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# Gas Turbine Power Plant Modelling for Operation Training

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## 1. Introduction

Of the \$11.4 billion worth of non-aviation gas turbines produced in 2008, \$9.6 billion—more than 80 percent—were for electrical generation (Langston, 2008). Particularly, in Mexico, about 15% of the installed electrical energy (no counting the electricity generated for internal consuming by big enterprises) is based on gas turbine plants (CFE web page), either working alone or in combined cycle power plants (and 8% produced directly by gas turbines) that offers an important roll in improving power plant efficiency with its corresponding gains in environmental performance (Rice, 2004).

The economical and performance results of a power plant, including those based on gas turbines, are directly related to different strategies like modernisation, management, and, in particular, the training of their operators. Although the proportion that corresponds to the training is difficult to be assessed, there exists a feedback from the plant's directors about improvement in speed of response, analysis of diverse situations, control of operational parameters, among other operator's skills, due to the training of the operation personnel with a full scope simulator. In general, all these improvements lead to a greater reliable installation. The Comisión Federal de Electricidad (CFE<sup>1</sup>, the Mexican Utility Company) generates, transmits, distributes and commercialises electric energy for about 27.1 millions of clients that represent almost 80 millions of people. About one million of new costumers are annually added. Basically, the infrastructure to generate the electric energy is composed by 177 centrals with an installed capacity of 50,248 MW (the CFE produces 38,791 MW and the independent producers 11,457 MW).

The use of real time full scope simulators had proven trough the years, to be one of the most effective and confident ways for training power plant operators. According to Hoffman (1995), using simulators the operators can learn how to operate the power plant more efficiently during a lowering of the heat rate and the reducing of the power required by the auxiliary equipment. According to Fray and Divakaruni (1995), even not full scope simulators are used successfully for operators' training.

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<sup>1</sup> Some acronyms are written after their name or phrase spelling in Spanish. A full definition of the used acronyms in this chapter is listed in Section 13.

The Simulation Department (SD) belongs to the Electrical Research Institute (IIE) and is a group specialised in training simulators that design and implement tools and methodologies to support the simulators development, exploiting and maintenance.

In 2000 the CFE initiated the operation of the Simulator of a Combined Cycle unit (SCC) developed by the IIE based on ProTRAX, a commercial tool to construct simulators. However, because there is no full access to the source programs, 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: the gas-turbine part and the steam-heat recovery part. In this chapter the gas-turbine simulator development and characteristics are described.

## 2. Modelling approaches and previous works

There is not a universal method to simulate a process. The approach depends on the use the model will be intended for and the way it is formulated. A model may be used for different purposes like design, analysis, optimisation, education, training, etc. The modelling techniques may vary from very detailed physical models (governing principles) like differences or finite elements, to empirical models like curves fitting, in the extremes, with the real time modelling approach (for operators' training) somewhere in the middle. In fact there would be a huge task trying to classify the different ways a model may be designed.

Here, deterministic models of industrial processes are considered (ignoring the stochastic and discrete events models). The goal is to reproduce the behaviour of, at least, the variables reported in the control station of a gas turbine power plant operator in such a way the operator cannot distinguish between the real plant and the simulator. Thus, this reproduction may be made considering both, the value of the variables and their dynamics. The approach was a sequential solution with a lumping parameters approach (non-linear dynamic mathematical system based on discrete time). A description of the technique to formulate and solve the models is explained below in this chapter.

To accomplish with the described goal, the "ANSI/ISA S77.20-1993 Fossil-Fuel Power Plant Simulators Functional Requirements" norm was adopted as a design specification.

The models for operation training are not frequently reported in the literature because they belong to companies that provide the training or development simulators services and it is proprietary information (see, for example, Vieira *et al.*, 2008). Besides, Colonna & van Putten (2007) list various limitations on this software. Nevertheless, a comparison between the approaches of the IIE and other simulators developer was made, showing the first to having better results (Roldán-Villasana & Mendoza-Alegría, 2006).

Some gas turbine models have been reported to be used in different applications. A common approach is to consider the work fluid as an ideal gas. All the revised works report to have a gas turbine system like the presented in Figure 1.

A dynamic mathematical model of a generic cogeneration plant was made by Banetta *et al.* (2001) to evaluate the influence of small gas turbines in an interconnected electric network. They used Simulink as platform and they claim that the model may be utilised to represent plants with very different characteristics and sizes, although the ideal gas assumption was used, the combustor behaves ideally and no thermodynamic properties are employed.

Kikstra & Verkooijen (2002) present a model based on physical principles (very detailed) for a gas turbine of only one component (helium). The model was developed to design a control system. No details are given concerning the independent variables. The model validation was performed comparing the results with another code (Relap).

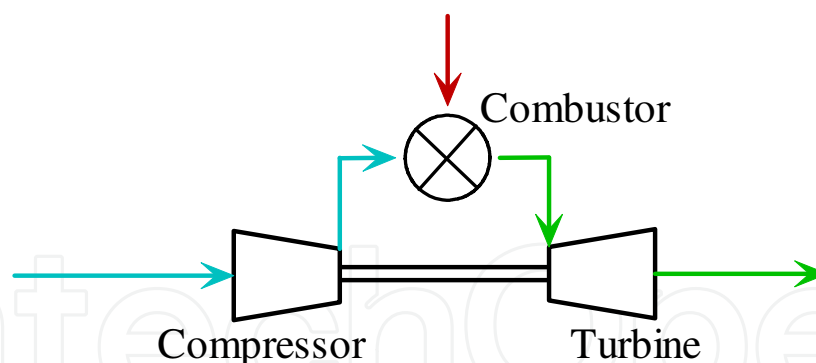


Fig. 1. Typical simplified gas turbine representation.

Ghadimi *et al.* (2005) designed a model based on ideal gas to diagnostic software capable of detecting faults like compressor fouling. The combustion was considered perfect and no heat losses were modelled. The fouling of the compressor was widely studied. No information was provided regarding the input variables.

Jaber *et al.* (2007) developed a model to study the influence of different air cooling systems. They validated the model against plant data. An ideal gas model was considered and the gas composition was not included. The input data were the ambient conditions and the air cooling system configuration. The combustion was simulated with a temperature increase of the gas as a function of the mass flow and the fuel high heating value.

A model for desktop for excel was elaborated by Zhu & Frey (2007) to represent a standard air Brayton cycle. The combustor model considers five components and the combustion reaction stoichiometrics with possibilities of excess of oxygen. Instead using well known thermodynamic properties, the output temperatures of the turbine are a second degree equation in function of the enthalpy. The inputs are variables like efficiencies, some pressure drops, temperatures, etc. This approach is not useful for a training simulator.

A model to diagnose the operation of combined cycle power plants was designed by González-Santaló *et al.* (2007). The goal was to compare the real plant data with those produced by a model that reproduces the plant variables at ideal conditions. The combustor was modelled considering a complete combustion like a difference between the enthalpy of formation of the reactants and the combustion products. Compressors and turbines take into account the efficiencies (adjusted with plant results) and the enthalpies of the gases (but no information was provided how the enthalpies are calculated as a function of measured plant data).

