Combined-Cycle Plant Simulation Toolbox for Power Plant Simulator.

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ABSTRACT

With the availability of powerful and high performance processors, advanced numerical methods, and flexible and capable software, there is a great opportunity to develop high performance simulators for analysis of and training on complex systems. Power plants are one group of complex systems with serious impacts on the economy and operations of industries. This paper addresses the development of a set of system component simulation modules combined with a control structure in a common software framework for a typical combined-cycle power plant. The simulation toolbox was designed for educational purposes using SIMULINK® based on Object Oriented Programming (OOP) and the C programming language. The simulation toolbox will be utilized to assess the long-time behavior of control systems and the overall plant performance following system disturbances. The developed simulation tool is able to use all MATLAB® toolboxes for research and education studies.

(Keywords: gas power plant, combined-cycle power plant, modeling and simulation, MATLAB®, SIMULINK®)

INTRODUCTION

The generalized trend in power generation all over the world is towards increasing the use of combined-cycle power plants. The need for modeling and simulation of these types of plants and their controllers is crucial to the understanding of their dynamic characteristics and impacts on power systems. It becomes important to assess the behavior of control systems and the overall plant performance following system disturbances.

There are several different combined-cycle configurations and control variation available [1-6]. This paper discusses the development of a physical simulation toolbox for a typical combined-cycle power plant with standard configuration. The heart of a plant simulation is its modeling block, which for a power plant is comprised of highly nonlinear and complex algebraic, and differential equations [6-10]. Various approaches such as modular technique and Object Oriented Programming (OOP) [11-13] could be utilized for this purpose.

The power plant will be modeled in the SIMULINK® environment based on OOP and the C-programming language, to create a new toolbox for constructing plant simulation. An important feature of this environment is building the Dynamic Link Library (DLL) of m-files and c-files of the block diagrams of this toolbox using a Visual C++ program linked with the MATLAB®. The developed simulation tool is able to use all MATLAB® toolboxes for research studies.

One of the major objectives in combined-cycle power plants is to maintain a good overall system dynamic performance and keep the efficiency high. This requires the inclusion of a control strategy for different subsystems in the combined-cycle power model. The developed simulation toolbox could be utilized for long-term stability analysis of the typical power systems.

The structure of the paper is as follows. After the above general introduction, design of a tool to construct the combined cycle plant simulation toolbox will be discussed and the simulation toolbox will be described. Different tests were undertaken to evaluate the performance of the typical plant simulation in a long-term stability analysis in the presence of disturbances. The authors offer their conclusions in the paper's final section.

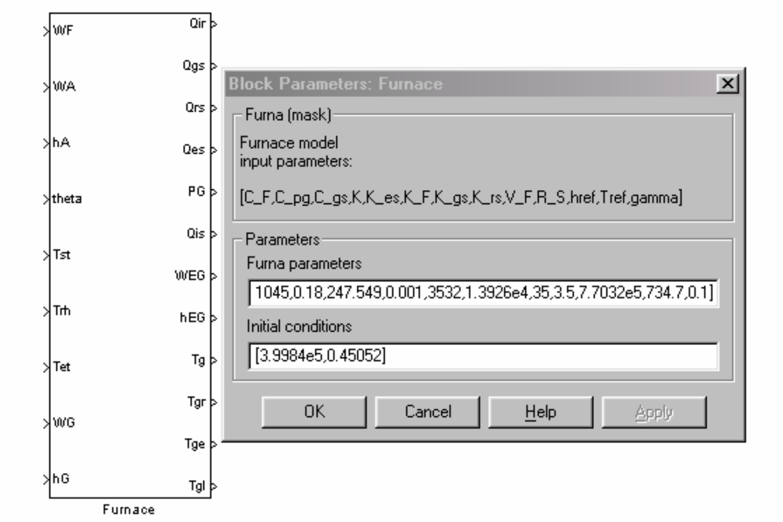
DESIGN OF TOOL TO CONSTRUCT THE COMBINED CYCLE PLANT SIMULATION TOOLBOX

To design a simulator, the programming language and the required software should first be selected. Modeling and programming can be run using any of the major programming languages. This method requires advanced techniques in programming or the simulator will not be economic or flexible. An alternate idea is to use simulator software to simulate and analyze the necessary calculations; this would be a better method for training and other applications.

One of the best software packages for this application is MATLAB® and its special simulator toolbox called SIMULINK®. This software can be developed as a simple OOP program. However, there are no block sets for power plant components in the default libraries. Therefore, it is possible to prepare the C-codes of system equations and add a new library in SIMULINK. The equations of each part of the plant (such as furnace, turbine, etc.) are functions defined by C-programming, which are fast enough in MATLAB® environment when they are converted to DLL-files.

Using these files, all of the components of the power plant will be constructed as block sets, which have SIMULINK® properties and are added to a library. Figure 1 shows this for the furnace block. Connecting these components together can simulate a complete power plant. To generate an environment for a simulator which acts in real time, a block set called "real time clock" is added to reduce the calculation time to actual time of the system. So a simulator based on object-oriented programming, C-programming, and SIMULINK® toolbox of MATLAB® is constructed which contains several programming languages and software. All of the components of the power plants have their special differential equations and state variables. Since the numbers of state variable of the power plant are so large, SIMULINK® cannot calculate the initial conditions of the system. So, the initial conditions of the plant have been calculated by the method in [14].

According to the equations of the system and measurable data in a power plant, initial conditions of each block can be computed.



