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Models for Training on a Gas Turbine Power Plant

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1. Introduction

In México, near 15% of the installed electrical energy of CFE, the Mexican Utility Company is based on gas turbine plants. The economical and performance results of a power plant are related to different strategies like modernisation, management, and the training of their operators.

The Advanced Training Systems and Simulation Department (GSACyS) of the Electrical Research Institute (IIE) in México is a group specialised in training simulators that designs and implements tools and methodologies to support the simulators development, exploitation, and maintenance. The GSACyS has developed diverse works related with the training. The main covered areas by the IIE developments are: computer based training systems, test equipment simulators, and simulators for operators training.

To use real time full scope simulators is one of the most effective and secure way to train power plant operators. According to Hoffman (1995), by using simulators the operators can learn how to operate the power plant more efficiently. In accordance with Fray and Divakaruni (1995), even not full scope simulators are successfully used for operators training.

Some advantages of using simulators for training are the ability to train on malfunctions, transients and accidents; the reduction of risks of plant equipment and personnel; the ability to train personnel on actual (reproduced) plant events; a broader range of personnel can receive effective training, and eventually, high standard individualised instruction or self-training (with simulation devices planned with these capabilities).

In the case of simulators, situations "what would have happened if…" arises when a cost benefit analysis is sought. A classical analysis for fuel power plants simulators (Epri, 1993) identified profit of simulators in four classes: availability savings, thermal performance savings, component life savings, and environmental compliance savings. A payback of about three months was estimated. Most often, the justification for acquiring an operators training simulator is based on estimating the reduction in losses (Hosseinpour and Hajihosseini, 2009). It is not difficult to probe the benefits for high-capacity plants where savings means millions of dollars for a few days of un-productivity. Besides, the ability of the simulator to verify the automation system and provide operators with a better

understanding of a new process must be addressed. Using a simulator help operators to improve the skills to bring the plant up and down, thus shortening start-ups significantly and improving the proficiency of less-experienced operators in existing plants.

In 2000 the CFE initiated the exploitation of a Combined Cycle Power Plant Simulator (CCS) developed by the IIE based on ProTRAX, a commercial tool to construct simulators. There is no full access to the source ProTRAX programs and the CFE determined to have a new combined cycle simulator using the open architecture of the IIE products. The new simulator was decided to be constructed in two stages: first the Gas Turbine (GT) part followed by the Heat Recovery Steam Generation (HRSG) part.

In this chapter a summary of the GT simulator development and its modelling characteristics are described. Stochastic and discrete events models are not considered, but deterministic models of industrial processes are contemplated.

2. Prior modelling approaches

A model to simulate a process may be developed using different approaches, basically depending on the use the model will be intended for. Certainly, trying to classify the different ways a model may be designed is a very difficult task. However, a model purpose may be: analysing, designing, optimisation, instruction, or training. The techniques to construct a model may vary, to mention two extreme situations, from governing principles based on differences or finite elements to obtain very detailed physical models, to curves fitting for limited empirical models. The real time modelling approach, particularly for operators training like the model presented in this chapter, lies somewhere in between.

Models for operation training are not frequently published, they belong to companies that provide simulation services and it is proprietary information (see, for example, Vieira *et al.*, 2008). Nevertheless, some models are available in recent publications as described in this section. All the revised works report to have a gas turbine system as presented in Figure 1.

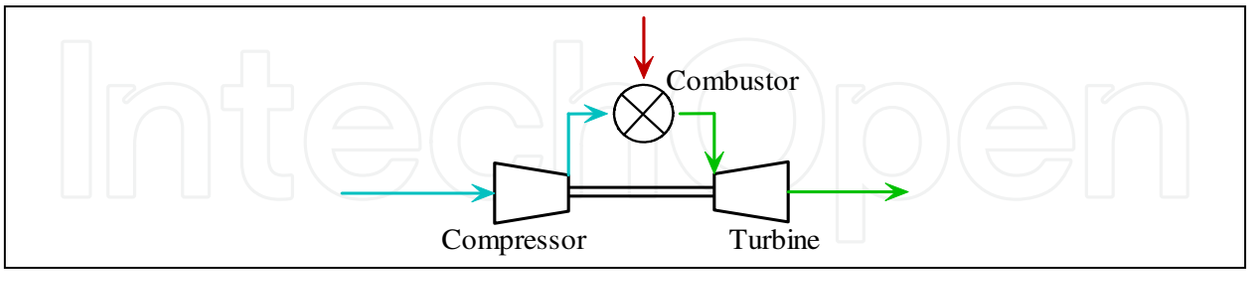


Fig. 1. Common representation of a gas turbine system

A summary of some published models is given in Table 1. None of the works revised here mentioned anything about real time execution.

In the present work, the total plant was simulated including all the auxiliary systems. For the composition of supply gas twenty components were included. There were simulated the variables in the 20 control screens and the tendency graphs. For example, the compressor-turbine system was simulated considering the schematics presented in Figure 2.

Authors (Reference)	Framework (Application)	General Approach and Commentary
Banetta *et al.*, 2001	Dynamic mathematical model of a generic cogeneration plant to evaluate the influence of small gas turbines in an interconnected electric network.	Ideal gas (IG) and perfect combustion (PX). Based on Simulink. They claim that the model may be utilised to represent plants with different characteristics and sizes.
Kikstra and Verkooijen, 2002	Gas turbine of only one component (helium) to design a control system.	Detailed model based on physical principles. No details are given concerning the independent variables.
Ghadimi *et al.*, 2005	Software diagnosis to detecting faults like compressor fouling	PX without heat losses.
Gouws *et al.*, 2006	To solve "practical problems" being experienced on a particular gas turbine combustor.	One-dim empirical model coupled with a commercial network solver (flows and pressures). The simplified model predicts the behaviour near a more detailed numerical model.
Jaber *et al.*, 2007	To study the influence of different air cooling systems	IG with no gas components. Input data were the ambient conditions and the air cooling system configuration. Model validated against plant data.
Zhu and Frey, 2007	Desktop model for excel to represent a standard air Brayton cycle considering five gas components and combustion stoichiometrics with possibilities of oxygen excess.	Output turbine temperatures are empirical enthalpy functions. Inputs are variables like efficiencies, some pressure drops, temperatures, etc. This approach is not useful for a training simulator.
Kaproń and Wydra, 2008	Model based on IG expansion and compression to optimise the fuel consumption of a combined cycle power plant when the power has to be changed.	Model adjusts the gradient of the generated power change as a function of the weather forecast. Authors indicate that the results have to be compared with the real plant and that that main problem is to develop highly accurate plant model.
Rubechini e*t al.*, 2008	Four stage gas turbine model to predict the overall turbine performance based on three-dim Navier-Stokes equations. Coolant injections, cavity purge flows and leakage flows were included.	Four different gas models were used: three based on gas ideal behaviour with different specific heat *Cp* evaluation and one using real gas model with thermodynamic properties from tables. Combustion was not simulated. Authors say that a good model is needed to reproduce the correct thermodynamic behaviour of the fluid.
Chen *et al.*, 2009	Model designed for optimisation running around the full load point ignoring combustion.	IG with detailed modelling of the flow through the equipment, heat transfer phenomena and basing the process on a temperature-entropy diagram.
Watanabe *et al.*, 2010	To analyse the dynamical behaviour of industrial electrical power system.	Simulink used as platform. The governor system model and a simple machine infinite bus were considered. Model was validated against real data. No details of the combustor model are mentioned.

Table 1. Summary of previous published works.

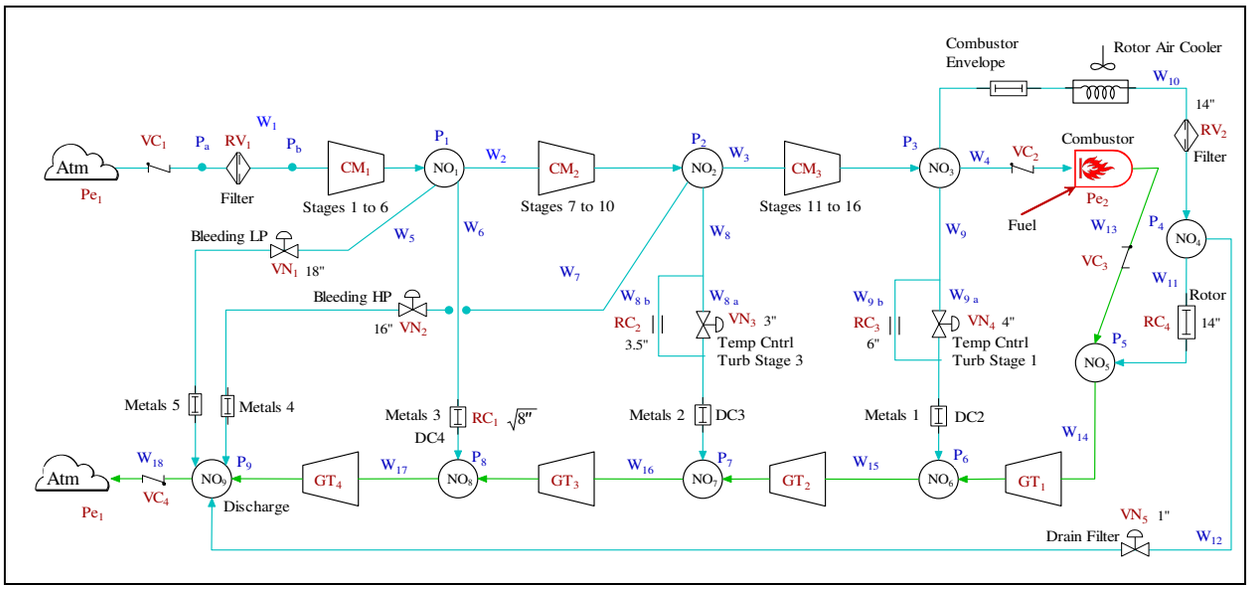


Fig. 2. Schematic diagram of the gas turbine-compressor-combustor system.