Kapron & Wydra (2008) designed a model based on gas ideal expansion and compression to optimise the fuel consumption of a combined cycle power plant when the power has to be changed by adjusting the gradient of the generated power change as a function of the weather forecast. In the conclusions the authors point that the results have to be confirmed on the real plant and that main problem is to develop highly accurate plant model.

Rubechini *et al.* (2008) simulated a four stage gas turbine using a fully three-dim, multistage, Navier-Stokes analyses to predict the overall turbine performance. Coolant injections, cavity purge flows and leakage flows were included. Four different gas models were used: three based on gas ideal behaviour (the specific heat  $C_p$  evaluation was the difference among them) and one using real gas model with thermodynamic properties (TP) from tables as basis of the modelling. The combustion was not simulated. The conclusion was that a good model has to reproduce the correct thermodynamic behaviour of the fluid.

Even when detailed modelling of the flow through the equipment, heat transfer phenomena and basing the process on a temperature-entropy diagram, the ideal gas assumption was present (Chen *et al.*, 2009). In this case the gas composition was neglected, (considering only an increase of the temperature) and the model, designed for optimisation, runs around the full load point.

Watanabe *et al.* (2010) used Simulink to support a model to analyse the dynamical behaviour of industrial electrical power system. An ideal gas approach was used. The governor system model and a simple machine infinite bus were considered (with an automatic voltage regulator model). The model was validated against real data. No details of the combustor model are mentioned.

None of the works revised here, mentioned anything about real time execution. In the present work, the total plant was simulated, including the combustion products and all the auxiliary systems to consider all the variables that the operator may see in his 20 control screens and all the combinations he desires to configure tendency graphs. For example, the set compressor- combustor -turbine was simulated considering the schematic presented in Figure 2.

The real time execution that is required for a training simulator is accomplished by the IIE simulator.

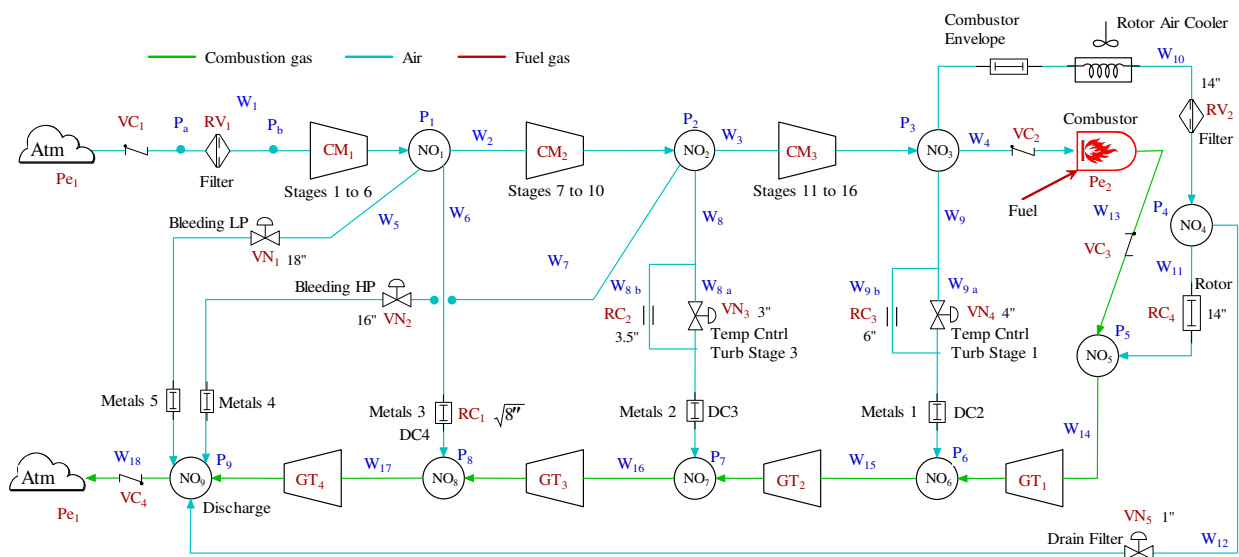


Fig. 2. Schematic gas turbine-compressor-combustor diagram.

3. The importance of training based on simulators

Some of the significant advantages of using training simulators 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 plant events; a broader range of personnel can receive effective training, and eventually, high standard individualised instruction or self-training (with simulation devices designed with these capabilities in mind).

A cost benefit analysis of simulators is very difficult to be estimated; especially because “what would have happened if...” situations should be addressed. However, in a classical study made at fossil fuel power plants simulators (Epri, 1993) there are identified benefits of simulators in four categories: availability savings, thermal performance savings, component



life savings, and environmental compliance savings. It is estimated a payback of about three months. Most often, the justification for acquiring an operator training simulator is based on estimating the reduction in losses (Hosseinpour & Hajihosseini, 2009).

This is easy to probe for high-capacity plants where savings approach millions of dollars for a few days of lost production. Justification also comes from the ability of the simulator to check out the automation system and provide operators with a better understanding of a new process. With greater exposure to the simulator, operators gain the confidence to bring the plant up and running quicker, thus shortening startups significantly and improving the proficiency of less-experienced operators in existing plants. Specifically in Mexico, in a period of 14 years, the use of simulators for operators' training has estimated savings of 750 millions dollars for the power plants (Burgos, 1998).

In Mexico exist three training centres based on simulators: the Laguna Verde Nuclear Power Plant Training Centre, the Geothermal Training Centre, and the National Centre for Operator's Training and Qualification (CENAC), the three of them belong to CFE and have infrastructure developed by the IIE.

Roldán-Villasana *et al.* (2006) show that in the Geothermal Training Centre, according to their statistics for the Cerro Prieto generation plants, the number of trips due to human errors and also the percentage of this kind of trips regarding the total numbers of trips have been diminishing through time since 2000 when the Centre began its training program. The operational cost of the training centre is inferior to the cost of the non generated energy because of trips due to human errors (considering only Cerro Prieto power plants).

The CENAC, a class world company, is the main centre in Mexico where the training of the operation personnel based on simulators is achieved. This centre attends people that work in fuel fossil generation plants, including combined cycle and gas turbine. Also trains operational workers of the independent producers (that base their production in combined cycle plants).

The CENAC receives in periodical basis information (retrofit) from its users that allows the improvement and development of new training technologies, considering from adjustments on their training plans to the changes on the scope or development of new simulators to meet the particular needs of the production centres.

The CENAC's commitment is provide excellent services, ensuring to the producers high levels of quality training not only within the technical areas but in all their processes:

- To guarantee, within a competency framework and updated technology, the continuous electricity service, in terms of quantity, quality and price, with well-diversified sources of energy.
- To optimize the utilization of their physical, commercial, and human resources infrastructure.
- To provide an excellent service to its clients.
- To protect the environment.
- To promote the social development.
- To respect the values of the population who live in the new areas of electrification.