Block Parameters: Furnace

Furna (mask)

Furnace model
input parameters:

[C_F,C_pg,C_gs,K,K_es,K_F,K_gs,K_rs,V_F,R_S,href,Tref,gamma]

Parameters

Furna parameters: 1045,0.18,247.549,0.001,3532,1.3926e4,35,3.5,7.7032e5,734.7,0.1]

Initial conditions: [3.9984e5,0.45052]

Figure 1: The Matching of Constructed Block with Default MATLAB® Library for Furnace.

MODELING REQUIREMENTS

The governing equation of combined-cycle power plant behaviors are highly nonlinear and complex and need to be accurately determined of acceptable responses are to be achieved. The components of the combined-cycle power plant are [6]:

Gas Turbine

A typical gas turbine is divided into five interconnected subsystems:

1-Fuel system
2-Compressor
3-Combustion chamber
4-Turbine
5-Generator

The governing equations of gas turbine behaviors are highly nonlinear and complex and need to be accurately determined if acceptable responses are to be achieved. All of the subsystems have been modeled by both algebraic and differential equations [6]. Figure 2 depicts the gas turbine internal structure.

Steam Power Plant

A typical steam power plant contains six main parts:

1-Boiler
2-Turbine
3-Condenser
4-Feed water system
5-Generator
6-Miscellaneous components

These parts will be described briefly, in the following text:

Boiler
The boiler contains the following components:

- Furnace
- Drum and Riser
- Superheater
- Reheater

The order of the dynamic mechanistic equations of the open loop boiler, without PID controllers and actuators, is 14 with 22 outputs and 14 input variable including 42 algebraic equations as is shown in Figure 3.

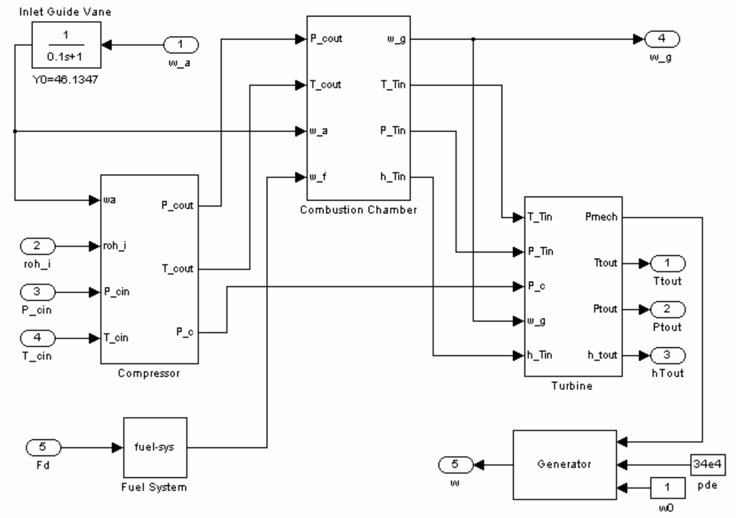


Figure 2: Gas Turbine Internal Structure.

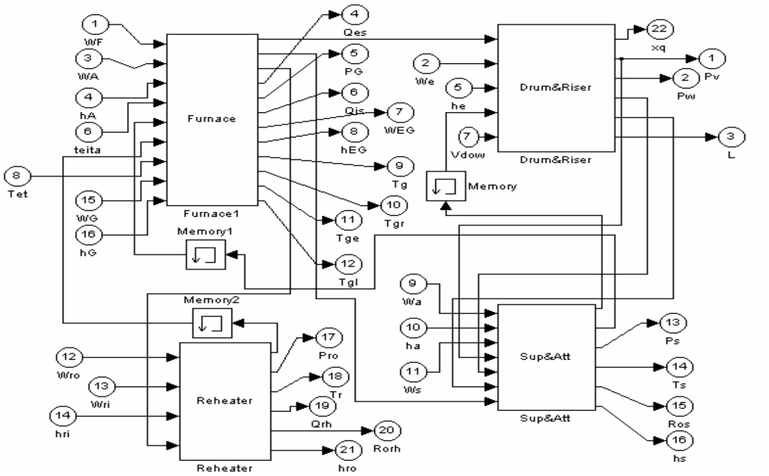


Figure 3: Boiler Internal Structure.

As mentioned, the number of governing equation for each element is quite high and complex. For instance, the governing equations of "furnace" are shown in Appendix A. there are ten inputs and twelve outputs.

Turbine

The components of turbine of the typical plant are:

- High Pressure (HP)
- Intermediate Pressure (IP)
- Low Pressure (LP)

The order of the dynamic equations of the open loop turbine is 10 with 11 outputs and 11 inputs and 32 algebraic equations [16].

Condenser

The condenser is constructed from the integration of the following components:

- Shell material
- Steam
- Tube Material
- Liquid

The model includes 6 differential equations with 20 algebraic equations. It consists of 8 outputs and 4 inputs (without PID controllers and actuators) [16].

Feedwater System

The feedwater system is constructed of five components:

- Deaerator
- Pump
- Economiser
- Two Valve

The model includes 5 differential equations and 19 algebraic equations with 13 outputs and 10 inputs (without PID controllers and actuators) [16].

Generator

The generator model includes the simple equation (swing equation), plus a stochastic noise generator to represented the real power electrical load fluctuations.

Miscellaneous Components

Apart from the components described above, a power plant includes other elements. Among them, the most important from control strategy viewpoints are valves (liquid and gas), actuators and elements with simple dynamics, which are represented via simple algebraic equations.