3. Description of the simulator

3.1 Hardware configuration

The simulation sessions are initiated and guided from the Instructor Console (IC). It consists in one PC (or simulation node) with two monitors. Two operators stations replicate the real control stations from the plant. Each of these stations has two monitors and one wall mounted screens (54″) to manage and control the simulated power plant. There is an additional PC that is used as a backup and to make modifications to the software, process or control models and where they are tested and validated by an instructor before to install it in the simulator. Figure 3 presents a view of the simulator.

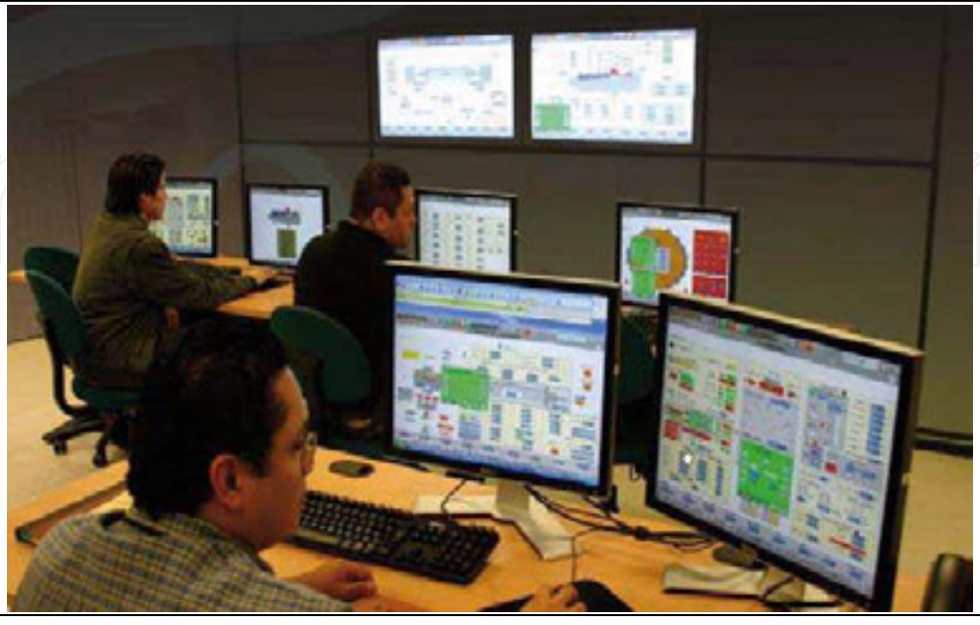


Fig. 3. GT simulator installed in the client facilities.

3.2 Software configuration

The simulator was developed under Windows XP and was programmed in Visual Studio Net, Fortran Intel, Flash and VisSim. The Simulation Environment (*MAS*) is copyright software of the IIE. A simplified conceptual diagram of the programs installed in the *MAS* is represented in Figure 4.

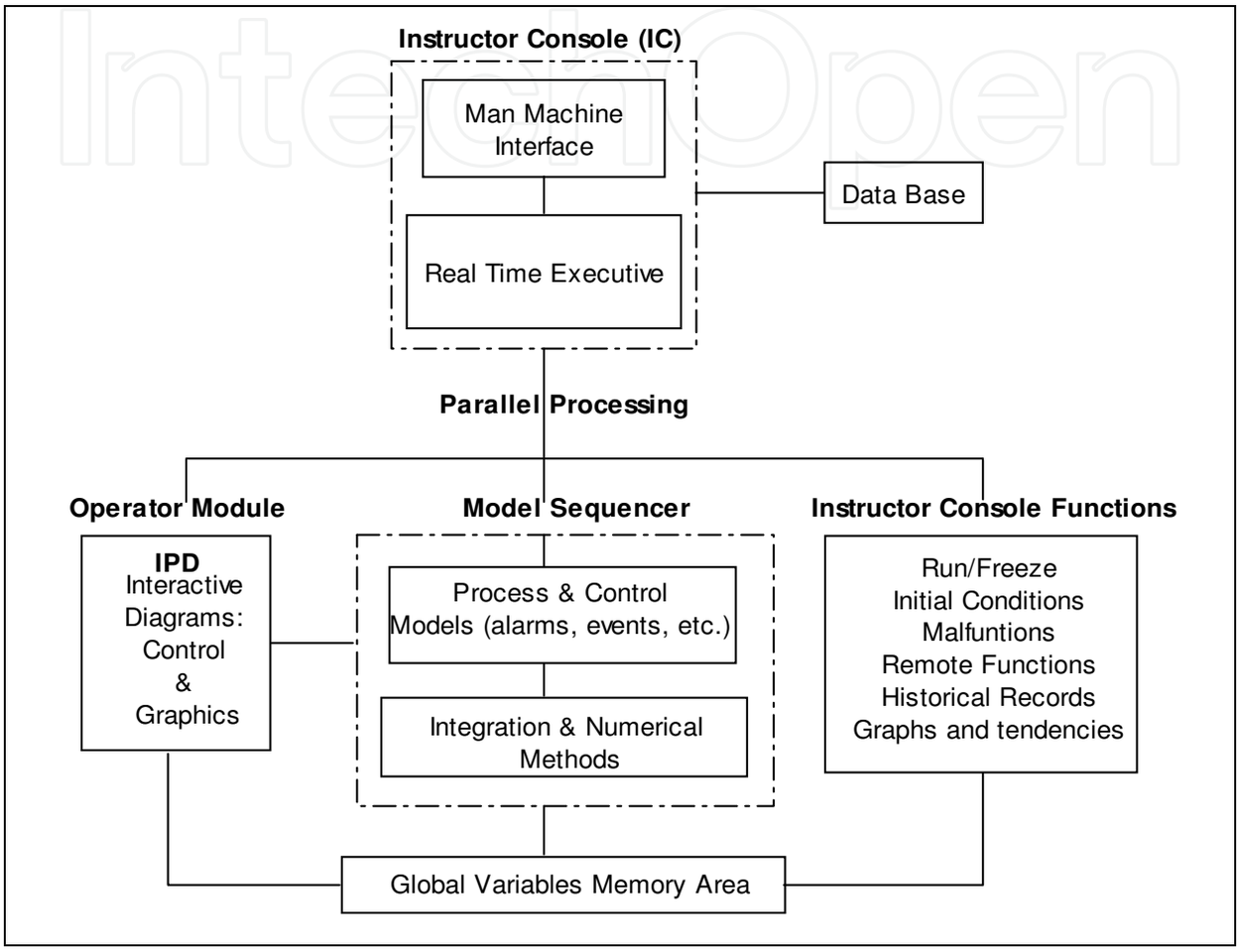


Fig. 4. Diagram of the Simulation Environment.

The platform, represented by the IC (with man-machine interfaces and a real time executive) has three main parts: the operator module, the model sequencer, and the IC functions. The communication between them is through a TCP/IP protocol. All the modules of the simulation environment except the Flash applications for the control interfaces are programmed with C# (Visual Studio).

The *MAS* is designed as a general tool for the GSACyS to develop simulators, it is very useful software that acts like a development tool and like the simulator man-machine interface. The *MAS* basically consist of four independent but coordinated applications: the real time executive, the operator module, the model sequencer and the instructor console.

The data base contains all the information required by the executive system. The tables contains information to support different process of the *MAS*, model sequencer, the number of times that a model is executed, Interactive Process Diagrams (IPD) for the instructor

console and functions for the operators consoles. All the information is configurable for each application that uses the *MAS*.

The global variables memory area is a dynamic memory created when the simulation starts. This special area is formed from information of data base and contains the direction of global variables for both models process and control. This function allows to modify and to consult variables.

3.3 Operator Module

The Operator Module is a replica of the real operation station, and it is formed by the IPD (operation interfaces) that links the control and process models providing and receiving variables between them. Other functions of the module are to call the operation modes of each IPD component (valves, pumps, buttons, etc.); to refresh each IPD periodically; and to coordinate the sequence of events in the operation consoles.

A total of 20 control screens, including the index, and as many tendencies displays as needed are available for the operator. As an example, the blade path and exhaust temperatures control screen of the operator, a replica of the Distributed Control System (DCS), is shown in Figure 5.