The SD has developed diverse work 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. Tables 1, 2 and 3 summarise the development indicating the year they were delivered to the costumers.

| Computer Based Training Systems  | Year |
|--|------|
| Computer-Based Training System Web Version                                   | 2003 |
| Substation Operator System Training Simulator with a Static Vars Compensator | 2005 |
| Computer Based Training System by Internet.                                  | 2007 |
| Virtual Reality System for the Transmission Lines Maintenance Personnel      | 2008 |

Table 1. Computer based training systems developed by the IIE.

| Testing Equipment Stimulated Simulators                                    | Year |
|--|------|
| Real-time Simulator for Synchronous machines SITIRAMS I.                   | 1995 |
| SITIRAMS II y III.   | 1996 |
| Update of the Simulator System for Tests of Excitation                     | 2005 |
| Expanding the Applications of the Simulator System for Tests of Excitation | 2008 |
| Simulation Module to Test Hydraulic Governors Responses                    | 2008 |

Table 2. Testing Equipment Stimulated Simulators developed by the IIE.

Present and near future developments include: a scope extension of the virtual reality system for the transmission lines maintenance personnel; duplication of the simulator system for tests for speed control and voltage regulator; national network simulation for the simulator system for tests for speed control and voltage regulator; simulator for training of the operators of a generator experimental rig; module for malfunction analysis of simulated equipments; training centre of hydrocarbon process (with at least eight full scope simulators); and simulators maintenance and clients support.

4. Reference plant

In order to have a comparison point, all the simulators developed by IIE have a reference plant. For this particular simulator the unit 5 of the power plant “El Sauz”, located in Querétaro, in the middle of the Mexican territory, was selected as the reference plant. The choice of this plant was based on the geographical proximity of the plant with the CENAC and IIE installations (to optimise the information compilation) and the availability of the design and operational data. In the plant, the used fuel is natural gas provides by PEMEX to produce a nominal electric power of 150 MW. The plant is a pack generation unit Econopac 501F from Westinghouse. This unit is formed for the gas turbine, the generator and the auxiliary systems, and uses a system of low nitrogen oxide emissions DLN2. In Figure 3 a general view of a gas turbine power plant is presented.

The plant was designed to operate in simple cycle with natural gas only. The primary equipment consists of a combustion turbine which impulse the hydrogen-cooled generator. The gas compressor-turbine system handles the fuel into a stream of compressed air. It has an upstream air axial flow compressor mechanically coupled to a downstream turbine and a combustion chamber in between. Energy is released when compressed air is mixed with fuel and it is burned in the combustor. The resulting gases are directed over the turbine's blades, spinning the turbine, and mechanically powering the compressor and rotating the generator. Finally, the gases are passed through a nozzle, generating additional thrust by accelerating the hot exhaust gases by expansion back to atmospheric pressure.

| Simulators for Operators' Training                                  | Year |
|---|------|
| Simulator I of a 300 MW Thermal-Electric Units                      | 1984 |
| Simulator of the Collective Transport System (Metro) of Mexico City | 1991 |
| Laguna Verde Nuclear Power Plant Simulator                          | 1991 |
| Partial Scope Simulator for Turbine Rolling Operations              | 1993 |
| Simulator of a 350 MW Units   | 1994 |
| Simulator of a 110 MW Geo Thermal-Electric Unit                     | 2003 |
| Simulator of a 350 MW Dual Unit (Coal and Fuel)                     | 2006 |
| Simulator of the Systems of a 300 MW Thermal-Electric Unit          | 2006 |
| Simulator of Thermal-Electric Units Based on Screens                | 2006 |
| Simulator of a 25 MW Geo Thermal-Electric Unit                      | 2006 |
| Hydrocarbon Processing Simulator Prototype of a PEP Platform        | 2006 |
| Gas Turbine of a 150 MW Power Plant Simulator                       | 2007 |
| Combined Cycle 450 MW Power Plant Simulator                         | 2009 |
| Simulator of a Dual Unit with Operation Tracing                     | 2009 |
| Simulator of a Combined Cycle Unit with Operation Tracing           | 2009 |
| Simulator for Boilers Analysis                                      | 2009 |
| Graphic System for the Developments of Simulators                   | 2009 |

Table 3. Simulators for Operators' Training developed by the IIE.



Fig. 3. General view of a gas turbine power plant.



Other plant systems that support the open cycle are: heating; ventilation and air conditioning; fire system; electrical distribution; equipment for excitation; mechanical package; lubrication oil; sealing oil of the generator; generator cooling (water/glycol); fuel gas; compressor water wash; electric turbine starting; compressed air; instrument and control air; combustor; and generator cooling air.

The plant is controlled by a Siemens TelepermXP (TXP) Digital Control System.

## 5. Configuration of the simulator

### 5.1 Hardware configuration

The gas turbine simulator consist of four PC interconnected through a fast Ethernet local area network. Each PC has a mini-tower PentiumDTM processor with 3.6 GHz, 1GB of RAM memory, 40GB HD, and Windows XP as operating system. Figure 4 shows a schematic of this architecture.

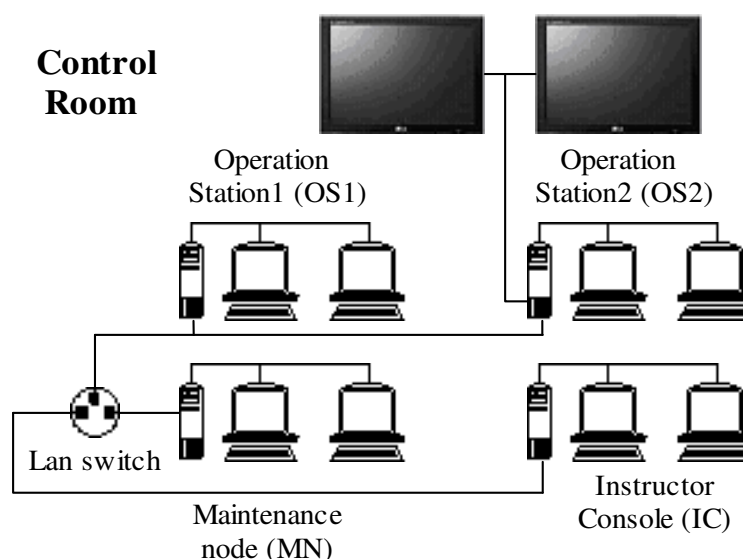


Fig. 4. Hardware architecture of the gas turbine simulator.

From the Instructor Console (IC), also named simulation node, the simulation sessions are initiated and guided. It has two 20" flat panel monitors. There exists two Operators' Stations (OS) that replicate the real control stations from the plant. The trainee uses four 20" monitors and two 54" screens to manage and control the simulated power plant. There is an additional PC, the maintenance node (MN), that is used 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. Also it is used as a backup of the IC. Figure 5 shows the real simulator architecture (without the MN) during a training session where the IC and the instructor appear in the first plane and the OS and two operators are at the rear.