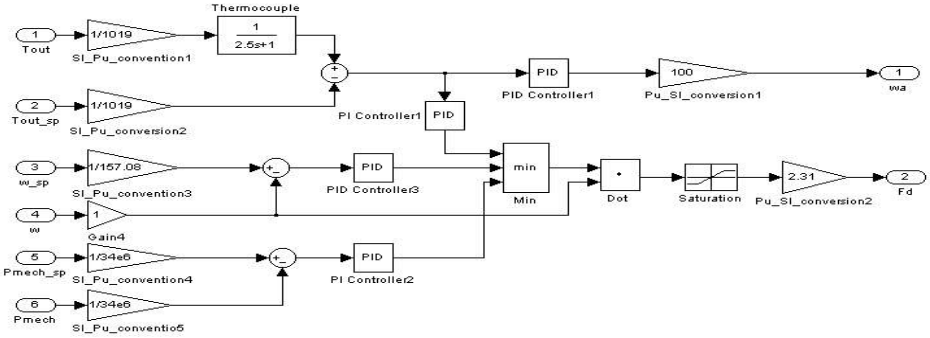


Figure 4: Gas Turbine Controller.

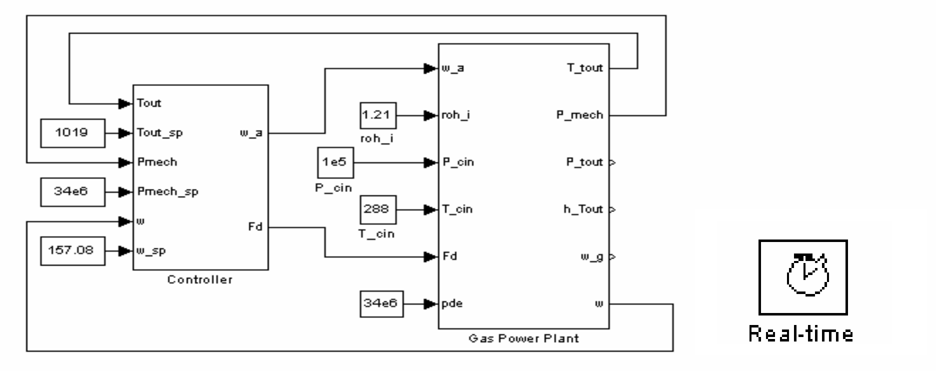


Figure 5: Overall Structure of the Gas Turbine.

CONTROLLER MODELING

In order to properly assess the performance of a supervisory plant controller, it is important that the lower level component controllers be adequately represented in the power plant simulation. PID controllers were used in each control loop. In the following, the low-level control loops for each component are described.

Gas Turbine Control Configuration

In a gas turbine, the main control loop adjusts the fuel flow to ensure the correct output power and frequency and also adjusts the air flow that control the exhaust gas temperature [1, 3, 6, 14, 15]. The block diagram of the control system is presented in Figure 4.

Steam Power Plant Control Configuration

Steam power plant control configuration will be described briefly, in the following text:

Boiler Control Configuration

The assignment of input and output variables for the boiler control is as follows [16]:

- Superheated steam pressure is regulated by adjusting the fuel flow
- Drum water level is regulated by adjusting the feedwater flow
- Superheated steam temperature is regulated by attemporation flow
- Furnace air pressure is regulated by the air flow to the furnace
- Reheated steam temperature is regulated by title angle

Steam Turbine Control Configuration

The inputs to the steam turbine controller, which are outputs from the steam turbine, the generator and the admission valves, are [16]:

- Delivered mechanical power
- Electrical frequency (rotation speed of the generator)
- Steam pressure at the inlet to the turbine

The first and second are controlled by throttle valve position (CV and IV) and the last is controlled by bypass valve position (BV).

Condenser Control Configuration

The condenser controller consists of only one loop regulating the temperature of the condensate by adjusting the cooling water flow [16].

Feedwater System Control Configuration

Two primary control objectives exist for the feedwater system; to maintain the vessel pressure and liquid level in the deaerator at desired values. Steam pressure is regulated by adjusting the flow of extraction steam supplied to the deaerator. Similarly liquid level is regulated via manipulation of inlet makeup flow [16].

The overall structure of the gas turbine and steam power plant are depicted in Figure 5 and Figure 6 respectively.

COMBINED-CYCLE POWER PLANT SIMULATION

The distinguishing feature of combined-cycle power (CC) plant is the joint production of electricity from a gas turbine and steam turbine, where the high heat content of the gas turbine exhaust flow is utilized to generate additional electricity by passing it through a waste heat boiler that raises steam for admission to the steam turbine. Figure 7 depicts the overall structure of the typical combined-cycle power plant. The base load operating characteristics of the selected combined-cycle power plant is presented in the Table 1.

The simulation toolbox for this typical combined-cycle power plant is developed in two steps; first gas turbine and steam power plants are simulated separately and then these two simulators are combined. Simulation of the steam power plant was fully addressed by the authors in [16, 17]. Performances of the gas turbine simulator and the overall combined-cycle power plant simulator are evaluated via simulation.

To evaluate the developed gas turbine simulator performance, two datasets related to the following tests are presented.

- Test 1: a +10% ramp in demanded power output of duration 200 seconds.

- Test 2: a +10% ramp in demanded power output of duration 200 seconds and a +10% ramp in demanded exhaust temperature of duration 200 seconds.

