Simulation of Automatic Control of the Experimental Power Plant

PAVEL NEVRIVA
Department of Cybernetics and Biomedical Engineering
VSB – Technical University of Ostrava
17. listopadu 15, 70833 Ostrava
CZECH REPUBLIC
pavel.nevriva@vsb.cz    http://www.fei.vsb.cz

LADISLAV VILIMEC
Department of Energy Engineering
VSB – Technical University of Ostrava
17. listopadu 15, 70833 Ostrava
CZECH REPUBLIC
ladislav.vilimec@vsb.cz  http://www.fs.vsb.cz

MARTIN PIES
Department of Cybernetics and Biomedical Engineering
VSB – Technical University of Ostrava
17. listopadu 15, 70833 Ostrava
CZECH REPUBLIC
martin.pies@vsb.cz    http://www.fei.vsb.cz

Abstract: - The paper deals with the simulation of automatic control circuits of the experimental power plant. The experimental power plant is developed by Vitkovice Power Engineering joint-stock company. At experimental power plant, the heating medium is flue gas of very high temperature. The heated medium is the gas mixture of air and steam. The highly superheated mixture of air and steam is lead to two gas turbines in series. The first turbine drives a compressor that supplies atmospheric air into system. The second turbine drives a generator of power energy. Supporting the design of the system the mathematical model of this experimental unit was constructed. The model serves as a base for simulation of both the power plant technological dynamics and control principles. The paper describes the scheme of the experimental power plant, structure of its mathematical model, and its selected control responses.

Key-Words: - simulation of power plant, model implementation, dynamics of system, control dynamics, system with distributed parameters

1 Introduction

The paper deals with the simulation of automatic control circuits of the experimental power plant. The power plant is developed by Vitkovice Power Engineering joint-stock company. Vitkovice JSC is a big Czech power plant boiler manufacturer. At experimental power plant, the heating medium is flue gas of very high temperature, generated by combustion of a fuel. The heated medium is the mixture of about 85% of air and 15% of steam. The highly superheated mixture of air and steam is lead to two gas turbines in series. The first turbine drives a compressor that supplies atmospheric air into system. The second turbine drives a generator of power energy. The second turbine drives a compressor that supplies atmospheric air into system.

Every fossil thermal power plant comprises many sophisticated and complex units that are situated in its technological chain. All of them have to be described mathematically and included in the mathematical model of the plant.

Problem of construction of a mathematical model of dynamical behavior of a power plant is a problem of a long-lasting cooperation between many designers and experts. In return, model aims to support them to develop new construction solutions and new materials.

The predominant energy source is the fossil fuel for the V-coil evaporator drum boiler. The boiler generates, see Fig.1, the flue gas 1 and the saturated steam 2. Near the output of the power circuit, there are two turbines. The first turbine is called the compressor turbine 3. The second turbine is called the generator turbine 4. The compressor turbine 3 drives the compressor 5 that supplies the power circuit by atmospheric air 6. The generator turbine 4 drives an asynchronous power generator 7. The power generator is connected to the 50 Hz energy supply network.
Temperature of the air after compression is about 250 deg. C. Specific heat capacity and other parameters of the compressed air are improved by adding small amount of demineralized water to the air by the injector 8. To simplify the terminology, both, the air and the gas mixture of air and steam behind the compressor are called the power gas.

Temperature of power gas after the water injection is increased by residual heat in the three stage residual convex heat exchanger 9. Then, power gas is lead to the three stage main heat exchanger 10. Both the temperature and the concentration of power gas between the residual heat exchanger 9 and the main heat exchanger 10 are controlled by controlling injectors of saturated steam 11 and demineralized water 12.

The major part of energy is supplied into power gas in main heat exchanger 10 where temperature of power gas is increased above 800 deg. C. The main heat exchanger 10 is designed as three-stage a counter-flow convex superheater. The superheated power gas is piped to the compressor turbine 3.

The compressor turbine 3 is in series with the generator turbine 4. The residual heat contained in power gas at the outlet of the generator turbine is used for power gas preheat in the residual heat exchanger 9. The cooled power gas is released to atmosphere in outlet 14.

Power circuit is controlled and protected by the exhaust and safety valve 13.

Power gas between individual units and inside the heat exchangers is transported by fourteen power gas pipelines. Pipelines should also be considered as separate technological units.