### 5.2 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<sup>2</sup>), the development

<sup>2</sup> The simulation environment is proprietary software of the IIE. Also they are the generic models. The internal reports that sustain these works are not referenced here.



Fig. 5. Training session in the gas turbine simulator.

platform, has three main parts (the real time executive, the operator module, and the instructor console module). Each of these modules is hosted in a different PC, and they are communicated through a TCP/IP protocol. All the modules of the simulation environment are programmed with C# (Visual Studio), with the exception of the Flash applications. The MAS was designed as a general tool for the SD to develop simulators. The MAS is a very useful software that acts like a development tool and like the simulator man-machine interface (MMI). The MAS basically consist of three independent but coordinated applications: the real time executive, the operator module, and the instructor console.

*Real Time Executive*

The real time executive coordinates all simulation functions; it is constituted for six modules according Figure 6.

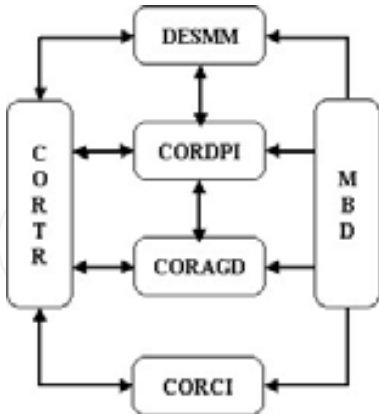


Fig. 6. Diagram of the real time executive application.

1. DESMM Mathematical model launcher. Its function is to manage the execution sequence of each mathematical model. These models may be executed in a parallel scheme, with a distributed architecture of PCs or with multi-core equipment. For the case of the gas turbine simulator, the models run sequentially.
2. CORDPI Manager module for interactive process diagrams (IPD). This module executes the IPD, provides the values of the variables, and receives/responds from/to the

- control commands messages of the operator console. Other functions of the module are: to control the alarms system, to control the historical trends, to call the methods of each IPD component (valve, pump, etc), refresh each IPD periodically, and to coordinate the sequence of events in the operation consoles.
- 3. CORAGD Manager module for the global area of mathematical models. It is composed of a group of methods to initialise the global area of state variables belonging to the mathematical models. These values are located in a table loaded in memory for a fast access. This module is also in charge of synchronise the access of the table when parallel process attempt to connect it.
  - 4. CORCI Manager module for the instructor console. This module receives/responds the commands from/to the instructor console (stop, freeze, malfunctions, etc.) and executes the tasks in a synchronised way during a simulation cycle. With the TCP/IP communication, this module may be hosted in a different PC of the instructor console.
  - 5. MBD Data base driver. It is devoted to get, from each data base table, all the required information by the executive system.
  - 6. CORTR Main module. This is the main module of the simulator and coordinates all the functions of the mentioned modules.

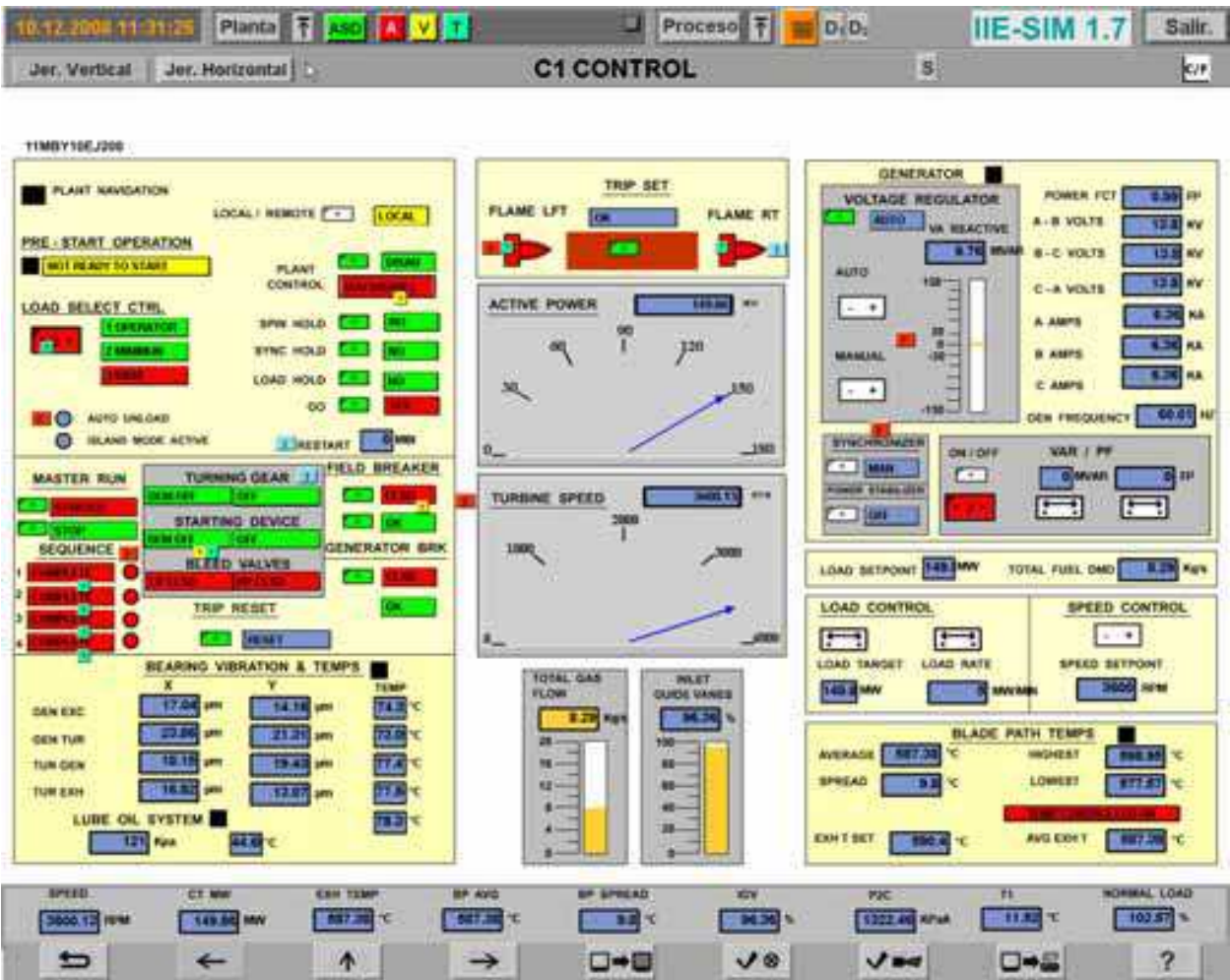


Fig. 7. Main display of the operator console.





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 operator (student) perceives his actions and simulator response in a very close way as it happens in the actual plant.

#### *Instructor Console*

This module is the MMI of the instructor and has a main menu of functions which is presented in Figure 9.