These tests were performed in the normal conditions. Increasing electrical power causes a decrease in mechanical speed. As shown in Figure 8 and 9, the control system compensates it and returns the speed to its normal value. In addition, the temperature converges to its desired value. The satisfactory performance of the controllers is obvious from Figure 8 and 9.

The following tests were done to evaluate the performance of the combined-cycle power plant control system.

- Test 1: decrease the electrical power of the steam power plant from 11 to 10 MW and decrease the furnace air pressure by 10% of duration 200 seconds.

When the electrical power decreases in a real power plant, the fuel rate and the output steam rate from control valves are expected to decrease. Variations of the superheated steam pressure, air furnace pressure, and level of the drum water, superheated steam temperature, steam turbine power output, steam turbine speed, and condensate water temperature, level of deaerator water, gas turbine power output and gas turbine speed are depicted in Figure 10. It is obvious from that a 10% decrease in the generated electrical power is approximately equivalent to a 10% decrease in fuel rate, which seems to be reasonable.

- Test 2: failing of the cooling water control valve of the superheater steam.

Failing of a control valve, is one of the usual disturbances occurring in power plants. The developed simulation toolbox is able to simulate such disturbances under normal conditions. For example, the failing of the cooling water control valve of the superheater steam for previous disturbance was investigated.

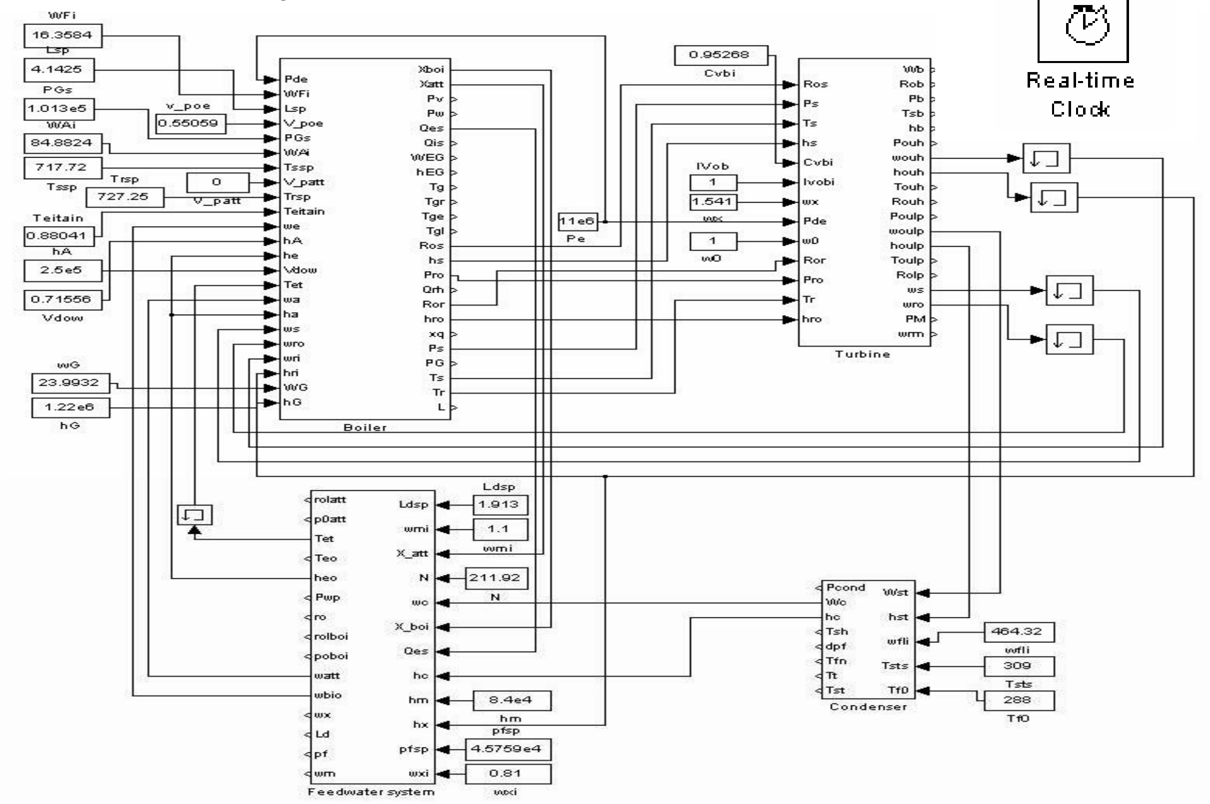


Figure 6: Overall Structure of the Steam Power Plant.