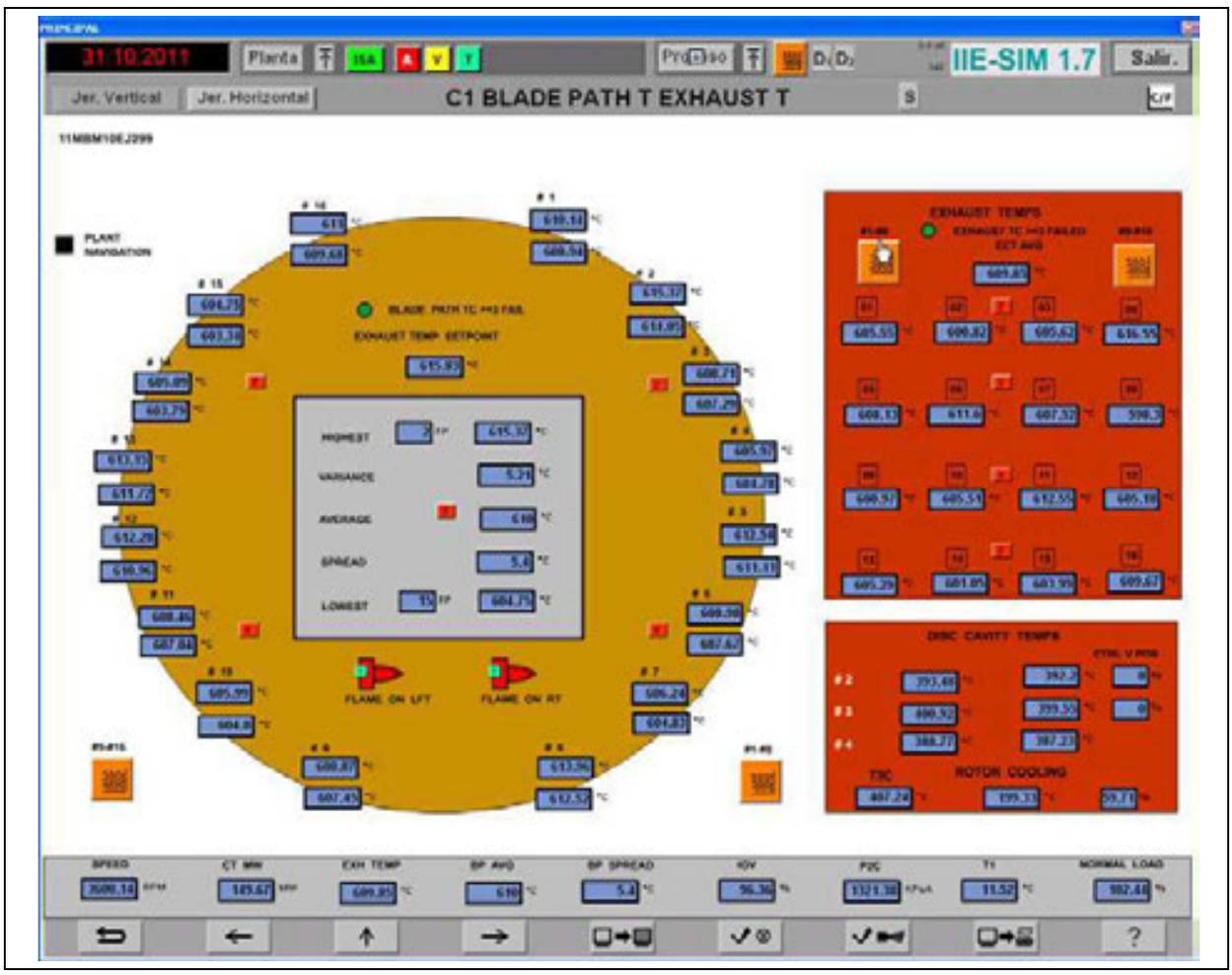


Fig. 5. Combustor blade path and exhaust temperatures control screens.

The flash movies have both, static and dynamic parts. The static parts are constituted by drawings of some particular control screens that are fixed on the screen. The dynamic parts are configured with graphic components stored in a library which are related to each one of the controlled equipments (pumps, valves, motors, etc.). These components have their own "moving" properties and they are employed during the simulation execution.

The main parts of the operator module are:

1. A main module (an "action-script" code) that loads the interactive process diagrams and gets information about the properties of the movie components.
2. A module to exchange information with the main module and with the executive system.
3. A module for the TCP/IP communications.

As a result of these functions, the student perceives his actions and simulator response in a very close way as it happens in the actual plant.

3.4 Models sequencer

The models sequencer coordinates the execution of mathematical models in a parallel scheme on a distributed architecture of PCs or with multi-core equipment. This module also has a group of methods to initialise variables belonging to the mathematical models. These values (initial conditions) represent a particular state of the plant and are located in the global variables memory area.

The models themselves and its mathematical treatment are explained in Section 5.1.

3.5 Instructor console functions

The Instructor console is presented in Figure 6.



Fig. 6. View of the instructor console.

The Instructor console has menus to activate different functions according the instructor necessities. The main functions are listed in this section.

Run/Freeze. The instructor may start or freeze a dynamic simulation session.

Initial conditions. The instructor may select an initial condition to initiate the simulation session, either from the general pre-selected list of initial conditions or from their own catalogue. Each instructor has access up to 100 initial conditions. Also in this function it is possible to create an initial condition or to erase an old one. As a instructional help, the

simulator is capable of getting the automatic snapshooting function, every 15 seconds and may be configured up to a frequency of 10 minutes.

Simulation speed. From the beginning of the simulation session the simulator is executed in real time, but the instructor may execute the simulator up to ten times faster or ten times slower than real time.

Malfunctions. It is used to introduce, modify, or remove a simulated failure of plant equipment. For the case of the gas turbine simulator, there are 98 available malfunctions. Examples of malfunctions are: pumps trips, heat exchanger tubes breaking, heaters fouling, and valves obstructions. For the binary malfunctions (like trips), the instructor has the option to define its time delay and its permanence time. For analogical malfunctions (like percentage of a rupture), besides the mentioned time parameters, the instructor may define both intensity degree and evolution time.

Remote functions. The instructor has the option to simulate the operative actions not related with actions on the plant performed from the control screens. These actions are associated with the local actions made in the plant by auxiliary workers. Examples of them are: to open/close valves and to turn on/off pumps or fans. There are more than 200 of them and they may have time and intensity degree parameters as instructor options.

External parameters. The external conditions such as: atmospheric pressure and temperature (dry and wet bulb), voltage and frequency of the external system, fuel composition, gas fuel delivery pressure, etc. can be modified by the instructor.

Repetition. Simulation session may be repeated, exactly as operated by the trainees, including the trainer actions, as many times as the instructor considers it necessary. An action registration is the basis for this function.

Automatic exercises. This is a function that allows to create a file indicating a series of instructor functions to be automatically tripped along the simulation scenario in defined times.

Development tools. The simulator has implemented some others helpful tools to use during simulation session development, for example: to monitor and change on line the value of any selected list of global variables, tabulate any selected list of variables and plot them.

4. Real gas turbine power plant

The reference plant for this simulator is the unit 5 of “El Sauz”, located in México. The nominal electric power is 150 MW and the plant is a pack generation unit Econopac 501F from Westinghouse. Generally speaking, this unit is formed for the gas turbine, the generator and auxiliary systems. It uses a system of low nitrogen oxide emissions DLN2 (Dry Low NOx - 2). The plant is designed to operate in an open cycle with natural gas.

Typically, a gas turbine power plant unit is based on the kinetic energy resulting from the expansion of compressed air and combustion gases. Resulting gases are directed over the turbine's blades, spinning the turbine, and mechanically powering the compressor and rotating the generator resulting in the production of electricity. After working in the turbine, the combustion gases are discharged directly into the atmosphere. In Figure 7, a simplified diagram of a gas turbine power plant process is shown.

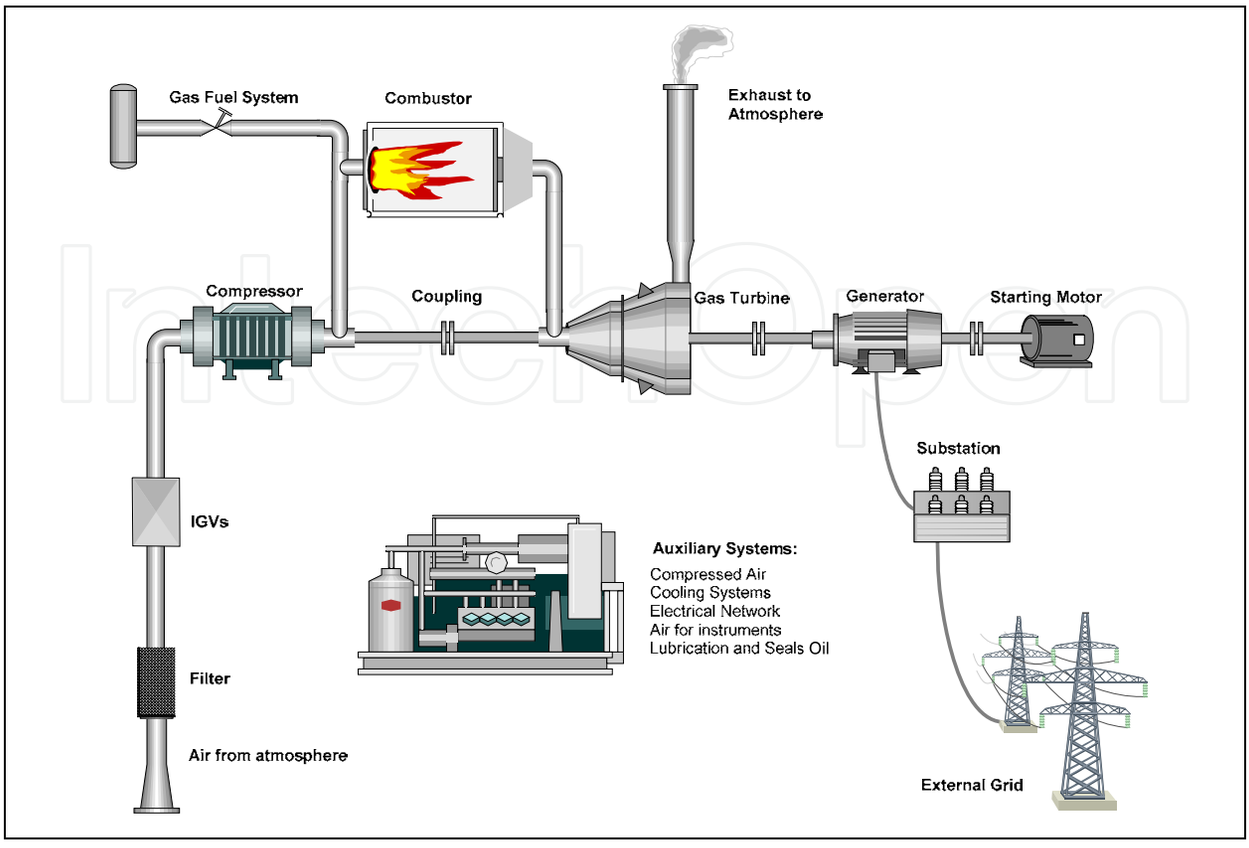


Fig. 7. Simplified diagram of a gas turbine power plant.

5. Developing of the gas turbine models

5.1 Execution of the models in the simulator

For an operators training simulation, the objective is to reproduce the behaviour of, at least, the reported variables in the plant control station in such a way the operator cannot distinguish between the real plant and the simulator performance considering both, the value of the parameters and their dynamics. The models were designed to work for all plant conditions, from 0% to 100% of load including all the possible transients that may be present during an operational session in the real plant. In order to accomplish with these objective, the "ANSI/ISA-S77.20-1993 Fossil-Fuel Power Plant Simulators Functional Requirements" norm was followed and adopted as design specification.