In the experimental system described below, both input flue gas and input saturated steam are obtained from an external source. Parameters of input saturated steam are constant. Parameters of input flue gas are controlled with respect to the power of the power plant. The evaporating part of the boiler is not connected to the system.

2 Mathematical Model of the System

Mathematical model of the simulated power plant consists from composition of mathematical models of its technological units.

To construct the dynamic model of the experimental power plant the available files of their technical and mathematical description of technological units have to be in most of the cases simplified. This simplification was a compromise between a large amount of knowledge on behavior and dynamics of these units accumulated by previous authors or supported by its manufacturers and urgency to construct the mathematical model of the system with the resources that were available. The requirement was that the simulation would run about ten times faster than the actual simulated process and that the model would be implemented on a PC in MATLAB & Simulink.

Every technological unit represents a nonlinear subsystem of its own. From the point of view of their mathematical description, the individual units can be separated into two groups as follows.

In the first group, there are the units where the movement of power gas along the longitudinal space axis can be neglected. The group includes the source of flue gas, the source of saturated steam, the water injector, the control steam injector, the control water injector, the safety valve, the compressor turbine, the compressor, the generator turbine, the asynchronous generator, and controllers. These units can be approximated by systems with lumped parameters. In the model, every unit with lumped parameters is described by the set of ordinary nonlinear differential equations, ODE.

In the second group, there are headers, pipelines and the heat exchangers. Small inertias of headers are included to adjacent pipelines. In the second
group, the dynamics of movement of air or of power gas along the space axis plays the important role. These units are typical systems with distributed parameters. In the model, every unit with distributed parameters is described by the set of partial nonlinear differential equations, PDE.

The simulated system extends to at least three specialized engineering area. It trespasses to thermodynamics, mechanics and electrical engineering.

Systems with distributed parameters are the thermodynamic systems. State variables of heat exchangers have to describe states of both moving gases. The standard basic state variables for gases are temperature, pressure, flow rate, and here also redundant concentration of steam. For convenience, some other redundant thermodynamic state variables are introduced and calculated, for example enthalpy and entropy of gases. At pipelines, the corresponding state variables describe the transported power gas. Note that temperature has to be calculated also for both the walls of the conduit bundles of the heat exchangers and the walls of the pipelines that transfer power gas.

Description of separate units of the system is beyond the scope of this paper. Let us select the heat exchanger for the illustration of the complexity.

Heat exchanger transfers heat energy from a heating media to a heated media. Typical power plant heat exchanger is a tube bundle located into a gas channel.

Tube bundle transports the heated fluid, the gas channel transports the heating fluid or vice versa. Heat from the heating media is transmitted to the heated media through the walls of the steel tubs. Fig. 2 shows the principal scheme of the physical state variables of a counter-flow heat exchanger.

where

\[ x \text{ is the space variable along the active length of the heat exchanging surface of the heat exchanger } \text{ m} \]

\[ t \text{ time } \text{ s} \]

\[ L \text{ active length of heat exchanging surface of the heat exchanger } \text{ m} \]

To simulate the dynamics of a heat exchanger as a single tube, the values of parameters of the actual device have to be rectified.

Applying the principle of continuity, the energy equation, Newton’s equation, and the heat transfer equation for power gas plus energy equation for flue gas, the behavior of five state variables of the convex heat exchanger can be well described by five nonlinear PDE. Similarly, every pipeline can be described by three nonlinear PDE [4]. To construct the model that runs about ten times faster than the actual simulated technological process, description of both the heat exchanger and the pipeline was simplified. The heat exchanger was described by three nonlinear PDE. Similarly, the pipeline was described by two nonlinear PDE as follows.

\[
\begin{align*}
T_1(x,t) & \text{ temperature of power gas } \text{ deg. C} \\
p_1(x,t) & \text{ pressure of power gas } \text{ Pa} \\
M_1(x,t) & \text{ power gas flow mass rate } \text{ kg.s}^{-1} \\
w_1(x,t) & \text{ concentration of power gas, redundant, 1} \\
T_W(x,t) & \text{ temperature of the wall of the heat exchanging surface of the heat exchanger } \text{ deg. C} \\
T_2(x,t) & \text{ temperature of flue gas } \text{ deg. C} \\
p_2(x,t) & \text{ pressure of flue gas } \text{ Pa} \\
M_2(x,t) & \text{ flue gas flow mass rate } \text{ kg.s}^{-1}
\end{align*}
\]