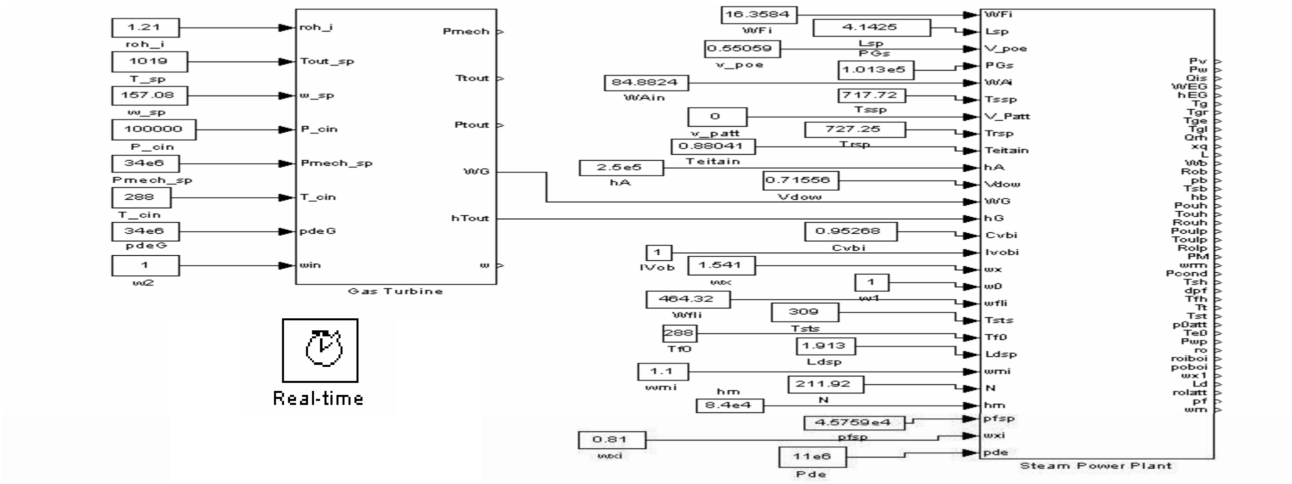


Figure 7: Overall Structure of the Typical Combined-Cycle Power Plant.

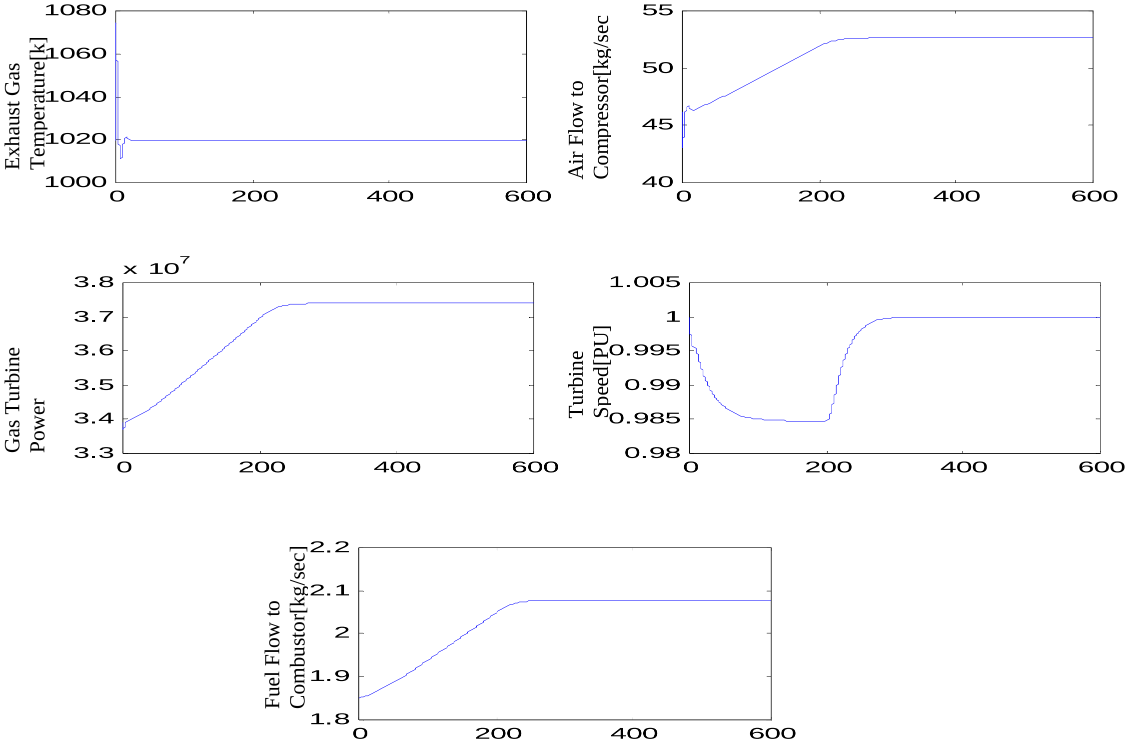


Figure 8: Closed-loop response of gas turbine for a +10% ramp in demanded power output of duration 200 seconds.