The gas turbine power plant was divided into a set of systems to be simulated, trying these to coincide with the real plant systems. A modelled system is a mathematical representation of the behaviour of the variables of the real system. The model of a simulated system (MSS) in the simulator responds to the operator's actions in the same way that the real system does, in tendency and time.

Each MSS is divided in algebraic and ordinary differential equations (AE and ODE, respectively). The AE may have to be solved simultaneously if necessary but they are independent of their ODE. For this work, different solution methods were adapted for linear and non-linear equations: Newton-Raphson, Gaussian elimination and bisection partition search. They are used depending on the characteristics of each particular model. The final

equations set of each MSS are mathematically independent of the set of equations of any other MSS.

The ODE are solved numerically with Euler method or trapezoidal rule with one or two corrections. The integration step depends on the dynamic characteristic of the MSS. The determination of the proper integration method and integration step for a MSS is made running the model under a multistep multirate method to find out its "critical transient" (where the method reports more potential numerical instabilities). A numerical analysis involving calculation of Jacobian matrixes, eigenvectors and eigenvalues and its relation with the state variables is used.

For the simulator, an execution second (cycle) was divided into ten frames of 0.1 s. In this way, any model could be executed with an integration step of 0.1 s, 0.2 s, 0.5 s or 1 s. The sequence matrix indicates the execution precedence of the models defined by the developer. The sequence matrix indicates, besides the execution sequence, the integration method and integration step of each model, and the initial execution frame of each model for each cycle.

The definition of the sequence matrix was based on an algorithm that considers the number of inlet and outlet variables (causality variables) between the models to minimise the probability of mathematical instabilities. The sequence matrix data are actually in the simulator data base.

To exemplify the concept of sequence matrix, let say a simulator had four MSS: M1, M2, M3 and M4 and three integration methods. The sequence matrix as defined in Table 2, means that model M2 is the first in being executed in the first frame integrated with the method 1 and has a integration step of 0.1s, followed by model M1 with method 3 and integration step 0.2s; in the second frame model M4 with method 2 and integration step 0.2s is executed followed by model M2; in the third frame model M3 with method 1 and integration step 0.5s is executed, followed by models M2 and M1; and so on.

With the tenth frame executed, one simulation second has been finished. The executive program synchronises all the tasks in order to match the simulator time with real time. Typically, each control model is executed just after its controlled process model (and so the sequence matrix is constructed).

Model	**Frames (10 frames is a second or cycle)**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
M3			1					1		
M4		2		2		2		2		2
M2	1	1	1	1	1	1	1	1	1	1
M1	3		3		3		3		3	

Table 2. Sequence matrix exemplified

5.2 General modelling methodology

The models of the simulator were implemented by the use of generic models, some times getting an improved version, and developing new models. In any case, a general procedure

developed by the IIE is followed to obtain the final models as described in this section (Roldán-Villasana *et al.*, 2009).

Typically, the models are divided in process and control. However, there exist some common tasks to be done by any of the models:

- Data information of the process is obtained and classified: system description, system operation guidelines, thermal balances, operational curves of the equipment, operational plant data, etc.
- The information is analysed and a functional description of the MSS is made (conceptual model).
- Simplifications on the system are stated obtaining a simplified diagram (with the simulated equipment and their nomenclature). In the diagram the modelled equipment and measurements points are included and it is possible to identify, for example, the valves controlled automatically from those operated by the operator or locally.

5.2.1 Process models

The developing of the MSS of the process is described below, but regarding the general developing methodology, next points are observed:

- Main assumptions are stated and justified.
- The flow and pressure network configuration is obtained and the parameters of pumps, valves and fittings are obtained in a excel data sheet being this is a part of the final documentation. If it is modified, the updating of the simulator is automatically performed by reading the changes.
- Energy balances are programmed using the required generic models. Again, parameterisation with excel is performed. The calculations of energy balances consider possible sets of equations to be solved simultaneously.
- Other equipments are parameterised (boilers, condensers, etc.) using predefined excel sheets considering the simulator generic models or developing adequate models.

5.2.2 Control models

In the same way that the real plant, the control models acquire and process the actions realised by the operator on the control screens. The control models generate possible changes (perturbations) on the process models, for example, the demand of the valves to regulate some process variables like levels of tanks, pressures, temperatures, etc.

The DCS has most of the controls but some of them are local (out of the distributed control system). The graphics package VisSim was used for the development of the control models. Printed diagrams from the plant were the sources of the information in the format defined by the Scientific Apparatus Makers Association (SAMA).

The development of control models was carried out in five stages:

- Two hundred SAMA diagrams were reviewed and analysed to include all the control logic for the pre-start and start permissive; speed control; temperature monitoring; load control; and temperature control. As a result of this stage 21 control models were developed.

- Some equipments are not included in the DCS and the diagram or description of the local controls was sought. When the information was not available, the control diagrams were proposed and accorded with the client.
- A generic graphics library was integrated to create the analog and logic diagrams into the VisSim environment.
- The diagrams were transcribed into the VisSim program using the generic modules. Each SAMA control diagram was drawn into a single VisSim drawing.
- VisSim generates ANSI C code. Some adjustments to the code have to be done with a program developed by the IIE to translate the code to C#, which can run in the simulator environment. This application generates the variables definitions that are loaded into the simulator database (global variables, remote functions, malfunctions, etc.). The control models are kept in graphic form to facilitate the updates and future adjustments.

5.2.3 Coupling and adjustments

Once the process and controls models are ready, they have to be coupled and tested according next steps:

- Local tests are performed and necessary adjustments on the models are made, *i.e.* in the *MAS* the model is run alone (with its control) and changes in some input variables are made in order to evaluate the general response of the model.
- Coupling of the MSS and their controls are performed. All models are coupled into the *MAS*. In this case, the first model incorporated was the turbine, combustor and compressor model with its associated control. Then the fuel gas, then generator and electrical grid. Finally the models of the auxiliary systems, each with its control. The coupling order is an important factor and was done considering the best sequence to avoid as much as possible mathematical problems. An algorithm proposed and used previously in a simulator is to consider an execution sequence trying to minimise the retarded information (variables). To prove the successful integration of each model added, operation actions on the models were done.
- Fabric global test are made with the needed adjustments.
- Final acceptance tests are achieved by the final user according their own procedures.

5.3 Process modelling

5.3.1 Systems considered to be simulated

The systems that finally were simulated have all the information the instructor needs to train an operator and they may be controlled from the control screens, from the process itself, trough remote functions in the simulator, or from the DCS.

The systems included in the simulator are presented in Table 3. The simulator resulted with 13 process and 21 control models.

The combustor model includes the combustor blade path temperatures with 32 display values, the exhaust temperatures with 16 displays, the disc cavity temperatures with 8 displays, and emissions.

5.3.2 Models development

For the modelling, fundamental conservation principles were used considering a lumped parameters approach and widely available and accepted empirical relations. The lumped parameters approach simplifies the modelling of the behaviour of spatially distributed real systems into a topology consisting of few discrete entities that represent the behaviour of the distributed system (under certain assumptions). From a Mathematical point of view, the simplification reduces the state space of the system to a finite number, and the partial differential equations of the continuous (infinite-dimensional) time and space model of the physical system into ordinary differential equations with a finite number of parameters.

No.	Process Model	No.	Control Model	No.	Process Model	No.	Control Model
1	Fuel Gas	1	Pilot & stage control	10	Generator Cooling with Hydrogen	-	Temperature control
2	Gas Turbine and Compressors	2	Supervisory turbine	11	Electrical Network	12	Electrical system
		3	Rotor cooling control	12	Generator	13	Generator control
		4	Inlet Guide Valves control			14	VARS/Power Factor control
3	Turbine Metals, Temperatures, and Vibrations	5	Temperature control				
4	Combustor	6	Combustor	13	Performance Calculations (Heat Rate and Efficiencies)	-	-
		7	Combustor control	-	Several systems	15	Prestart and starting logic
		8	Flashback temperature monitoring			16	Auto-unload control
		9	System DLN control			17	Trip logic
5	Compressed Air	10	Air instrument control			18	Simulation/Test
6	Air for Instruments					19	Counter and timer logic
7	Lubrication Oil	11	Lube oil control			20	System alarms
8	Seals Oil						
9	Water-Ethylene Glycol Cooling	-	Temperature control			21	Graphic trends

Table 3. List of process and control models

Figure 8 shows the flow information of MSS. For each MSS, the independent variables (inlets) are associated with the actions of the operators like open or close a valve, trip a

pump manually, etc., with the control signals, with the integration methods and with the information from other models.

A process model consists typically in the solution of the basic principles equations according the diagram shown in Figure 9. In this section the models related with the gas turbine, compressors and combustor are commented.

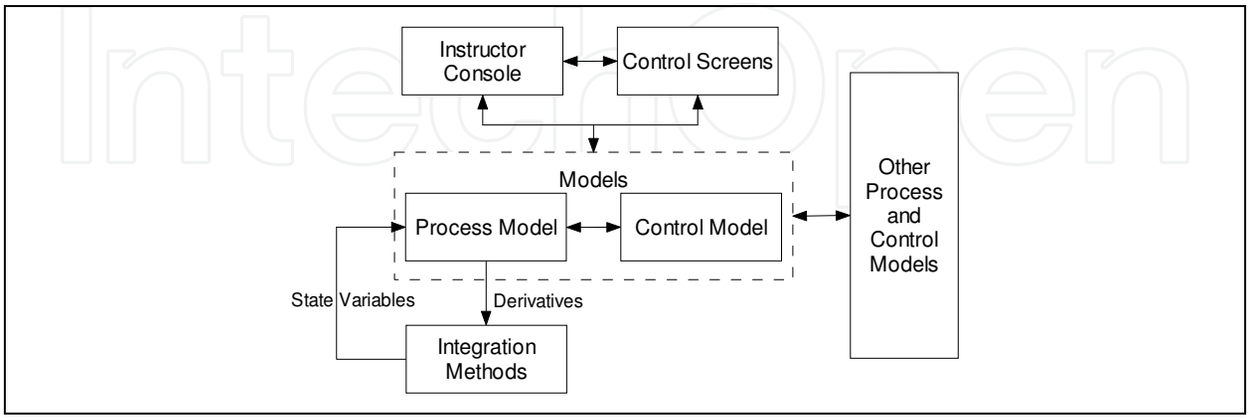


Fig. 8. Information flow of a model.