Fig. 9. Main display of the instructor console.

The IC is constituted by five modules:

1. A main module to execute all the tasks related with the graphical interface of the instructor (DPI).
2. A module to retrieve the static information of the simulation session, for instance, malfunctions, remote actions, etc. (CONINS)
3. A module to store information in a data base using SQL (DBSM).
4. The mathematical models.
5. A module to communicate the instructor console with the real-time executive (Console Application).

In the IC the simulation session is controlled. The functions of the IC may be invoked from the list menu of the display with the mouse pointer; the functions are popped up to be selected. However, thanks that the instructor has a modified copy of the operator control screens where may follow the actions of the students some of them may be accessed from the IPD by special icons. In Section 6, the functions of the IC are fully described.

### **5.3 Processes and control models**

To simulate the gas turbine power plant, this was divided into a set of systems (procuring these coincide with the real plant systems). A modelled system is a mathematical representation of the behaviour of the variables of the real system of the gas turbine gas power plant. The model of a simulated system (MSS), once installed in the simulator, respond to the operator's action in the same way that the real systems do (in tendency and time). Typically, the final equations are stated for each MSS system in such a way the set of equations of one MSS is mathematically independents of the set of equations of any other MSS.

Now, for each MSS the algebraic equations have to be solved simultaneously if necessary but they are mathematically independent of their differential equations. For the development of simulators, the IIE has adapted different solution methods for both, linear and non-linear equations (Newton-Raphson, Gaussian elimination and bisection partition search) and are used depending on the structure of each particular model.

The differential equations are numerically solved with one of the available methods (Euler, trapezoidal rule with one or two corrections). The integration step of the equations depends on the dynamical response of the system. The selection of the proper integration method for



a MSS is made running the model under a multistep multirate method to determine its “critical transient” (that, where the method reports more potential numerical instabilities). A numerical analysis is made on that point to determine the final method and step that the MSS should use (this analysis involves the calculation of Jacobian matrixes, the calculation of eigenvectors and eigenvalues and its relation with the state variables). Each execution second (cycle) of the simulator was divided into ten periods of 0.1 s (frames). Thus, a particular model could be executed with an integration step of 0.1 s, 0.2 s, 0.5 s or 1 s. The sequence matrix (defined by the user) indicates the precedence of execution of the models (scheduler), the integration method and integration step of each model, and the initial period of execution of each model for each cycle.

The sequence matrix was defined using an algorithm to find an appropriated execution order. The algorithm considers the number of inlet and outlet variables between the models and the integration step to minimize the probability of mathematical instabilities.

For example, if a simulator had four MSS, let say M1, M2, M3 and M4 and three integration methods, a sequence matrix as defined in Table 4, means that model M2 is the first in being executed in the first frame (it is integrated with the method 1 and has a step of 0.1s), followed by model M1 (method 3, step 0.2s); in the second frame model M4 (method 2, step 0.2s) is executed followed by model M2; in the third frame model M3(method 1, step 0.5s) is executed, followed by models M2 and M1; the sequence continues in the same way.

| 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 4. Example of a sequence matrix.

6. Instructor console

This is the main MMI for the instructor, from where the simulation sessions are initiated and guided. From there, the instructor controls and coordinates the scenarios seen by the operator under training. These scenarios could be presented to the operator as a steady state of the plant operation or under any malfunction of a particular system or equipment. To perform his tasks, the IC has a set of functions that may be invoked from the list menu of the display with the mouse pointer; the functions are popped up to be selected. The instructor has a modified copy of the operator control screens, from where can follow the actions of the students. Additionally, in these control screens some of the IC functions may be accessed from the DPI in special icons. An example of the functions displayed by pop-up is presented in Figure 10.

The main functions of the IC are explained in the following sections.

6.1 “CONTROL” menu (Control)

It has the functions that allow the instructor to define the simulator’s status.

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

*Repetition.* A simulation session can be repeated automatically including the actions of the operator and the instructor on the simulator.

*Simulation speed.* Normally, 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. For example, slow thermal processes such as the cooling of the plant after a shut down process can be simulated to occur faster. Also, this option is useful when the trainee has to analyse a fast transient, therefore the simulator may run in a slow way

*Automatic Exercises.* The instructor may create automatic training exercises where initial conditions, malfunctions, and any action are triggered at a specified event or time. They may be stored for their subsequent use.

*Simulation of a single step.* This function activates the simulation for just one simulation step (0.1 s).

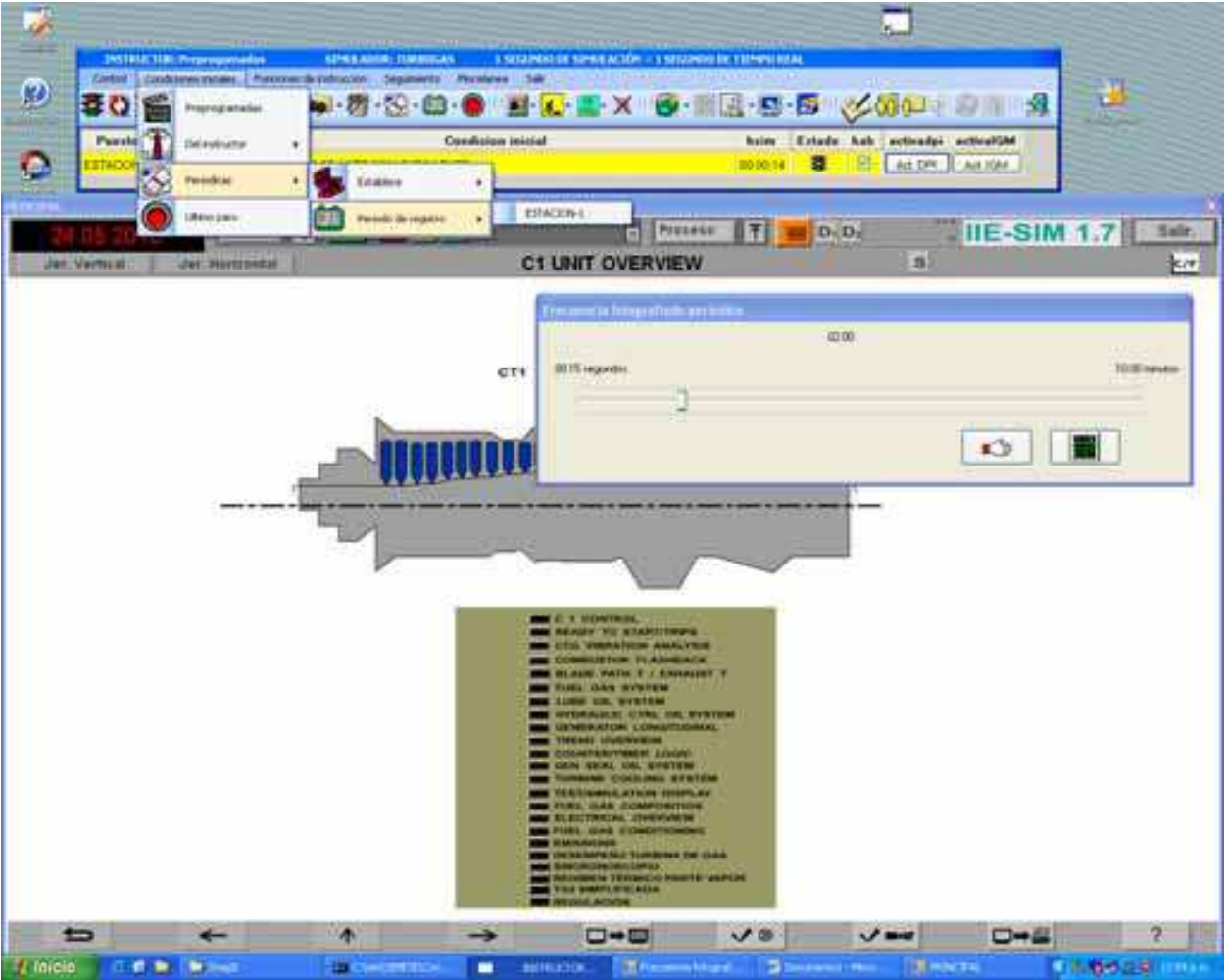


Fig. 10. Example of the functions displayed by pop-up.

6.2 “CONDICIONES INICIALES” menu (Initial conditions)

The initial conditions (ICO) allow: to establish the state of the process at the beginning of the simulation; to create a new ICO from any simulation instant; to rename an ICO; to change the description of an ICO; or to delete an existing ICO.

*Initial Condition.* The instructor may select an initial condition to begin the simulation session, either from the general pre-selected list or from their own catalogue (each instructor has access up to 100 initial conditions of his own). As mentioned above, it is also possible to manipulate the ICO or to record a new one.

The ICO may be one of the next:

*Pre-programmed.* These are the pre-defined ICO, with the main operation states of the simulator, and any instructor can establish them. The client defines how many and which ICO of this kind requires.

*From an instructor.* Every instructor has associated a directory in which can take or register his own ICO.

*Periodicals.* The simulator has an implicit function to register (snapshot) automatically and periodically an ICO. The simulator has a capacity to storage the last twenty snapshots. This function is currently running during a simulation session and the instructor may define the period of time for each snapshot between 15 seconds and 10 minutes; by default it is established in two minutes (see Figure 10).

*From last stop.* When the simulator is running and it is stopped, in an automatic way an ICO is registered. This ICO may be established as initial condition.

### 6.3 “FUNCIONES DE INSTRUCCIÓN” menu (Instruction functions)

The instruction functions allow modify the operation mode of the simulator during a training session. Such modifications may be effected in an instant or with a delay, according the instructor necessities and preferences.

*Malfunctions.* It is used to introduce/remove a simulated failure of equipments. There are 98 malfunctions available. Examples of them are: pumps trips, heat exchanger tubes breaking, heaters fouling, and valves obstructions. For the binary malfunctions (like trips), the instructor has the option of 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 Actions.* 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 effected in the plant by an auxiliary worker. 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.* They allow the instructor to modify the external conditions: atmospheric pressure and temperature (dry and wet bulb), voltage and frequency of the external system, fuel composition, etc.

### 6.4 “SEGUIMIENTO” menu (Tracking)

The simulator has a series of very helpful implements especially during the simulation development: simulate just one step (0.1 s), monitor and change on line the value of selected global variables, and tabulate any list of variables.

*Tabulation.* This function creates a file in ASCII format (in a tabular display) of a list of variables defined in other file created by the user (the first column is always the simulation time). The user may define the total period of time and the frequency of the registration. It generates a results file in ASCII code for the manipulation of the obtained data.

*Values of models variables.* It allows to display and to modify the value of a model on line.

*Monitoring.* With this function it is possible to have a continuous monitoring window for a group of variables on line. It is possible to modify the variables values.

*To create a variables group.* It opens an ASCII window editor to create a file with variables to be tabulated or monitored. The file can be stored for its future use.

*Perturbation of a variable.* It allows defining an initial value to a group of variables.

## 6.5 “MISCELANEOS” menu (Miscellaneous)

This menu contains several auxiliary functions that help to the administration of the instruction sessions of every one of the instructors, in order that everybody has their own accounts and the control of his own simulation sessions.

*Agenda.* This button enables and disables the registration of the operators’ actions on the control screens. The function also registers the action of the instructor in his MMI.

*Switch an instructor.* This function allows changing the instructor account for another without leaving the simulation environment simulation.

*Creation of an instructor account.* With this function it is possible to create a new account for news instructors.

## 7. Modelling methodology

The models of the simulated plant were divided in two groups: the control models and the process models.

### 7.1 Processes

The models are a set of algebraic and differential equations obtained from the application of basic principles (energy, momentum and mass balances). The models were designed to work under a full range of performance. This is from 0% to 100% of load including all the possible transients that may be present during an operational session in the real plant.

The simulator was developed applying a methodology developed by the IIE. In fact, some of the modelling tools (concretely some generic models) were developed and/or adapted during the execution of this project. The methodology may be summarised as:

- a. Information of the process is obtained and classified (system description, system operation guidelines, thermal balances, operational curves of the equipment, operational plant data, etc.).
- b. The information is analyzed and a conceptual model is stated (a functional description of the system).
- c. Simplifications of the system are made obtaining a simplified diagram (showing the simulated equipment with 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.
- d. Main assumptions are stated and justified.
- e. The configuration of the flow and pressure network is obtained and with the design operational point (normally 100% of load) the parameters of pumps, valves and fittings are automatically obtained in a excel data sheet. This sheet is a part of the final documentation and when it is modified, the updating of the simulator may be automatically performed (from excel, global variables, data and code are copied into the programs and data bases of the simulator).

- f. Energy balances are programmed using the required generic models. Again, parameterisation with excel is performed. The calculations of energy balances are programmed following the flow direction and considering possible sets of equations to be solved simultaneously
- g. The Equipments out the limits of the hydraulic network are parameterised (tanks, boilers, condensers, etc.) using predefined excel sheets considering the generic models available in the simulator's libraries or developing the adequate models.
- h. Local tests are performed and, if necessary, adjustments in the models are made. The MAS and its utilities are used for this task. The local tests were performed, i.e. in the MAS the model is run alone and changes in some variables (inputs) are made in order to evaluate the general response of the model. At this time the MAS included the control screens. Eventually, some adjustments in the models were made.
- i. Integration between all the different systems and their controls are performed (the coupling order is an important factor). All models are integrated into the MAS. For the integration, the first model incorporated was the turbine, combustor and compressor model with its associated control. Then the generator and electrical grid was added. The lubrication oil system was next and finally the models of the auxiliary systems (each with its control). The coupling 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 minimize the retarded information (variables). To prove the successful integration of each model added, an operator achieved some actions on the models.
- j. Global test are made with the needed adjustments.
- k. Final acceptance tests are achieved by the final user according their own procedures. The acceptance tests were performed first in the factory and finally in site in both cases with the help of the customer.