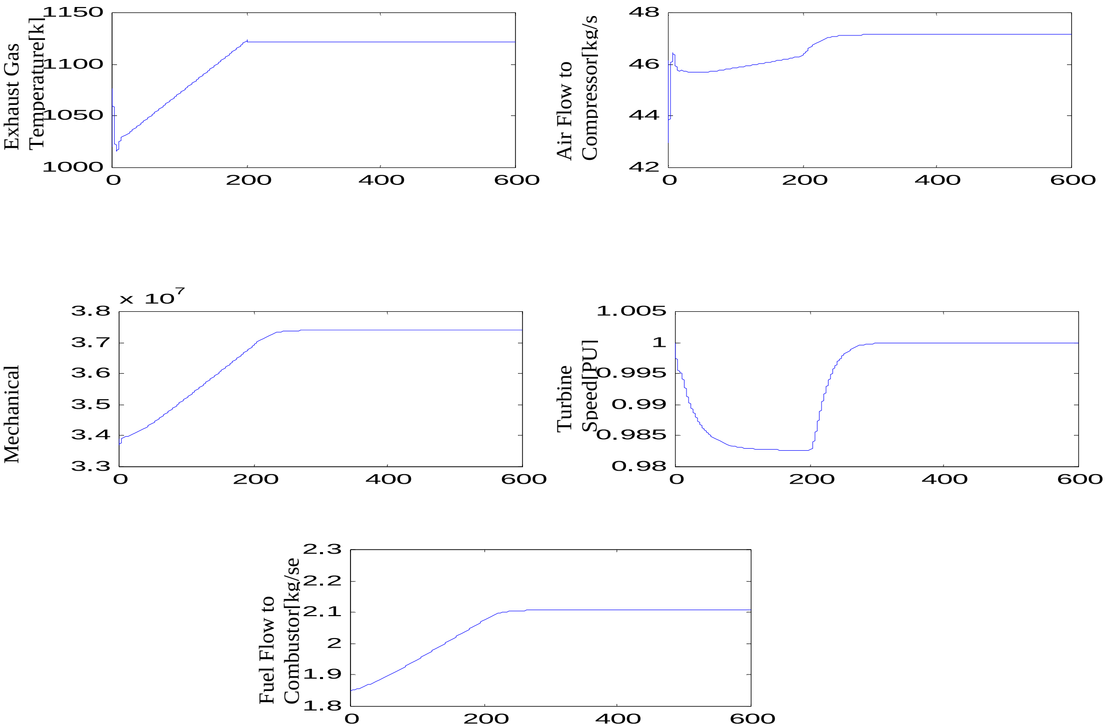


Figure 9: Closed-loop response of gas turbine for: a +10% ramp in demanded power output of duration 200 seconds and a +10% ramp in demanded exhaust temperature of duration 200 seconds.

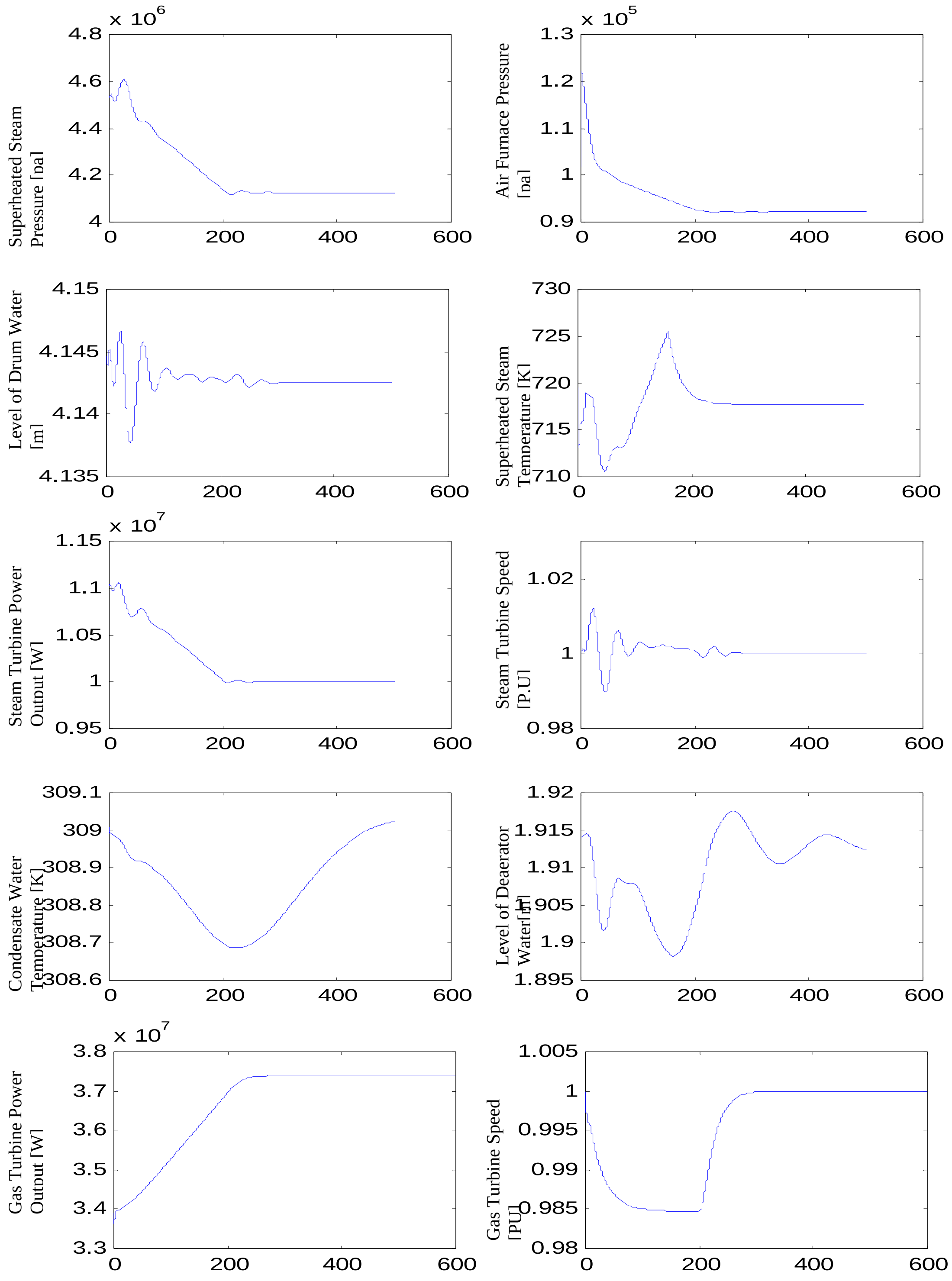


Figure 10: Closed-loop response of typical combined-cycle power plant for: decrease the electrical power of the steam power plant from 11 to 10 MW of duration 200 seconds and decrease the furnace air pressure by 10% of duration 200 seconds.