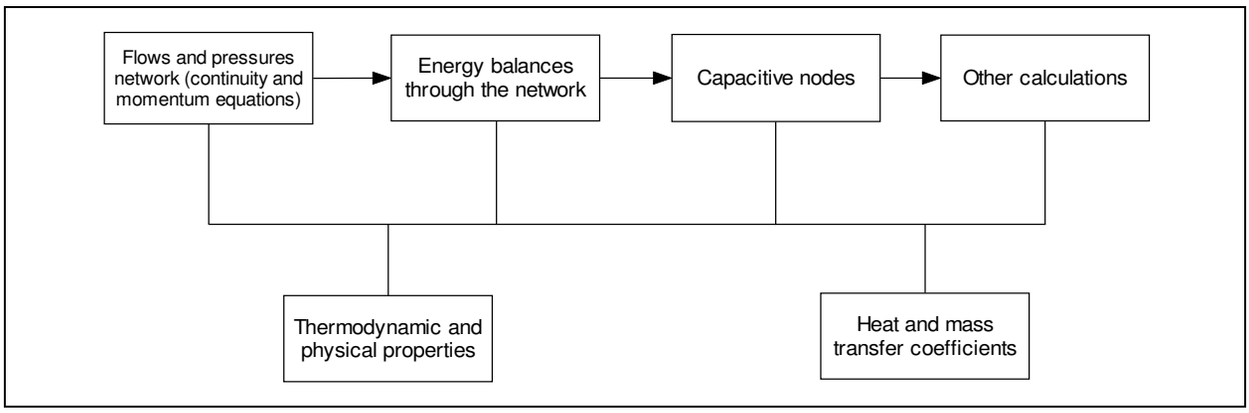


Fig. 9. Structure execution of a model.

Thermodynamic and physical properties

These properties are calculated as water (liquid and steam) and hydrocarbon mixtures thermodynamic properties and transport properties for water, steam and air.

For the water the thermodynamic properties were adjusted as a function of pressure (P) and enthalpy (h). The data source was the steam tables by Arnold (1967). The functions were adjusted by least square method. The application range of the functions is between 0.1 *psia* and 4520 *psia* for pressure, and -10 ^0C and 720 ^0C (equivalent to 0.18 *BTU/lb* and 1635 *BTU/lb* of enthalpy). The functions also calculate dTP/dP (being TP any thermodynamic property) for the saturation region and $\partial TP/\partial P$ and $\partial TP/\partial h$ for the subcooled liquid and superheated steam.

The hydrocarbon properties were applied for the gas fuel, air, and combustion products. Calculations are based in seven cubic state and corresponding state equations to predict the equilibrium liquid-steam and properties for pure fluids and mixtures containing non polar

substances. The independent variables are pressure and temperature. The validity range is for low pressure to 80 bars. Twenty components were considered: nitrogen, oxygen, methane, ethane, propane, n-butane, i-butane, n-pentane, n-hexane, n-heptane, n-octane, n-nonane, n-decane, carbon dioxide, carbon monoxide, hydrogen sulphide, sulphur dioxide, nitrogen monoxide, nitrogen dioxide, and water.

The transport properties (viscosity, heat capacity, thermal expansion, and thermal conductivity) are calculated for liquid, steam and air with polynomial functions up to fourth degree.

Flows and Pressures Networks

This model simulates any hydraulic or gas network in order to know the values of the flows and the pressures along the system. The general approach to represent the network is considering that a hydraulic network is formed by accessories (fittings), nodes (junctions and splitters) and lines (or pipes). Accessories are those devices in lines that drop or increment the pressure and/or enthalpy of the fluid, like valves, pumps, filters, piping, turbines, heat exchangers and other fittings. A line links two nodes. A node may be internal or external. An external node is a point in the network where the pressure is known at any time, these nodes are sources or sinks of flow (inertial or capacitive nodes). An internal node is a junction or split of two or more lines.

The model is derived from the continuity equation on each of the nodes, considering all the inlet (*i*) and output (*o*) flowrates (*w*):

$$\Sigma w_i - \Sigma w_o = 0 \tag{1}$$

Also, the momentum equation may be applied on each accessory on the flow direction *x*, being ρ density, *v* velocity, *g* the gravity acceleration and τ viscous stress tensor:

$$\rho \frac{\partial v}{\partial t} = - \frac{\partial P}{\partial x} - \frac{\partial \tau_{xx}}{\partial x} - \rho v_x \frac{\partial v_x}{\partial x} + \rho g_x \tag{2}$$

Considering that the temporal and space acceleration terms are not significant, that the forces acting on the fluid are instantly balanced, a model may be stated integrating the equation along a stream:

$$\Delta P = -L \Delta \tau + \rho g \Delta z \tag{3}$$

The viscous stress tensor term may be estimated with empirical expressions for any accessory. For example, for a valve, the flowrate pressure drop (ΔP) relationship is:

$$w^2 = k' \rho A p^{\zeta} \left(\Delta P + \rho g \Delta z \right) \tag{4}$$

Here, the flow resistance is function of the valve aperture *Ap* and a constant *k´* that depends on the valve itself (size, type, etc.). The exponent ζ represents the behaviour of a valve to simulate the relation between the aperture and the flow area. The aperture applies only for valves or may represent a variable resistance factor to the flow, for example when a filter is getting dirty. For fittings with constant resistance the term Ap^{ζ} does not exist. For a pump (or a compressor), this relationship may be expressed as:

$$\Delta P = k_1^{'} w^2 + k_2^{'} w \omega + k_3^{'} \omega^2 - \rho g \Delta z \quad (5)$$

where ω is the pump speed and where $k^{'}_i$ are constants that fit the pump behaviour.

If it is considered that in a given moment the aperture, density, and speed are constant, both equations (4) and (5) may be written as:

$$w^2 = k_a \Delta P + k_b \quad (6)$$

Applying equation (1) on each node and equation (6) on each accessory a set of equations is obtained to be solved simultaneously. A more efficient way to get a solution is achieved if equation (6) is linearised. To exemplify, equation (6) is selected for the case of a pump with arbitrary numerical values (same result may be obtained for any other accessory). Figure 10 presents the quadratic curve of flowrate w on the x axis and ΔP on the y axis (dotted line). In the curve two straight lines may be defined as AB and BC and represent an approximation of the curve. The error is lower if more straight lines were "fitted" to the curve. In this case two straight lines are used to simplify the explanation, but the model allows for any number of them.

For a given flow w, the pressure drop may be approximated by the correspondent straight line (between two limit flows of this line). If there are two or more accessories connected in series and/or two or more lines in parallel are present, an equivalent equation may be stated:

$$w = C \Delta P + D \quad (7)$$

Substituting equation (7) on (1), for each flow stream, a linear equations system is obtained where pressures are the unknowns. The order of the equations system matrix is equal to the number of internal nodes of the network. Flows are calculated by equation (7) once the pressures were obtained.

The topology of a network may change, for instance, if a stream is "eliminated" or "augmented" for the network because a valve is opened and/or closed or pumps are turned on or off. The full topology is that theoretical presented if all streams allow flow through them. During a session of dynamic simulation a system may change its topology depending on the operator's actions. This means that the order of matrix associated to the equations that represent the system changes. To obtain a numerical solution of the model is convenient to count with a procedure that guarantees a solution in any case, *i.e.* avoiding the singularity problem. An algorithm was developed to detect the active topology in order to construct and solve only the equations related to the particular topology each integration time. The solution method is reported by Mendoza-Alegría *et al*. (2004). Figure 2 represents the flows and pressures network for the compressor and turbines.

Energy balances on internal nodes

Valves are considered isoenthalpic. The heat gained by the fluid due the pumping Δh_{pump} when goes through a turned on pump is:

$$\Delta h_{pump} = \left(\frac{\eta \Delta P}{\rho} \right) \quad (8)$$

where η is the efficiency.

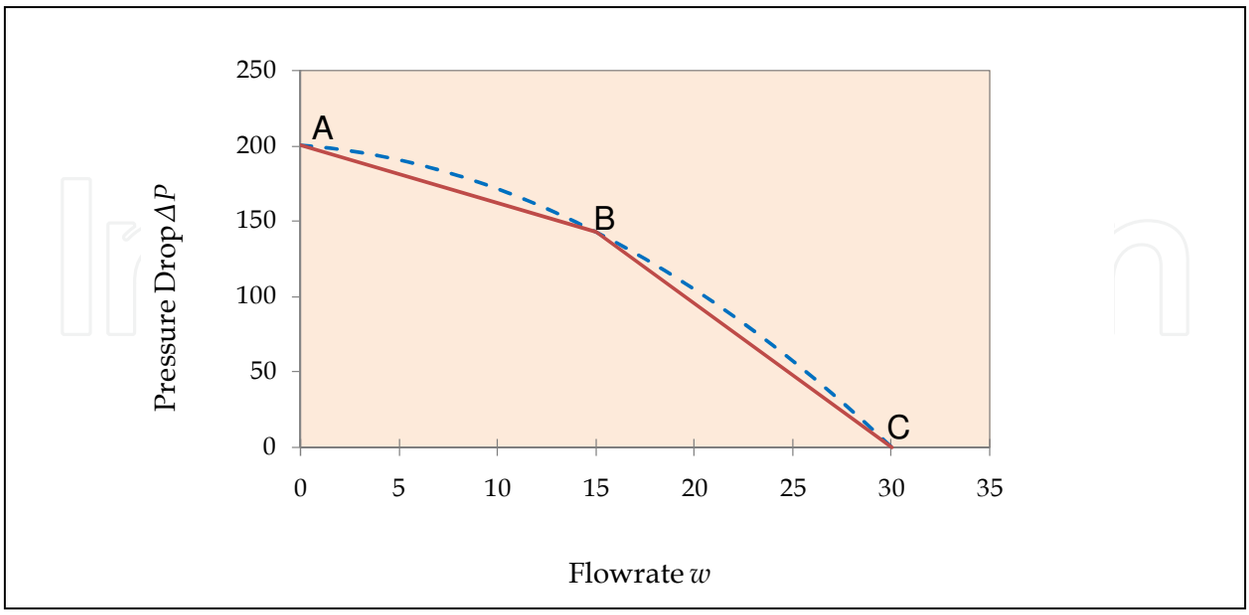


Fig. 10. Flowrate versus pressure drop linearization.