\[
\begin{align*}
& \text{here} \\
& T_1(x,t) = \frac{1}{l_1} \left[ u_1 \frac{\partial T_1}{\partial x} + \frac{\partial T_1}{\partial t} \right] \\
p_1(x,t) = \frac{1}{\tau_1} \left[ u_1 \frac{\partial p_1}{\partial x} + \frac{\partial p_1}{\partial t} \right] \\
M_1(x,t) = \frac{1}{\tau_1} \left[ u_1 \frac{\partial M_1}{\partial x} + \frac{\partial M_1}{\partial t} \right] \\
w_1(x,t) = \frac{1}{\tau_1} \left[ u_1 \frac{\partial w_1}{\partial x} + \frac{\partial w_1}{\partial t} \right] \\
T_W(x,t) = \frac{1}{\tau_1} \left[ u_1 \frac{\partial T_W}{\partial x} + \frac{\partial T_W}{\partial t} \right] \\
T_2(x,t) = \frac{1}{l_2} \left[ u_2 \frac{\partial T_2}{\partial x} + \frac{\partial T_2}{\partial t} \right] \\
p_2(x,t) = \frac{1}{\tau_2} \left[ u_2 \frac{\partial p_2}{\partial x} + \frac{\partial p_2}{\partial t} \right] \\
M_2(x,t) = \frac{1}{\tau_2} \left[ u_2 \frac{\partial M_2}{\partial x} + \frac{\partial M_2}{\partial t} \right] \\
w_2(x,t) = \frac{1}{\tau_2} \left[ u_2 \frac{\partial w_2}{\partial x} + \frac{\partial w_2}{\partial t} \right]
\end{align*}
\]
Most of pipelines are heavy isolated from atmosphere. The heat loses from these pipelines were neglected. As a result, these pipelines were described by two PDE as follows.

\[ T_W - T_1 = \tau_1 \left[ \frac{\partial T_1}{\partial x} + \frac{\partial T_1}{\partial t} \right] \]

\[ \frac{T_1 - T_W}{\tau_1} = \frac{\partial T_W}{\partial t} \]  

(2)

Where \( \tau_1 \) and \( \tau_W \) are functions of technological parameters of both the actual pipeline and physical variables of power gas.

For physical state variables of (2) adopt the above table from ‘heat exchanger’ to ‘pipeline’.

At two pipelines the heat loses to atmosphere could not be neglected. These pipelines were described by the set (1) of the three PDE of a heat exchanger, where power gas was replaced by ambient air.

Mathematical models of safety valve, the water injector and the controlling steam and water injectors are described by the sets of thermodynamic relations and equations of motion. Their dynamics are defined by the inertias of the imbedded mechanics and associated controllers. Under the condition it is allowed to discuss different types of energy, the other lumped systems change one type of energy to the other form. Turbines change the mechanical and thermal energy to mechanical one. Compressor converts the mechanical energy to both mechanical and thermal energy. Asynchronous generator changes mechanical energy to electrical energy.

State variables of systems with lumped parameters extend the list of state variables to standard mechanical and standard electrical variables. With partial exception of the asynchronous generator, the state spaces of all technological systems with lumped parameters contain also the above thermodynamic state variables.

The state variables of controllers complete the state vector.

The model comprises many technological coefficients and relations. Most of them are nonlinear. The accuracy of the model depends on both the accuracy and correctness of these coefficients and functions.

In the presented model the state variables were defined for every unit independently. The SI International System of Units is strictly observed at the mathematical model.

Temperature, pressure, flow rate, and concentration of steam are the variables of both input and output vectors of most of subsystems. Other variables are added to the input and output vectors from case to case.

3 Operating Range of the Model

Mathematical model of the system describes the system in the wide vicinity of its standard operating point. Under standard operating conditions, the technological loop is stable. It could be shown that in this case the standard operating point of the power plant is defined by the standard energy inputs of the main power loop of the power plant.

The standard steady value of electric power generated by experimental power plant is about 0.5 MW. The basic information on the model reliability and accuracy gives the comparison of steady state values of system state variables obtained by simulation with the values defined by the detailed technological project report of the power plant. The detailed technological project report was engineered by the Vitkovice, JSC. The simulation runs were organized as follows.