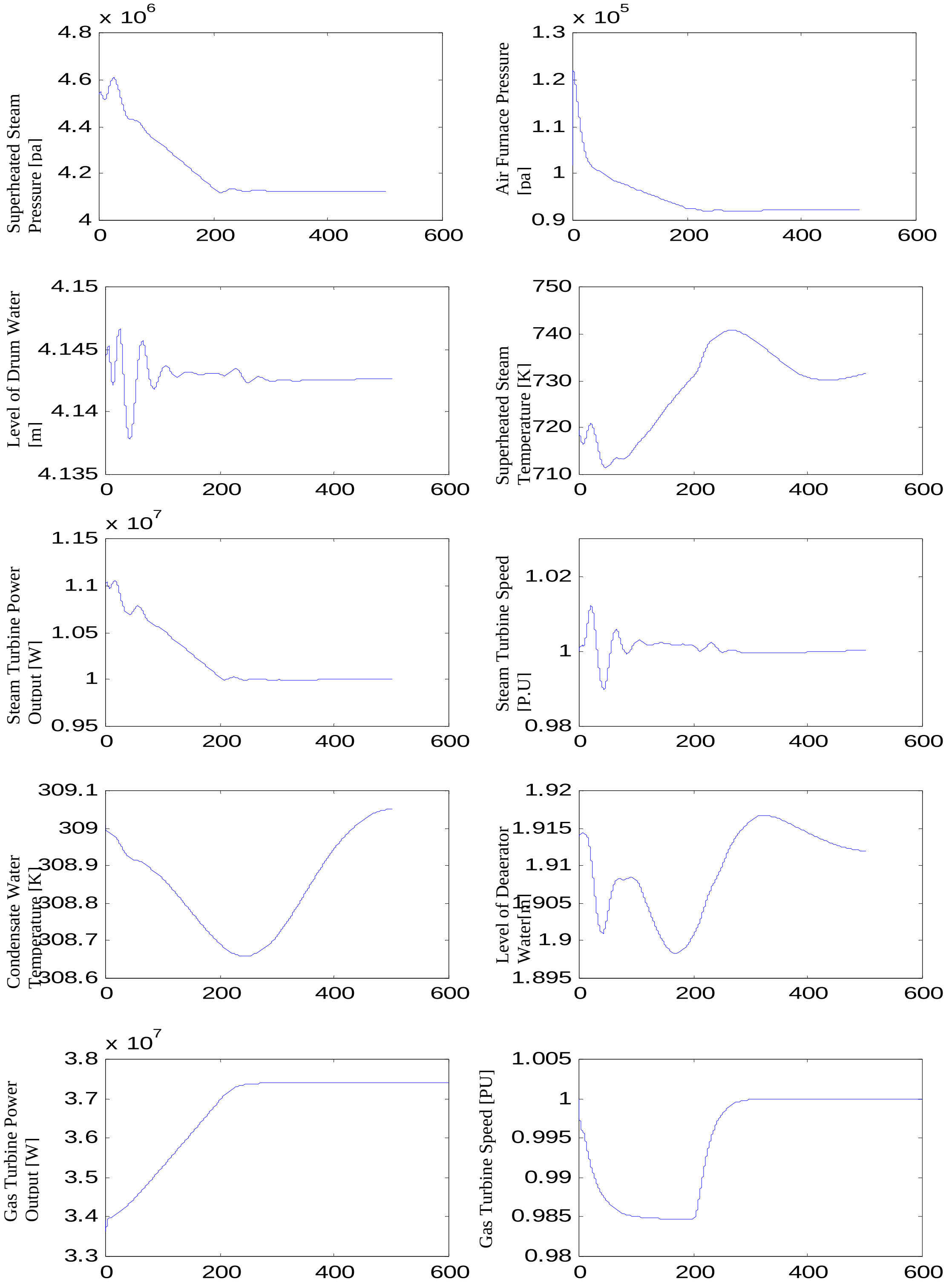


Figure 11: Closed-Loop Response of a Typical Combined-Cycle Power Plant for Failing of the Cooling Water Control Valve of the Super-heater Steam.

Table 1: Typical Operating Characteristics of the Selected Typical Combined-Cycle Power Plant at Base Load.

POWER		
Gas Turbine	34	MW
Steam Power Plant	11	MW
Total Net Power	45	MW
Gas Turbine		
Output power	34	MW
Exhaust gas flow	47	kg/s
Exhaust gas temperature	1019	˚K
Compression ratio	10:1	
Steam Power Plant		
Boiler		
Superheated steam pressure	45	bar
Superheated steam temperature	717	˚K
Superheated steam flow	12	kg/s
Reheated steam pressure	13	bar
Reheated steam temperature	727	˚K
Furnace fuel flow	14	kg/s
Steam Turbine		
Total output power	11	MW
Extraction steam flow	1.4	Kg/s
HP section outlet pressure	14	bar
HP section outlet temperature	602	˚K
HP section output power	3.4	MW
IP section outlet pressure	5	bar
IP section outlet temperature	610	˚K
IP section output power	2.7	MW
LP section outlet pressure	371	bar
LP section outlet temperature	376	˚K
LP section output power	4.9	MW
Condenser		
Operating pressure	60	mbar
Condensate flow	10.5	kg/s
Condensate temperature	309	˚K
Feedwater System		
Deaerator operating pressure	640	mbar
Economiser outlet water flow	12	kg/s
Economiser outlet water temperature	409	˚K

Figure 11 shows the variations of the superheated steam pressure, air furnace pressure, level of the drum water, superheated steam temperature, steam turbine power output, steam turbine speed, condensate water temperature, level of deaerator water, gas turbine power output and gas turbine speed. Although the temperature of the superheater steam has increased, this increase has been compensated to some extent due to the action of the controller of the reheater steam temperature.

CONCLUSIONS

The simulation toolbox of a combined-cycle power plant was developed within MATLAB® and SIMULINK®. This approach was employed so that the resulting power plant toolbox was fast, in terms of computational speed, robust, in terms of convergence problem, efficient and flexible, in terms of modeling capabilities and yet can use various capabilities of MATLAB® and SIMULINK®. PID controllers were designed for different control loops of the power plant, using the NCD Block set of MATLAB®, to improve the overall dynamic performance of the system. The developed simulation toolbox was successfully used to analyze and simulation of the combined-cycle power plant and its controllers at the presence of different disturbances.

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APPENDIX A

This appendix represents furnace differential and algebraic equations with the equations representing steady state values.

Inputs

W_F : Fuel flow to furnace (kg/s)

W_A : Air flow to furnace (kg/s)

W_G : Gas flow to furnace (kg/s)

h_G : Inlet gas enthalpy (J/kg)

h_A : Inlet air enthalpy (J/kg)

θ: Tilt angle coefficient (rad)

T_{st} : Temperature of superheater metal tubes (˚K)

T_{rh} : Temperature of reheater metal tubes (˚K)

T_{et} : Temperature of economizer metal tubes (˚K)

Parameters

C_F : Fuel calorific (J/kg)

C_{pg} : Specific heat of exhaust heat at constant pressure (J/kg°K)

C_{gs} : Combustion gas specific heat capacity (J/kg°K)

k : Attenuation coefficient

k_{es} : An experimental coefficient (J/kg°K)

k_f : Friction coefficient (m.s)

k_{gs} : An experimental coefficient (J/kg°K)

k_{rs} : An experimental coefficient (J/kg°K)

V_F : Combustion chamber volume (m^3)

R_S : Stoichiometric air/fuel volume ratio

h_{ref} : Reference exhaust gases enthalpy condition (J/kg)

T_{ref} : Reference exhaust gases temperature condition (˚K)

σ : Stefan-Boltzman constant

R_{EG} : Ideal gas constant for exhaust gases

States

X_{F1}: $(\rho_{EG} h_{EG})$ (J/m^3)

ρ_{EG} : Density of exhaust gas from the boiler (kg/m^3)

Outputs

Q_{ir} : Heat transfer to the riser

Q_{gs} : Total heat transfer to the superheater (J/s)

Q_{rs} : Heat transfer to the reheater (J/s)

Q_{es} : Heat transfer to the economizer (J/s)

P_G : Furnace air pressure (pa)

Q_{is} : Heat transfer by radiation to the superheated (J/s)

W_{EG} : Mass flow of exhaust gas from the boiler (kg/s)

h_{EG} : Enthalpy of exhaust gas from the boiler (kg/s)

T_g : Gas temperature at the superheater (˚K)

T_{gr} : Gas temperature at the reheater (˚K)

T_{ge} : Gas temperature at the economizer (˚K)

T_{gl} : Boiler exhaust gas temperature (˚K)

Algebraic Equation

$$h_{EG} = \frac{X_{F1}}{\rho_{EG}}$$

$$T_g = \frac{h_{EG} - h_{ref}}{C_{pg}} + T_{ref}$$

$$P_G = R_{EG}\rho_{EG}T_g$$

$$W_{EG} = k_f P_G$$

$$Q_{ir} = \theta k V_F \sigma T_g^4 \frac{W_{EG}}{\rho_{EG}}$$

$$Q_{is} = (1-\theta) k V_F \sigma T_g^4 \frac{W_{EG}}{\rho_{EG}}$$

$$Q_{gs} = Q_{is} + k_{gs} W_{EG}^{0.6} (T_g - T_{st})$$

$$T_{gr} = T_g + \frac{1}{C_{gs} W_{EG}} (Q_{is} - Q_{gs})$$

$$Q_{rs} = k_{rs} W_{EG}^{0.6} (T_{gr} - T_{rh})$$

$$T_{ge} = T_{gr} - \frac{1}{C_{gs} W_{EG}} Q_{rs}$$

$$Q_{es} = k_{es} W_{EG}^{0.6} (T_{ge} - T_{et})$$

$$T_{gl} = T_{ge} - \frac{1}{C_{gs} W_{EG}} Q_{es}$$

$$y = 100 \frac{(W_A + \gamma W_G - W_F R_s)}{W_F R_s}$$

Differential Equation

$$\frac{d}{dt} X_{F1} = \frac{1}{V_F} (C_F W_F + h_A W_A + h_G W_G - Q_{ir} - Q_{is} - W_{EG} R_s (1 + \frac{y}{100}) h_{EG})$$

$$\frac{d}{dt} \rho_{EG} = \frac{1}{V_F} (W_F + W_A + W_G - W_{EG})$$

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