The exit properties for each turbine and compressor stage are calculated in a similar way, as an isoentropic expansion (or compression) and corrected with its efficiency. For example, the properties at the compressor's exhaust are calculated as an isentropic stage by a numerical Newton-Raphson method (i.e. the isoenthalpic exhaust temperature T_o* is calculated at the exhaust pressure P_o with the entropy inlet s_i):

$$f(T_o^*) = s_i(T_i, P_i, c) - s_o^*(T_o^*, P_o, c) = 0 \tag{9}$$

where c is the gas composition. Then, the leaving enthalpy is corrected with the efficiency of the compressor:

$$h_o = \frac{(h_o^* - h_i)}{\eta} + h_i \tag{10}$$

For the turbine it was considered that the work is produced instead of consumed. All other exhaust properties are computed with the real enthalpy and pressure. The efficiency η is a function of the flow through the compressor and turbine.

An energy balance on the flows and pressures network is made in the nodes where a temperature or enthalpy is required to be displayed or when a mixture of flowrates is made. In this case, the state variables are the enthalpy h, and the composition of all the components c_j is necessary in order to determinate all the variables of the node:

$$\frac{dh}{dt} = \frac{\sum w_i h_i - w_o h - q_{atm}}{m} \tag{11}$$

In this equation, m is the mass of the node, and q_{atm} the heat lost to the atmosphere. The subindex i represent the inlet conditions of the different flowstreams converging to the

node. With the enthalpy and pressure it is possible to verify if the node works as a single or a two phase.

All the mass balances are automatically accomplished by the flows and pressures network solution, however, the concentration of the gas components must be considered through the network. The concentration of each species j is calculated as the fraction of the mass m_j divided by the total mass m in a node. The mass of each component is calculated by integrating next equation:

$$\frac{dm_j}{dt} = \sum w_i \, c_{i,j} - \sum w_o \, c_j \tag{12}$$

Combustor

To calculate the flame temperature, the oxidation equations for each one of the 20 potential components were stated. Some of the reactions for the combustion process are:

$$\begin{aligned}
&2n_{1,1}\,N_2 + 4n_{1,2}\,O_2 \rightarrow 0m_{1,1}\,N_2 + 0m_{1,2}\,O_2 + 0m_{1,18}\,NO + 4m_{1,19}\,NO_2\\
&n_{2,1}\,O_2 \rightarrow m_{2,2}\,O_2\\
&n_{3,1}\,H_2S + 1.5n_{3,2}\,O_2 \rightarrow 0m_{3,2}\,O_2 + 0m_{3,3}\,H_2S + 1m_{3,16}\,H_2O + m_{3,20}\,SO_2\\
&n_{4,1}\,CO_2 \rightarrow m_{4,4}\,CO_2\\
&n_{5,1}\,CH_4 + 2n_{5,2}\,O_2 \rightarrow m_{5,4}\,CO_2 + 2m_{5,16}\,H_2O + 0m_{5,2}\,O_2 + 0m_{5,5}\,CH_4\\
&\qquad + 0m_{5,17}\,CO\\
&\bullet\\
&\bullet\\
&\bullet\\
&10n_{15,1}\,C_{10}H_{22} + 155\,n_{15,2}\,O_2 \rightarrow m_{15,4}\,CO_2 + m_{15,16}\,H_2O + 0m_{15,2}\,O_2 + 0m_{15,15}\,C_{10}H_{22}\\
&\qquad + 0m_{15,17}\,CO\\
&2n_{16,1}\,H_2O \rightarrow 2m_{16,16}\,H_2O\\
&n_{17,1}\,CO + 0.5n_{17,2}\,O_2 \rightarrow m_{17,4}\,CO_2 + 0m_{17,17}\,CO + 0m_{17,2}\,O_2\\
&n_{18,1}\,NO + 0.5n_{18,2}\,O_2 \rightarrow m_{18,19}\,NO_2 + 0m_{18,18}\,NO + 0m_{18,2}\,O_2\\
&n_{19,1}\,NO_2 \rightarrow m_{19,19}\,NO_2\\
&n_{20,1}\,SO_2 \rightarrow m_{20,20}SO_2
\end{aligned} \tag{13}$$

The excess of oxygen may be calculated from the flowrates of the reactive components. The total combustion efficiency for each reaction i $\alpha_{i,1}$ is defined as the fraction of the theoretically amount of oxygen that is consumed for a total combustion: is 1 if a complete combustion reaction is hold, for example production of CO_2 and 0 if none of the products of a reaction is completely oxidised. The partial combustion efficiency $\alpha_{i,2}$ is defined as the fraction of the theoretically amount of oxygen that consumed for a partial combustion (is 1 if partial oxidised products are generated, for example production of CO and 0 if none of the products of a reaction is partially oxidised). The efficiencies are normally not constant and any function could be adjusted but considering that, to avoid imbalance problems, the restriction

$$\alpha_{i,1} + \alpha_{i,2} \leq 1 \tag{14}$$

must be satisfied at any moment.

The kinetics is not taken into account, but this approach considering these original two efficiencies, allows simulate the behaviour of the combustor. For this particular application of the combustor model, a linear function was defined for each efficiency, and for each reaction, based on the excess of oxygen (a thumb rule, but any equation could be defined).

As an example the equations to obtain the stoichiometric coefficients related with the nitrogen (and the oxygen in the nitrogen reaction) are:

$$\begin{aligned} & N : 2n_{1,1} = 2m_{1,1} + m_{1,18} + m_{1,19} \\ & O_2 : \mathrm{n}_{1,2} = 0.5m_{1,18} + m_{1,19} \; ; m_{1,2} = 0.0 \\ & \text{If excess of oxygen} >= 200\% \qquad a_{1,1} = 0.1 \; ; a_{1,2} = 0.0 \\ & \text{If excess of oxygen} = 100\% \qquad a_{1,1} = 0.0 \; ; a_{1,2} = 0.1 \\ & \text{If excess of oxygen} <= 50\% \qquad a_{1,1} = 0.0 \; ; a_{1,2} = 0.0 \end{aligned} \tag{15}$$

Here, a linear interpolation is used between the boundaries.

The reactive stoichiometric coefficients n are known variables except for the oxygen. Thus, for the nitrogen oxidation:

$$\begin{aligned} m_{1,19} &= 2\mathrm{a}_{1,1} n_{1,1} \\ m_{1,18} &= 2\mathrm{a}_{1,2} n_{1,1} \\ m_{1,1} &= 0.5 \left(2n_{1,1} - m_{1,18} - m_{1,19} \right) \\ n_{1,2} &= 0.5m_{1,18} + 1m_{1,19} \end{aligned} \tag{16}$$

Similar equations may be stated for the oxidation reaction of each component and all the coefficients may be calculated. With the coefficient m, the concentration of the product is obtained. This formulation may be applied in a generic way for any quantity and any number of reactants.

An iterative process may be followed to find the flame temperature as a function of the amount of all the present species considering: the heat of combustion, calculated from the component's formation enthalpies; reactive and product sensitive heat; and heat losses by radiation and convection.

To develop the combustor model, it was conceptualised according Figure 11. Basically, the division considered a mixing node, the reaction and the capacitive node.

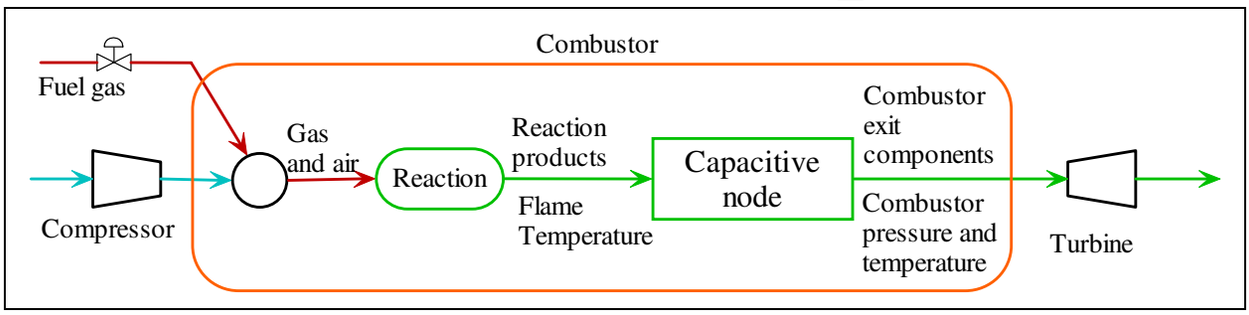


Fig. 11. Conceptual model of the combustor.

The mixing node just takes the air and fuel flowrates and concentrations to have single flowrate considering a perfect and instantaneous mixing. The reaction considers equations 13 to 16 to calculate the flame temperature, the flowrate and concentration of the products that enters into the combustor capacitive node, that has a volume and a concentration of the different species. Equation (12) applies for the mass of each component. The energy balance is done calculating the internal energy u in the node. The derivative of the internal energy is evaluated as:

$$\frac{du}{dt} = \frac{\sum w_i h_i - \sum w_o h - u\frac{dm}{dt} - q_c}{m} \tag{17}$$

The derivative of the total mass is the sum of the derivatives of each species as equation (12).