The set of simulation runs in the interval from 0.35 MW to 0.65 MW of the generated electrical power were was generated. The flue gas input values were set by the technical project. So were the all injected media. All control loops were disconnected.

Comparison of steady state values of representative physical state variables of power gas obtained by simulation with those defined by the detailed technological project report revealed the maximal differences of about 4 % in temperature, 2 % in pressure, less than 1.5 % in flow rate, and less than 0.5 % in concentration. The difference in generated electric power was 3.5 % against the detailed technological project report. As mentioned hereinbefore, the differences shown above were obtained for the model with all control loops in disconnected state. The feedback control minimizes the presented differences below the desired limits.

For comparison of simulated and measured values of 4×200 MW power plant, see [4].
4 Implementation of the Model

The model of whole power circuit runs on a PC with quad-core processor. It is implemented in MATLAB & Simulink environment. Besides standard Simulink blocks, both firmware, commercial software, and also some freeware from web was downloaded into the simulation program.

From the point of view of calculation efficiency, S-functions were preferred for construction of crucial parts of the simulation software. Embedded functions were implemented for calculation of enthalpy, specific heat capacity, and other thermodynamic parameters of power gas. Combination of S-functions and embedded functions lead to high efficiency and performance of simulation. Due to extensive use of C, the simulation runs about twelve times faster than real time. The time responses of individual groups of blocks often differ by several decimal orders of magnitude. This offers the possibility of synchronized grid computing in the future.

The MATLAB & Simulink blocs correspond to units of experimental power plant scheme, compare Fig. 1. Every Simulink block has its multilevel modular structure [10].

5 Power Gas Temperature Control

Temperature of power gas is measured and controlled in a number of points of technological power circuit. Under steady power plant operating mode, the desired values of controlled temperatures are constant. Under power plant start-up mode and under similar varying operating modes are these values variable. In this paper, the example of dynamics of control of temperature of power gas at the inlet of the compressor turbine is presented.

The temperature of power gas at the inlet of the compressor turbine is controlled by many means.

The long-response control algorithm is associated with control of power-plant power and is made by change of heating. The change of heating results in changes of both the flue gas temperature and the flue gas flow rate. The result is the change of other state variables in the system.

The medium response control algorithm modifies the power gas flow rate. The medium response control is simulated by changing the power gas flow rate through the exhaust and safety valve.

The short-response control algorithm adjusts both control injectors at the input of the main heat exchanger.
The short-response temperature control of power gas at the inlet of the compressor turbine adjusts control injectors at the input of the main heat exchanger. It changes the amount of saturated steam injected to power gas by injector 11 and/or the flow rate of water injected to power gas by the injector 12. In this paper, the second case is presented.

The location of the controller C in the system is shown in Fig. 4. The difference between the controlled temperature $T$ of power gas and its desired value $T_R = 800$ deg. C is led to the controller C. The controller is basically a PID type, with nonlinearities given by technological requirements.

In the presented example, the system is agitated by the step change of temperature of flue gas from 1100 to 1210 deg. C. The Fig. 5, 6, and 7 show the responses of temperature $T(t)$, flow rate $M(t)$, and concentration $w(t)$ of the power gas at the compressor turbine inlet.

Analysis of results shows a good stability of both the technological system and its short-response temperature control loop [7]. The system time responses, however, are rather long [2]. So have to be the time constants of the control algorithm. The control algorithm must take into account many additional technological limits. Well-known examples are the thermal stresses in materials.

6 Conclusion

Experimental power plant is a complex technological unit. In the paper, mathematical model of the power plant were presented.

Mathematical model is implemented in MATLAB& Simulink environment. Besides standard Simulink blocks, both firmware, commercial software, and also some freeware components from web are downloaded into the
simulation program. Simulation runs about ten times faster than does the actual simulated process.

Global dynamic of the experimental power plant was outlined. In detail, the dynamics of the short-response control algorithm of automatic control of temperature of power gas at the inlet of compressor turbine was demonstrated. The algorithm is based on the injection of cooling water to power gas.

Selected open-loop and closed-loop control responses of the power plant were presented and compared.

At present time, the presented mathematical model is adapted to the commercial power station. In the future, the model will be modified for real time processing to synchronize its run with the technological process.

Acknowledgement:
The work was supported by the grant No. FR-TI1/073 of the Czech Department of Industry and Commerce.

References: