

MATHEMATICAL MODELING OF A HEAT RECOVERY STEAM GENERATOR AND ITS INTEGRATION TO A COMBINED CYCLE POWER PLANT SIMULATOR

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ABSTRACT

To expand the scope of a gas turbine power plant simulator to a combined cycle power plant simulator, the mathematical models of process and control and the operation interfaces were developed and integrated in the available hardware-software architecture. To accomplish these goals, software tools were developed and applied to build and simulate a typical distributed control system of this type of power plants with a suitable operation interface for the trainees. Relating to the elaboration of process models, this paper highlights the development of the heat recovery steam generator and the steam turbine. The static and dynamic response of the simulator has been tested and validated regarding plant data. This full-scope simulator provides a suitable human machine interface to train operators of modern power plants. Currently the simulator has been installed in an operators training centre and it is being utilized as a part of the corresponding training courses.

Keywords: mathematical modelling combined cycle power plant simulator, operator training.

1. INTRODUCTION

Currently, full-scope simulators are recognized worldwide as the only realistic method to provide real time and hands-on training of operators (International Atomic Energy Agency, 2004). Full scope simulators include a detailed modeling of all reference plant systems, with which the operator interacts from the control room, and usually include replicas of consoles operation (Instrument Society of America, 1993). In these simulators, and under similar conditions of operation, the response of the simulated unit is very similar in time and indications to the response obtained from the real plant control room. A significant part of expenditure made in these simulators is due to the high fidelity simulation software development. The training quality using a full-scope simulator is clearly better to the one obtained with other simulators, since the operator is acting in an environment that is "identical" to the actual control room, therefore, the operators can be effectively trained due to the variety of initial conditions, malfunctions and operation scenarios.

Since more than 25 years, the simulation department of the Mexican Electric Research Institute

(IIE) has designed, developed and started-up all the power plant simulators required for the Mexican Federal Commission of Electricity (CFE) to train its operators of thermal, geothermal, gas turbine and combined cycle power plants. These simulators have different scopes, therefore in their training centres, the CFE have classroom simulators, full-scope replica and no-replica simulators. At this time, the training centre of the CFE with the largest number of simulators is the Ixtapantongo National Training Centre (CENAC-I), which is dedicated to train the operators of thermal power plants. In 2007 the IIE finished the development of a simulator to train operators of gas turbine power plants. This simulator is installed at the CENAC-I, and it replicates the behaviour of a generating unit of 150MW based on a gas turbine, with their control loops and additional systems as: electrical generator, fuel gas, compressed air, lubricating oil and control oil, among others (Roldán, Mendoza, Zorrilla, Cardoso and Cruz 2008). The simulator has a personal computer-based operation interface. As is described by Melgar, Tavira, Rodríguez and Cruz [2008], this type of interface allows operator (trainee) to view and perform the operation actions required from Interactive Process Diagrams (IPD). With this architecture the operator navigates through any IPD, and operates at any moment each one of the simulated systems. Due to the additional functions of the interface, the operator can monitor the behaviour of the simulated unit by means of trend graphs and be aware of any problem thanks to the alarms monitor. Furthermore, the operator has interactive windows to modify the status of any equipment, for instance: turn pumps on, open valves, or modify set points of controls.

To expand the scope of its gas turbine power plant simulator, CFE requested to the IIE to develop the process and control models, as well as the operation interfaces necessary to integrate a simulator of a 450 MW combined cycle power plant. This article describes the major features of the software and hardware architecture and presents the main results achieved in this development.

2. HARDWARE AND SOFTWARE ARCHITECTURE

The current gas turbine power plant simulator is installed at the CENAC-I on a computers network, therefore the 450 MW combined cycle power plant simulator was implemented in the same computers, which are personal computers with Pentium 4 (3.6 GHz) processor with 1 GB of memory and Windows XP operating system. Figure 1 shows the arrangement of these computers. The OC-1 and OC-2 are the operator consoles, the OC-1 has two 20" monitors and the OC-2 has two 20" and two 50" monitors. The OC-1 and OC-2 are utilized by the trainee to perform the required operation actions and/or monitoring the simulated process. On the other hand, the IC is the instructor console, and it is where the instructor of the training session guides the simulation practice.



Figure 1: Computer Platform

2.1. Software Architecture

The general architecture of the simulator software is shown in Fig. 2. The Executive, Operator and Instructor Console modules are described in detail by Távira, Jiménez, and Romero [2010]; therefore just a brief description of these modules is given here. The Executive module is responsible of sequencing the real-time tasks requiring a cyclical execution as: mathematical models of process and control, interactive process diagrams, Transducer module (Models-Control Communication Manager), and the managers of the Instructor Console and Operator modules. For its part, the Operator module represents the Human-Machine Interface (HMI) of the simulator user, and it consists of a group of IPDs with which the user operates the simulated process. Finally the Instructor Console module is the interface of the instructor who is leading the simulation session, from this interface the instructor establishes the initial condition, supervises the user actions, introduces malfunctions or performs some other type of actions required during simulation. The real time operation of the simulator is guaranteed because of the implementation of a "hard" real-time module. This module allows the creation of timers (from 0.1 to 1

millisecond) and system threads. This module also carries out the managing of resources such as memory, ports and interrupts.

2.1.1. Control Simulation Modules

While previous modules are the basis for the implementation of the simulator, the complexity and size of modern control systems, requires the use of generic tools that allow optimizing development and also obtaining an appropriate representation of the simulated system regarding to the control utilized as reference. Control Editor and Control modules represent these tools, which for purposes of this project were adapted to the requirements of the control system of a combined cycle unit.

The Control Editor module is a program whose main goal is to make a graphical modelling of modern control systems; these control algorithms are organized into components with a very specific function (PID, high/low detector, set/reset, etc.). This organization represents a network of components which transfer information through connections. These networks are organized hierarchically. At the lowest level of the hierarchy are basic elements or gates, which are organized in diagrams, a diagram or a group of diagrams constitutes a control loop, and a group of loops a module. Finally, a set of modules simulates the control system of the power unit.

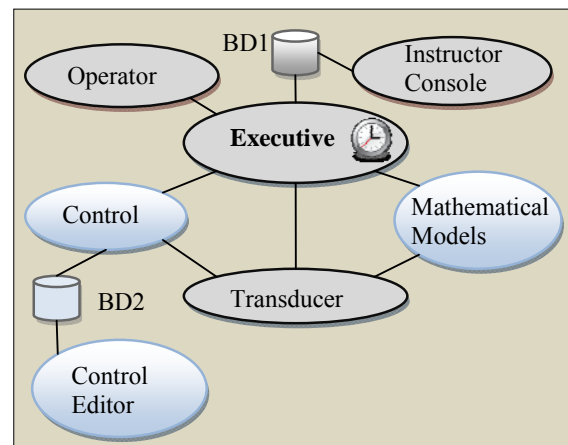


Figure 2 : Software Architecture

For its part the Control module is a tool that allows the dynamic assembly of predesigned software components. This methodology is based on the design of components which have a generic description of their dynamic behaviour; this allows generating an executable model in real time. The use of this development facilitates the construction of the model to simulate the control system, and has the ability to view during simulation the flow of logic and analogue signals of control algorithms. This allows understanding the functional conduct of the control, tuning parameters and helping with detection of problems associated with the

model. Once the control models are assembled, they can be executed in parallel on multiple processors because they can be distributed in several computers and/or multi-core computers.

The control system developed for the simulator has the following features: logical protection equipment, alarms system, turbine interlock, automatic sequencing for turning equipment (e.g. turbine start-up) on, and automatic controls of level, pressure and temperature for each Heat Recovery Steam Generator (HRSG). On the other hand, the operation interface of the control system is based on the IPD of the simulated process areas (e.g. HRSG1, HRSG2, steam turbine, etc.). These IPDs contain information such as: indications of equipment status, major variables displays, trends graphs, control stations for turning equipment on, and auto/manual transfers, among others.

3. HUMAN MACHINE INTERFACES

The HMI for the instructor console is a windows-friendly application with pull-down menus and icons, as it is shown in Fig. 3.

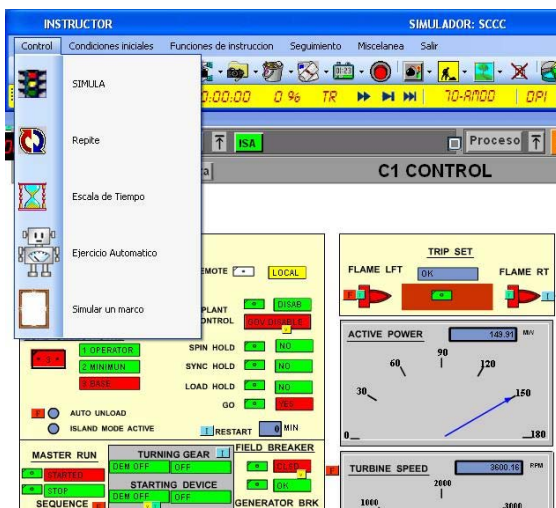


Figure 3: Partial View of Instructor HMI

The main functions of this interface are:

- 1) Run/Freeze. The instructor starts or freezes a dynamic simulation, during this simulation, the mathematical models of control and process respond to the actions of the trainee in a similar way as it happens in the actual plant.
- 2) Initial Condition. This function has the following options:
 - a. Selecting an initial condition to begin the simulation session. Each instructor has its own set of one hundred initial conditions;
 - b. Recording a new initial condition (snapshot) or to erase a previous initial condition;
 - c. Specifying the time interval to get automatic snapshots.
- 3) The option of malfunctions is used to introduce/remove an equipment malfunction at any time during the simulation session. There are 205 malfunctions. Some examples are: pumps trip, tubes break in heat exchangers, and valves obstruction. All the malfunctions are grouped in systems and subsystems for an easy location. For binary malfunctions, the instructor has the option of defining its time delay and its duration. For analog malfunctions, besides the former time parameters, the instructor can also define their intensity and their time evolution.
- 4) The instructor has the option of internal parameters for simulating the operative actions not related to automated equipment. These operative actions are associated with the local actions performed in the actual plant by an auxiliary operator, e.g., open (close) valves. Similarly to the malfunctions, they are grouped in systems and subsystems and they have time and intensity parameters as instructor options.
- 5) The option of external parameters allows the instructor to modify the external conditions to the process. Some of these conditions are: atmospheric pressure, ambient temperature, voltage and frequency of the external electric system.
- 6) The instructor also can create automatic training exercises. Each one of these exercises can include: initial conditions, malfunctions, local actions, and a time sequence. The exercises are stored in a database for their subsequent use.
- 7) In its default mode, the simulator is executed in real time, but the instructor can execute the simulator up to ten times faster or up to ten times slower than real time. This option is especially important when the trainee wants to analyse a fast transient, allowing him to simulate slower, or in the case of a slow thermal process, like state turbine's iron warming, it can be simulated faster.

Some additional important features of the instructor console are its portability and its auxiliary functions, like trends graphs and variables monitoring, so during the development stages of the project, the personnel in charge of the mathematical models utilized these functions to simulate, tune and debug the models. On the other hand, the HMI for operator is also completely graphical and based on a multi-window environment with interactive process diagrams, these diagrams are organized in hierarchical levels following the organization of the power plant systems, i.e. HRSG-1, HRSG-2, steam turbine, etc.

There are two main types of diagrams: information diagrams and operation diagrams. The first one shows to the trainee the values of his selected variables, or a predefined set of variables. The values are presented as trends graphs. The operation diagrams are utilized by the trainee to control and supervise the whole process; with them he turns equipment (pumps, fans and compressors) on(off), opens (closes) valves, modifies

set points of automatic controls, and carries out any feasible operation in a similar way as he would do in the actual power plant. When the trainee needs to perform an action, he selects the suitable icon, and then a pop-up window appears with the corresponding operation buttons. Figure 4 shows a partial view of the operation diagram of steam lines for HRSG-1 and HRSG-2.

4. MATHEMATICAL MODELLING

Figure 5 shows a schematic of the main parts of a combined cycle power plant. Each one of the gas turbines delivers 150 MW, while the two HRSGs and the steam turbine generate 150 MW of electric power.

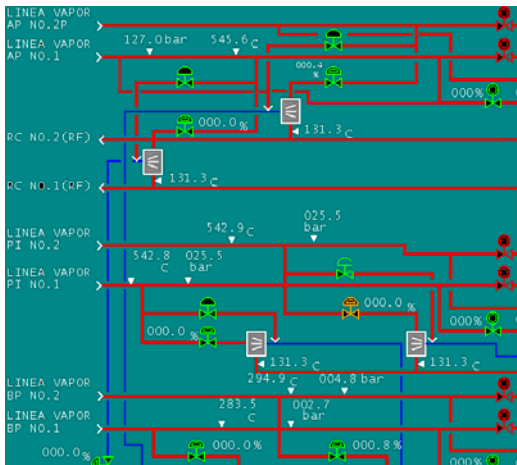


Figure 4: Partial View of HMI for operator

The Mathematical Models simulate the behaviour of the actual power plant in any feasible operation condition. Depending on its complexity, the mathematical models may be constituted by linear algebraic equations, non-linear algebraic equations, ordinary differential equations, or in most cases, by a combination of them. Usually linear equations are solved by LU decomposition methods, non-linear algebraic equations by Newton-Raphson methods and differential equations are solved by fixed step integration methods. The mathematical models of the simulator are divided into electric models and process models. The complete simulator includes all models required to represent the full conduct of the reference unit, in this paper, as an example of the type of models developed, the main equations related with the simulation of the HRSG and the steam turbine are presented.

Figure 6 shows a simplified diagram of the two HRSG array. Each HRSG is in charge of receiving the output hot gases (620 deg C) of the respective gas turbine, and because of a group of heat transfer equipment, liquid water from feedwater system is transformed into superheated steam of three pressure levels: high pressure (126.1 bar and 538 deg C), intermediate pressure (25.5 bar and 536 deg C) and low pressure (4.5 bar and 273 deg C). For each one of the HRSGs, their steam lines of a similar pressure are

joined to feed the steam turbine as appropriate. Each one of the HRSGs has sixteen sections divided in three pressure levels, and each level has their corresponding economizers, evaporators and superheaters.

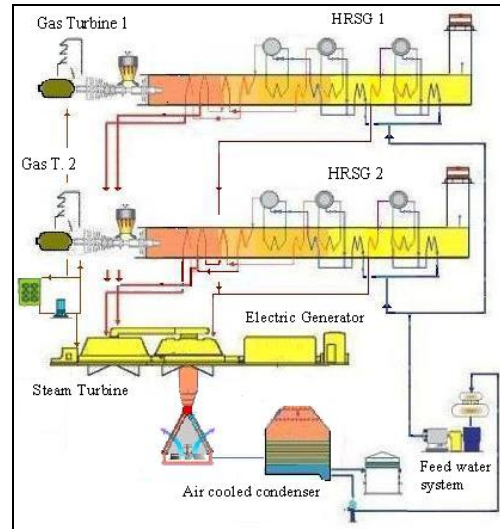


Figure 5: Combined Cycle Power Plant

For each section of the HRSG the main calculations carried out are:

- 1) Flow rates of gas and water (liquid/steam).
- 2) Heat flow rates from gases and to the water.
- 3) Levels of water in drums and evaporators.
- 4) Temperature of gases
- 5) Internal energy of water
- 6) Temperature of tubes (metal)

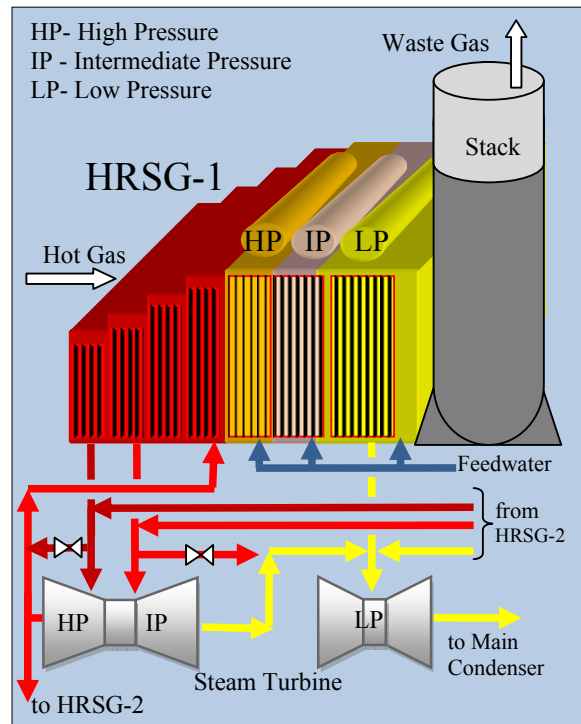


Figure 6 : HRSGs and Steam Turbine

The model was developed under the approaches of lumped parameter and perfect mixing, in this way; the gas temperature variation for each element of the HRSG is represented by:

$$\frac{dT_g}{dt} = \frac{W_g C p_g (T_{g(e)} - T_g) - Q_g}{\rho_g V_g C p_g} \quad (1)$$

In a similar way, the water energy variation inside the tubes for each element of the HRSG is calculated by:

$$\frac{dU_f}{dt} = \frac{W_f (h_{f(e)} - h_f) + Q_f}{\rho_f V_f} \quad (2)$$

For the tubes, the metal temperature variation is:

$$\frac{dT_m}{dt} = \frac{Q_g - Q_f}{m_m C p_m} \quad (3)$$

Heat flow rates from gas and to the water are calculated as:

$$Q_g = j_g A_g (T_g - T_m) \quad (4)$$

$$Q_f = j_f A_f (T_m - T_f) \quad (5)$$

The above equations are evaluated for each one of the elements of the HRSG. The model is complemented with the calculation of: thermodynamic properties of water, properties of combustion gases, heat transfer coefficients, and flow rates. In this case the equation utilized is:

$$W = K Y \sqrt{X \rho P_e} \quad (6)$$

where, $X = 1 - P_e / P_s$, and Y is the expansion factor. This factor compensates changes in the fluid properties by pressure variations. For liquids $Y = 1$, for gases the calculation is based on the verification of the conditions of critical flow (Crane Co. 1988).

The pressure and liquid mass variations for each one of the drums are calculated from the mass and energy balances over the corresponding equipment.

$$\frac{dP}{dt} = \frac{\sum h_e W_e - \sum h_s W_s + x1 [\sum W_e - \sum W_s]}{x2 m_L - V} \quad (7)$$

$$\frac{dm_L}{dt} = \frac{x3 \frac{dP}{dt} - x4 [\sum W_e - \sum W_s]}{x5} \quad (8)$$

where: $x1$, $x2$, $x3$, $x4$ and $x5$ are partial derivatives of density and enthalpy of saturated states of the water evaluated to the pressure P of each one of the drums, and the summations are applied over all the inlets and outlets streams of the drums.

On the other hand, the model for the steam piping and steam turbine is based on the development presented by Tavira, Melgar, García, and Cruz [2008]. This model solves the continuity equation for all points where steam flows are mixed or separated, these points are called nodes.

$$\sum W_e - \sum W_s = 0 \quad (9)$$

The flows from each one of the elements (valves and turbine stages) of the flow network are always associated with a pressure drop, in the case of the valves (governing, stop and bypass), Eq.(6) is utilized too. The calculation of the flow rate through the turbine stages is based on the following equation:

$$W = J \sqrt{2 \frac{m}{m-1} P_e \rho_e} \sqrt{P^{2/m} - P^{(m+1)/m}} \quad (10)$$

where m is the polytrophic coefficient for steam and p is defined as:

$$p = \frac{P_i - \frac{P_e - P_s}{\delta}}{P_e} ; \delta \geq 1 \quad (11)$$

δ is the stage number where the flow rate is being evaluated

In this way, if each one of the flow rate equations is replaced into the continuity equation for every node, a system of non-linear algebraic equations is obtained, where the pressures of the nodes are the independent variables. This system is resolved by the Newton-Raphson method.

The turbine model is complemented with the calculation of the enthalpy output for every stage:

$$h_j = h_{j-1} - \eta_j (h_{j-1} - h_{id,j}) \quad (12)$$

and finally with the enthalpy differences between stages, the mechanical power produced is calculated.

All parameters of the models as: volumes inside and outside of tubes, mass of metals, valves conductance, turbine stages efficiencies, etc., are calculated with equipment design data and operation data of the combined cycle unit utilized as reference.

5. RESULTS

The developed simulator for a combined cycle unit has a distributed control system with an operation interface similar to the interface available in the actual power plant. The software tools used for these developments facilitate the elaboration, integration and debugging of the simulated control system.

In order to test and validate the dynamic response of the simulator, the instructors of the CENAC-I applied a group of acceptance tests, whose main objectives were: a) Verifying the simulator response in any feasible operation condition; b) Validating the simulator

response when a malfunction is inserted; c) Testing the right operation of the user interface.

Regarding the simulator response, it has been tested and from cold shutdown to nominal power and malfunctions. Table 1 shows the absolute error percentages of the temperatures and flow rates through all equipment elements for a 100% generation state; these errors are calculated between simulated values and design data. In general, the errors are lower than 10%, which is a reasonable measure of the model accuracy.

Table 1: Absolute Error Percentages of HRSG Model

HRSG		Water Side		Gas Side	
Pressure Level	Element	Outlet Temp.	Flow Rate	Outlet Temp.	Flow Rate
High	Superheater-2	2.08	0.37	0.91	0.18
Intermed.	Reheater-2	0.17	1.86	0.20	0.00
Intermed.	Reheater-1	0.04	1.88	0.59	0.00
High	Superheater-1	1.58	0.16	0.33	0.18
High	Evaporator	8.89	7.56	2.57	0.18
Intermed.	Superheater	0.76	0.96	0.01	0.02
Low	Superheater	3.89	5.73	0.60	0.02
High	Economizer-3	2.61	0.08	2.43	0.18
Intermed.	Evaporator	0.41	2.21	0.11	0.00
High	Economizer-2	1.66	0.08	0.74	0.18
Intermed.	Economizer-2	10.10	5.01	6.72	0.00
Low	Evaporator	0.95	12.7	2.44	0.00
High	Economizer-1	0.27	0.08	0.48	0.18
Intermed.	Economizer-1	5.79	5.01	4.90	0.00
Low	Economizer	6.60	0.96	2.30	0.00
Low	Preheater	8.40	7.89	4.07	0.00

About the dynamic response, Figs. 7, 8 and 9 show the results obtained during a start-up, from cold iron up to full load.

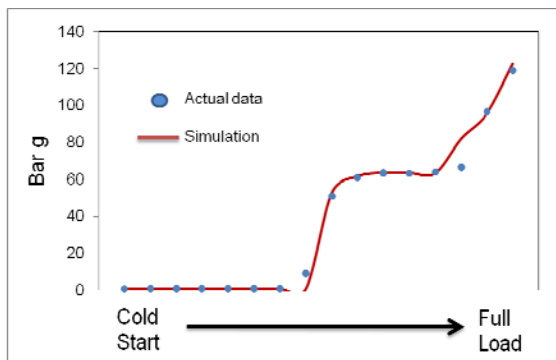


Figure 7: HRSG High pressure drum

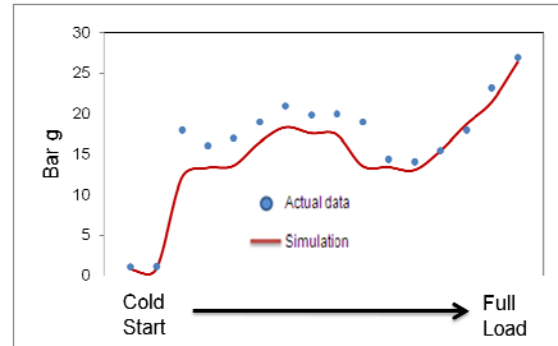


Figure 8: HRSG Intermediate pressure drum

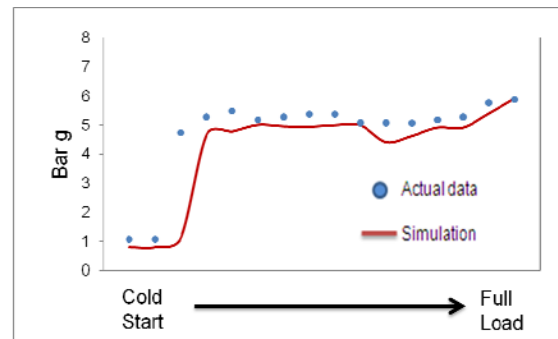


Figure 9: HRSG Low pressure drum

The simulated behaviours of the high, intermediate and low pressures of the HRSG follow the expected trends regarding actual data of the reference power plant.

6. CONCLUSIONS

In order to expand the capacity of a gas turbine power plant simulator, to a combined cycle power plant simulator to train operators, we integrated the control algorithms of a distributed control system, the operation interfaces, and the mathematical models of HRSG, steam turbine and auxiliary services into the prior simulator. The static and dynamic response of the simulator has been extensively tested and validated regarding plant data. This simulator has full-scope and real time features, and provides a suitable HMI for the operators of modern power plants.

The combined cycle power plant simulator is currently installed at the training centre for operators of the CFE, and it is being utilized as a part of the training courses for the operators.

ACKNOWLEDGMENTS

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NOMENCLATURE

A	Area
Cp	Heat capacity
h	Enthalpy
HP	High Pressure
IP	Intermediate Pressure
j	Heat transfer coefficient
J	Turbine stage conductance
K	Valve conductance
LP	Low Pressure
m	Mass
P	Pressure
Q	Heat flow rate
t	Time
T	Temperature
U	Internal energy
V	Volume
W	Flow rate

Greek letters

η	Stage turbine efficiency
ρ	Density

Subscripts

e	Inlet
f	Liquid, steam or mixture
g	Gas
id	Isentropic
j	Turbine stage
L	Liquid in the drum
m	Metal
s	Outlet

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