Here, the internal energy and density are known, this later by dividing the total mass and the volume of the node. The gas thermodynamic properties are a function of pressure and temperature, so all the properties are calculated with a double Newton-Raphson iterative method to have a solution. When two phases are present, some extra calculations are made to known the liquid and vapour volumes, but this is not treated here.

The combustor heat q_c is calculated as the sum of radiant and convective phenomena using appropriate correlations. The heat is absorbed by the combustor metal that is cooled with air flow in the rotor air cooler (see Figure 2). This heat is divided to be absorbed by different parts of the metal, like the blade paths presented in Figure 5. In each part, the modelling of the temperature may be represented by Figure 12.

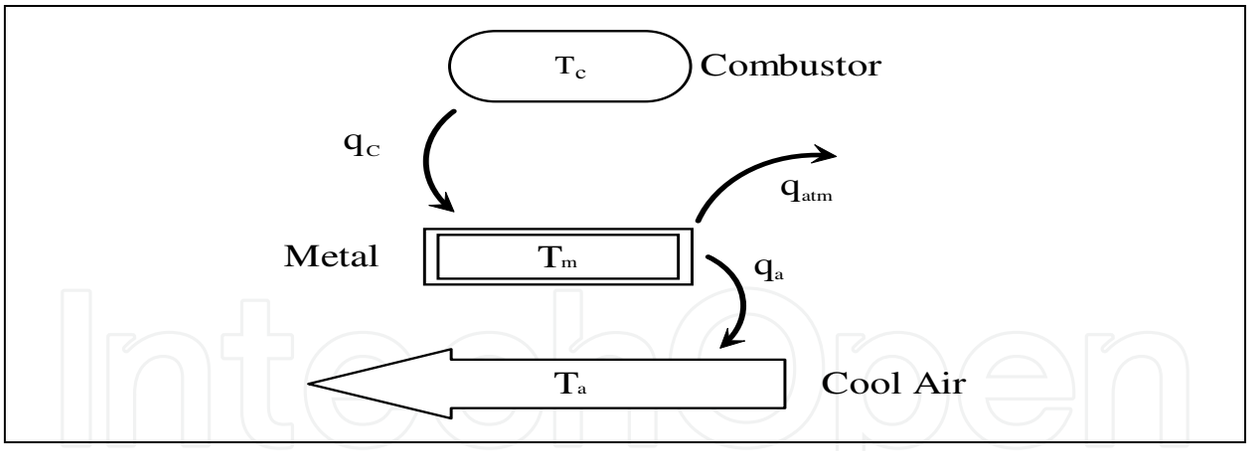


Fig. 12. Conceptual model of the combustor.

The temperature of the metal may be calculated by integration of next equation:

$$\frac{dT_m}{dt} = \frac{q_c - q_a - q_{atm}}{Cp_m\, m_m} \tag{18}$$

The metal heat capacity Cp_m is calculated with a polynomial function of temperature. Note that the term q_{atm} would not exist, depending on the particular position of each modelled metal. The exit air conditions changes due the absorbed heat. For these effects, Equation (11) is used.

Phenomena occurring in other equipments and systems like heat exchangers, electrical motors, generator, electrical network, tanks, etc., are used for other MSS but their formulations are not explained here.

6. Tests and results

The simulator testing was made with 16 detailed operation procedures elaborated by the costumer specialised personnel, namely the "Acceptance Simulator Test Procedures". The tests included all the normal operation range, from cold start conditions to full load, including the response under malfunctions and abnormal operation. In all cases the response satisfied the ANSI/ISA norm.

From the real plant an automatic start up procedure was documented (with a total of 302 variables obtained from the DCS). The tests presented here are the results of an automatic start-up followed by two malfunctions. During these transients no actions of the operator were allowed. In Table 4 a list of the events and the time they happen is presented.

Although they are not any more mentioned in this work, must be noted that all the expected alarms were presented in the precise time. Results include variables concerning the gas turbine power plant in general. The idea is demonstrate that the gas turbine model is capable to reproduce the real plant behaviour in all cases and that its response is adequate for training purposes. In all cases, plant data were available during the first 2780 s where the simulator results fit well.

Time Period (*s*)	**Time Period (*hh:mm:ss*)**	**Event ID**	**Description**
0 – 120	00:00:00 - 00:02:00	1	Simulation is initiated and plant stays in steady state for 5 s, then turbine is turned on in automatic mode and turbine roll-up initiates.
120 – 830	00:02:00 - 00:13:50	2	Combustor ignition is triggered and turbine reaches its nominal speed (3600 *rpm*).
830 – 2790	00:13:50 - 00:46:30	3	Initiates the electricity production up to nominal load (150 *MW*).
2790 – 2970	00:46:30 - 00:49:30	4	The plant is kept producing nominal load.
2970 – 3000	00:49:30 - 00:50:00	5	Progress malfunction of low efficiency in the combustor up to its final value (50% of severity).
3000 – 3500	00:50:00 - 00:58:20	6	Simulator runs without external changes, controls try to stabilise plant.
3500 – 3680	00:58:20 - 01:01:20	7	Progress malfunction of pressure loss in the delivery line of gas fuel up to its final value (4082 *kPa*).
3680 – 4200	01:01:20 - 01:10:00	8	Simulator runs without external changes, controls try to stabilise plant.

Table 4. Description of the programmed events for the test.

In Figure 13, the combustor pressure and the gas delivery pressure, an external parameter where the operator has no control, are presented on the *y* axis. The gas delivery pressure is measured in a pressure controlled header where the gas is stored from a duct that delivers the gas continuously.

Figure 13 shows how the gas delivery pressure changed with a ramp between the 3500 *s* and 3680 *s*. The behaviour of the combustor pressure may be explained as follows:

Event ID 4. The pressure stabilises.

Event ID 5. The pressure drops because the combustion is affected and the temperature in the combustor descents too.

Event ID 6. Pressure arises due the effect of the gas control valves that treats to keep the load of the plant by allowing more gas flowrate to the combustor.

Event ID 7. The pressure drops because the effect of the decreasing of the delivery pressure is greater than the effect of the gas control valves treating to keep the load. At about 3660 s the pressure increases and then descents because the aperture of the gas oscillate due the control algorithm.

Event ID 8. The pressure decreases lightly trying to reach a new, and final, steady state because the gas control valves tend to stabilise their aperture.

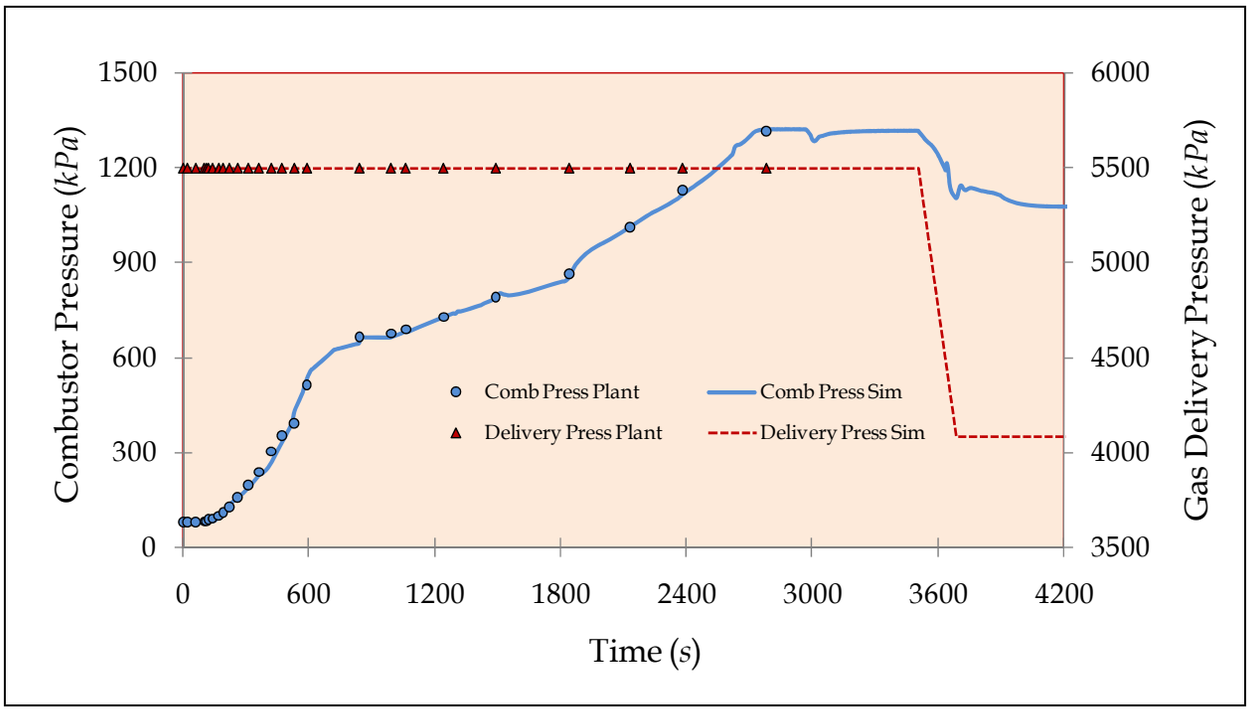


Fig. 13. Combustor pressure and gas delivery pressure

In Figure 14, the fuel gas flowrate and the apertures of two (A and C) of the gas control valve apertures are presented on the *y* axis. There exist four gas control valves, one for the pilots and three more that distribute the flow around the combustor inlet nozzles. All they open in a prefixed sequence and their function is to control the turbine speed and the produced electrical power.

The behaviour of the gas control valves dynamics and fuel gas flowrate during the malfunctions transients are:

Event ID 4. The apertures and the fuel gas flow remain stable.

Event ID 5. The apertures increase their value trying to compensate the load descending due the losing of electrical power because of the loss of combustion efficiency. The gas flowrate increases following the aperture of the gas control valves.

Event ID 6. The gas control valves adjust their value and control the load. The gas flowrate grows slightly according the gas control valves aperture.

