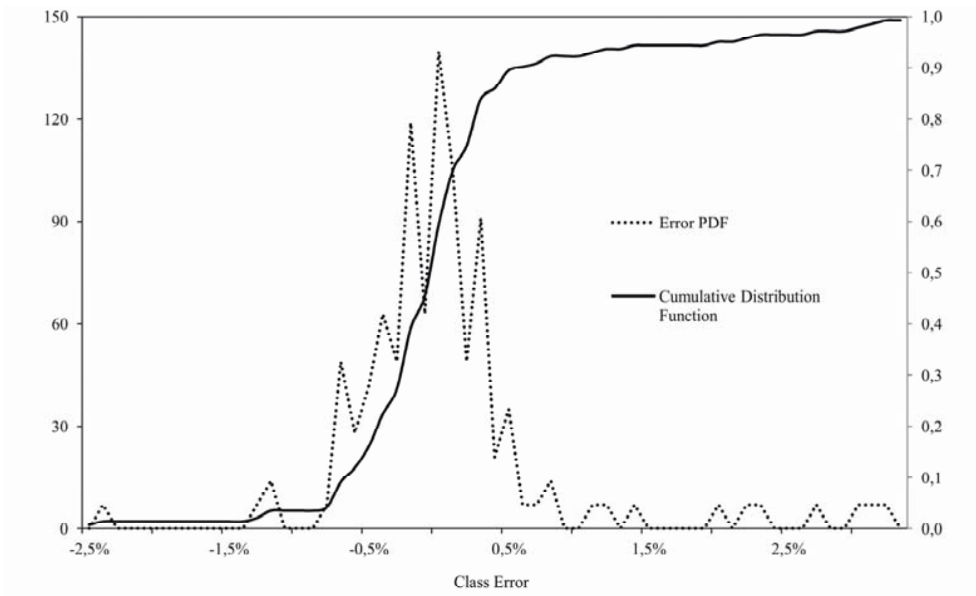

Fig. 4. Error PDF.

The model also had to take into account that the curves of efficiency loss given by the manufacturer, for power and thermal efficiency, are overrated because are intended for environmental conditions worse than those of this plant. So, their values should be adjusted downwards. Finally, it should be noted that the manufacturer states that the first 1500 hours the turbine operates without apparent aging.

After the corrections made to the model, there were further testing and model behavior was very well adjusted to the factory measurements. Fig. 3 shows the power delivered by the turbine for 143 cases measured with different operating conditions, the power predicted by the model and the error in the forecast as a percentage of the measured value.

The Probability Density Function of the modeling error and its distribution function are displayed in Fig. 4, which shows that the error in the calculation of power for nearly all cases is under the 1%, there are only a few isolated cases in which this error is bigger. In any case, the highest error is 3.35%. After some inquiries, authors found that the largest discrepancy points happens while factory operator do an on line-washing of the compressor, this changes the operating conditions above the nominal power which have been modeled. The cold entering water directly to the compressor blades causes it to improve its performance, producing a larger air intake.

5. Conclusions

The purpose of this work is to model and simulate a cogeneration Energy Central in a paper industry to enable the integration of a tool that, in an efficient way, estimates the amount of energy that will be generated as dictated by operating conditions of papermaking. For this, the process of cogeneration plant was analyzed and the information that defines the behavior of the elements of the plant was obtained. The relationships between variables and processes and relationships between plant equipment were implemented in a program based on Excel macros coded in Visual Basic.

After several tests, the model was adjusted to obtain a reliable tool to estimate the thermal and electrical energy generated. This allows obtaining optimal economic performance in paper plant under any conditions.

Currently this code is in use in a power plant of a paper mill as an on-line tool for use during the operation of the plant, allowing operation managers making decisions on the production of paper and setting the energy forecast to sell.

Additionally, the tool allows identifying behaviors outside nominal parameters of plant elements to detect necessary maintenance. The modeling performed can be opened to other processes, and has been implemented for the production of demineralized water at the factory.

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