Event ID 7. The gas control valves try to keep the load. At about 3660 s the gas control valves has a transient (open suddenly) but the control detects this abrupt change and limits the valve apertures producing a slight transient in the apertures. The gas flowrate descents because the gas control valves are not able to keep the load. The malfunction is too severe. At about 3660 s the gas flow follows the valves transient.

Event ID 8. The control algorithm allows decreasing the load and stabilise the apertures and the gas flow. The plant tends to a new steady state.

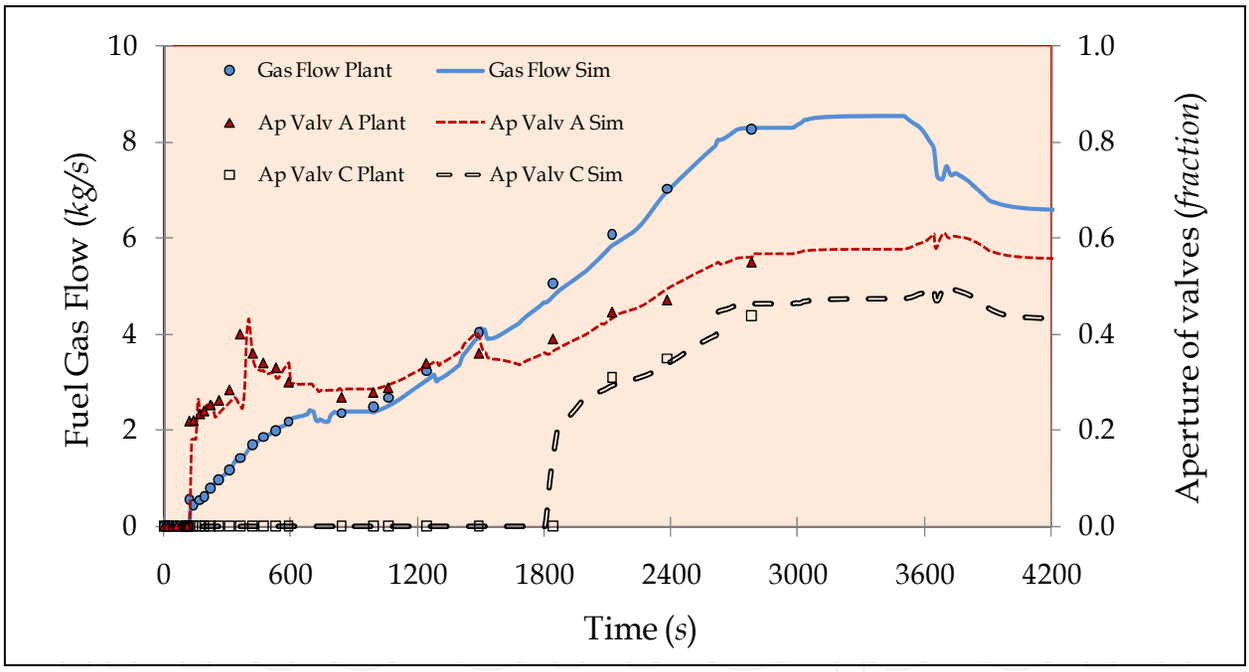


Fig. 14. Combustor pressure and gas delivery pressure

The exhaust temperature and the produced electrical charge by the generator are presented in Figure 15. The results may be summarised as follows:

Event ID 4. The exhaust temperature and load are in steady state.

Event ID 5. The exhaust temperature and load drop because the combustion is affected and the gas control valves do not respond immediately.

Event ID 6. The exhaust temperature goes up due the effect of the gas control valves that treats to keep the electrical power by opening and forcing more gas flowrate to the

combustor. The load recovers its original nominal value due the control by the gas control valves.

Event ID 7. The exhaust temperature drops. The effect of the malfunction is more important than the effect of the gas control valves. At about 3660 s the exhaust temperature has a transient because the gas control valves aperture behaviour. The load drops because the malfunction of losing delivery pressure that cannot be nullified by the gas control valves. At about 3660 s the load oscillates due the gas control valves aperture behaviour.

Event ID 8. The exhaust temperature and load tend to stabilise according the gas control valves position.

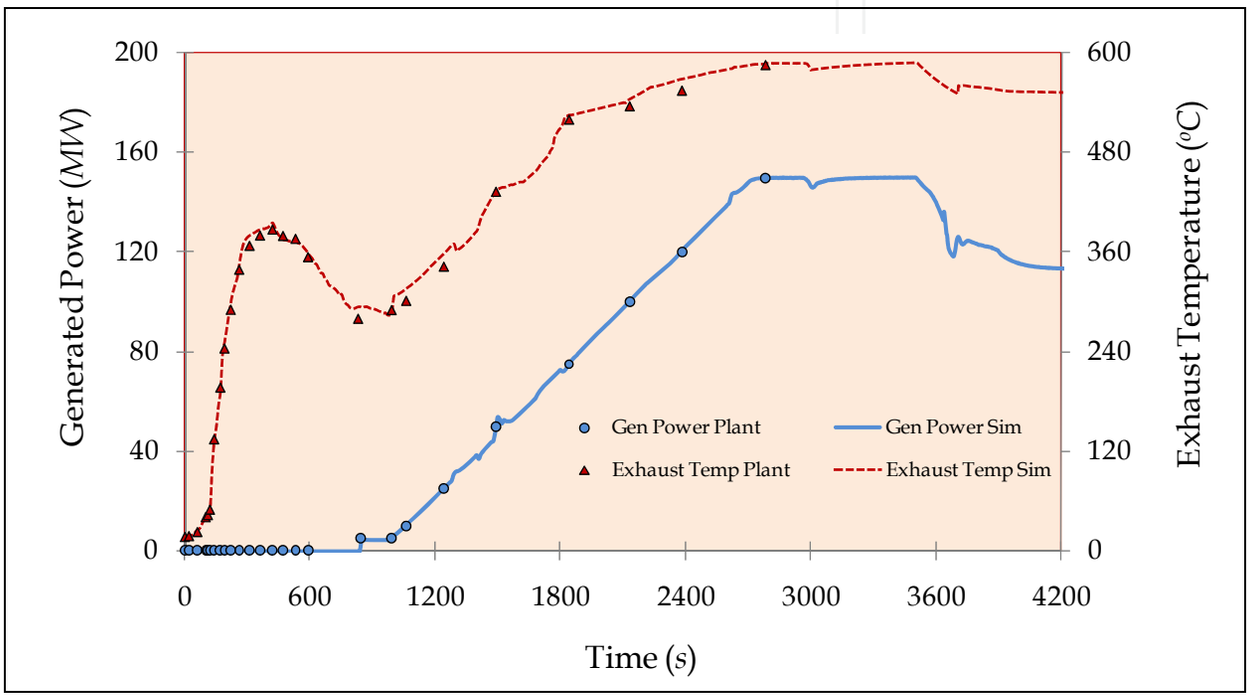


Fig. 15. Combustor pressure and gas delivery pressure

7. Conclusion

The convenience of the use of simulators for operators' training has been proved since long time ago.

The gas turbine simulator presented is a replica, high-fidelity, plant specific simulator for operators training.

The simulator was tested in all the operation range from cold start to 100% of load and fulfils the performance specified by the client, including a comparison of its results with plant data. It was tested and validated by the client itself (personnel having experience in the combined cycle power plant operation and in the use of simulators for qualification). This simulator presently is being used for training of CFE Turbo Gas power plant operators.

The project was designed and satisfactorily finished by following a methodology assuring the ending on time and with the goals properly accomplished. The *MAS* proved to be a developing platform as well as the final simulator platform.

The results confirmed that the simulator methodology and modelling approach is appropriate to develop a training device.

8. Acknowledgment

The GT simulator was successfully finished thanks to the endeavour, unconditional and professional work of researchers and technicians of the IIE as well as the good co-operation of operators, trainers and support personnel of the client. The simulator was developed with the financial support of CFE.

9. Acronyms

AE - Algebraic Equations
ANSI - American National Standards Institute
CFE - Mexican Utility Company
CCS - Combined Cycle Simulator
DCS - Distributed Control System
DLN - Dry Low NOx
GT - Gas Turbine
HRSG - Heat Recovery Steam Generation
IC - Instructor Console
IG - Ideal Gas
ISA - International Standardization Association
IPD - Interactive Process Diagrams
IIE - Electrical Research Institute
MAS - Simulation Environment
MSS - Model of a Simulated System
ODE - Ordinary Differential Equations
PX - Perfect Combustion
PC - Personal Computer
ProTRAX – Commercial Power Plant Simulation Software
SAMA - Scientific Apparatus Makers Association
GSACyS - Advanced Training Systems and Simulation Department
TCP/IP - Transmission Control Protocol/Internet Protocol
VisSim - Visual Solutions Inc.

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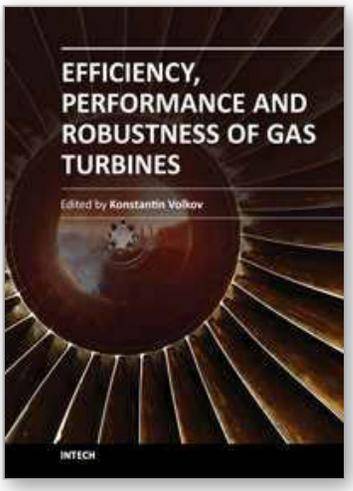
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Efficiency, Performance and Robustness of Gas Turbines

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A wide range of issues related to analysis of gas turbines and their engineering applications are considered in the book. Analytical and experimental methods are employed to identify failures and quantify operating conditions and efficiency of gas turbines. Gas turbine engine defect diagnostic and condition monitoring systems, operating conditions of open gas turbines, reduction of jet mixing noise, recovery of exhaust heat from gas turbines, appropriate materials and coatings, ultra micro gas turbines and applications of gas turbines are discussed. The open exchange of scientific results and ideas will hopefully lead to improved reliability of gas turbines.

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