## 7.2 Control

The control models acquire and process the actions realized by the operator in the control room by the action on the control screens. As a response, these models generate, via the digital and analogical exits, possible changes of the process models, depending of the general condition of the simulated plan. For example, the control adjusts the demand of the valves to regulate some variables of the processes around a set point fixed by the operator (levels of tanks, pressures, temperatures, etc.).

Most of the controls are part of the distributed control system (DCS) by Siemens-Westinghouse Power Corporation and some of them are local (out of the distributed control system).

For the development of the gas turbine control models the graphics package VisSim was used. The sources of the information were diagrams provided by the CENAC. These diagrams were drawn from the control provider of the real plant that are presented in the format defined by the Scientific Apparatus Makers Association (SAMA).

The IIE determined the use of this package that had all the necessary modules to develop the modules of the control charts and analog logic simulator. The development of control models was carried out in five stages:



- a. *Identification of generic control modules.* Two hundred SAMA diagrams were reviewed and analyzed 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 detected to be developed which are listed in table 5.

| No. | Control Model                    | No. | Control Model           |
|-----|----------------------------------|-----|-------------------------|
| 1   | Prestart and starting logic      | 12  | System DLN control      |
| 2   | Combustor                        | 13  | Rotor cooling control   |
| 3   | Combustor control                | 14  | Simulation/Test         |
| 4   | Lube oil control                 | 15  | VARs/PF control         |
| 5   | Auto-unload control              | 16  | System alarms           |
| 6   | Trip logic                       | 17  | Supervisory turbine     |
| 7   | Generator control                | 18  | Counter and timer logic |
| 8   | Temperature control              | 19  | Air instrument control  |
| 9   | Pilot & stage control            | 20  | Electrical system       |
| 10  | IGV control                      | 21  | Graphic trends          |
| 11  | Flashback temperature monitoring |     |                         |

Table 5. Control models of the gas turbine simulator.

- b. *Detection of the models not included in the DCS.* In the plant some equipments are not included in the DCS. In these cases, the diagram or description of the local controls was sought. When the information was not available, the control diagrams were developed and accorded with the client. Once the diagram was done, the model obtaining procedure was the same that for the SAMA diagrams.
- c. *Generic graphical modelling.* With generic blocks generated in VisSim, containing the functions of the SAMA diagrams, a generic graphics library was integrated to create the analog and logic diagrams into the VisSim environment. Figure 11 shows the generic modules that were developed in VisSim.
- d. *Control Modelling.* Based on the SAMA diagrams the control models of gas turbine plant simulator were developed. The diagrams were transcribed into the VisSim program using the generic modules. Each SAMA control diagram was done into a single VisSim drawing. As an example, Figures 12 and 13 show the diagram of speed control loop in the original SAMA version and in the VisSim drawing.
- e. *Translation from VisSim into C # language.* From control system diagram in VisSim an ANSI C code is automatically generated. Some adjustments to the generated code have to be done with a program developed by the IIE in order to translate the code to C#, which can run in the simulator environment. This application generates the variables definitions that are charged into the simulator database (global variables, remote functions, malfunctions, etc.). The source files of the control models kept in graphic form to facilitate the updates and corrections tests and adjustments. Table 6 presents a part of some C# code obtained from VisSim with the adjustments made by the IIE application.

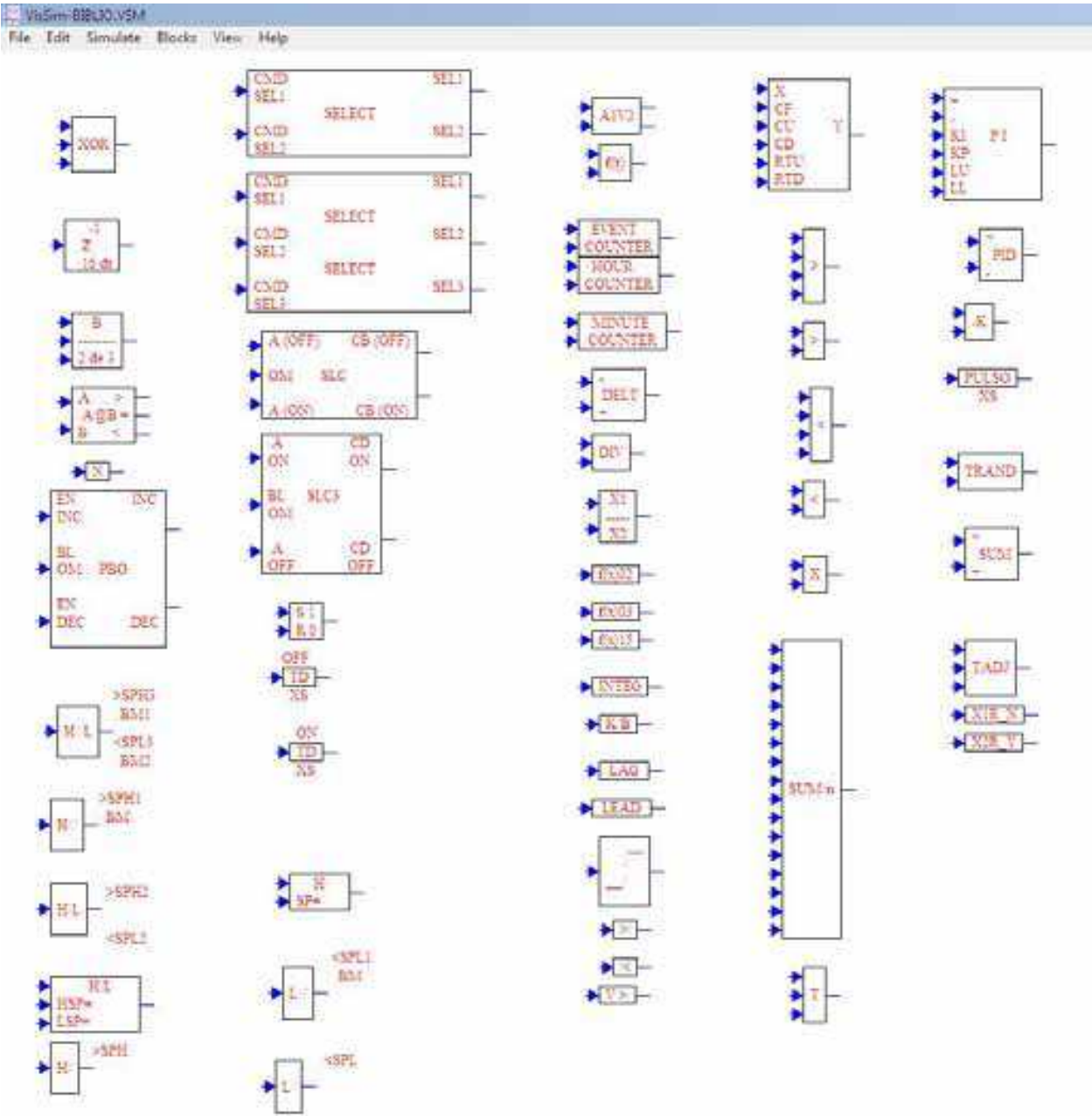


Fig. 11. Generic graphics library for the SAMA diagrams modelling in the VisSim environment.

8. Modelling development

8.1 Simulated systems

The systems that finally are simulated were selected in order to have all the information the instructor needs to train an operator. The main important characteristic of each simulated system is that it is controlled from the main control screens, from the process itself (trough remote functions in the simulator) or from the DCS, and that has an impact on the global plant status.

The systems included in the simulator are (each with its associated control systems): Fuel Gas; Gas Turbine; Compressed Air; Air for Instruments; Lubrication Oil, Control Oil, Water-



Ethylene Glycol, Cooling, Electrical Network; Generator; Generator Cooling with Hydrogen; Turbine (Metals Temperatures and Vibrations); Performance Calculations (Heat Rate and Efficiencies); and Combustor, including the combustor blade path temperatures (with 32 display values), the exhaust temperatures (with 16 displays), the disc cavity temperatures (with 8 displays) and emissions.

8.2 Generic models

The design of generic models (GM) allows reducing the time used to develop a simulator. For the case of a training simulation, a GM constitutes a standard tool with some built-in elements (in this case, routines), which represent a “global” equipment or system and can facilitate its adaptation to a particular case. A GM may be re-used for several applications (either in the same simulator or in different simulators).

```
using System;
using System.Collections.Generic;
using System.Text;
namespace ctrlmodturbogas
{
    unsafe public class Cc3 : inivarmod
    {
        const bool LTRUE= true;
        const bool LFALSE= false;
        public void c3()
        {
            float X0MXLL;
            bool t275;
            float X0YJ;
            bool LLEZ;
            •
            •
            •
            CXLCCS_2121 = (float)100.0;
            CXLCGR1_1903 = (float)0.0;
            CXLCGRS_1713 = (float)500.0;
            CXLCGRS_2442 = (float)100.0;
            CXLCGR1_2442 = (float)0.0;
            LIMIT(C3SPRYJE,CXLCGRS_1903,CXLCGR1_1903);
            LIMIT(C3SPR01E,CXLCGRS_1713,CXLCGR1_1713);
            LIMIT(C3SC001E,CXLCES_2121,*C3SCMXLI);
            LIMIT(C3SPR02E,CXLCGRS_2442,CXLCGR1_2442);
            X0MXLL = *C3SC002L ;
            t275 = (( *C3SPRYJE > (float)500.0)&&(( *C3SPRYJE > *C3SL0YMP )|| *C3SL0YMY ));
            X0YJ = *C3SC001L ;
            LLEZ = *C3SL006L ;
            XVL09_2003 = ( Math.Min(( Math.Max( (float)0.0, *C3SPRYJE ), (float)630.0));
            X0YJ2 = ((( XVL09_2003 >= 0 )&&( XVL09_2003 <= (float)1.0))?( ( XVL09_2003 *
(float)1500.0)+(float)0.0):((( XVL09_2003 > 1 )&&( XVL09_2003 <= (float)15.0))?( ( XVL09_2003 *
(float)7.14286)+(float)1492.86):((( XVL09_2003 > 15 )&&( XVL09_2003 <= (float)135.0))?( ( XVL09_2003 *
(float)5.0)+(float)1525.0):((( XVL09_2003 > 135 )&&( XVL09_2003 <= (float)255.0))?( ( XVL09_2003 *
(float)5.0)+(float)1525.0):((( XVL09_2003 > 255 )&&( XVL09_2003 <= (float)375.0))?( ( XVL09_2003 *
(float)4.58333)+(float)1631.25):((( XVL09_2003 > 375 )&&( XVL09_2003 <= (float)495.0))?( ( XVL09_2003 *
(float)1.66667)+(float)2725.0):((( XVL09_2003 > 495 )&&( XVL09_2003 <= (float)615.0))?( ( XVL09_2003 *
(float)0.416667)+(float)3343.75):(( XVL09_2003 * (float)0.66667)+(float)3190.0)))))))));
            X0SP = ( *C3SPR01E +( LLEZ ? *C3SP007P : X0YJ2 ));
            X0IN = Math.Abs((- X0YJ + X0SP ));
            *C3SC001E = X0API2;
            *C3SC0HXI = CXS6_2528;
        }
    }
}
```

Table 6. Example of C# code generated automatically from the design diagrams.

Fundamental conservation principles were used considering a lumped parameters approach and widely available and accepted empirical relations. The independent variables are associated with the operator's actions (open or close a valve, trip a pump manually, etc.) and with the control signal from the DCS.

#### *Physical Properties*

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

For the water the TP 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 °C and 720 °C (equivalent to 0.18 BTU/lb and 1635 BTU/lb of enthalpy).

The adjustment was performed to assure a maximum error of 1% respecting the reference data; to achieve this it was necessary to divide the region into 14 pressure zones. The functions are applied to three different cases: subcooled liquid saturated and superheated steam. For the saturation region, both the liquid and steam properties are only a function of pressure and they are calculated as follow:

$$(T, h, s) = k_{t,1} + k_{t,2} \sqrt{P} \quad (1)$$

where  $T$  is temperature,  $s$  is entropy,  $k_{t,1}$  and  $k_{t,2}$  are constants to determinate the particular TP and depends of the phase (liquid or vapour).

The densities  $\rho$  of saturated liquid and steam are calculated as:

$$\rho = k_{t,3} + k_{t,4}P + k_{t,5}P^2 \quad (2)$$

For subcooled liquid and superheated steam, the functions are:

$$(T, h, s, \rho) = k_{s,1} + k_{s,2}h + k_{s,3}h^2 \quad (3)$$

where:

$$k_{s,i} = k'_{s,i} + k''_{s,i} \sqrt{P} \quad (4)$$

To ensure an relative error less than 1%, the equations (3) and (4) were slightly modified in some regions of  $P$ .

The functions also calculate  $dTP/dP$  for the saturation region and  $\partial TP/\partial P$  and  $\partial TP/\partial h$  for the subcooled liquid and superheated steam.

The same functions may be used if the independent variables are  $P$  and  $T$ . The calculation is done for finding the unknown variable (or value) from equations (1) to (4).

Note: In all cases  $k_{t,i}$  and  $k_{s,i}$  has different values according to the calculated TP, the pressure region, and the specific point (liquid or steam) where the calculation is made.

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 (for different  $P$  and  $T$  regions).

For this simulator the hydrocarbon TP were applied for the gas fuel, air and combustion products. In this case, the calculation is based in seven cubic state and corresponding states equations to predict the equilibrium liquid-steam and properties for pure fluids and



mixtures containing non polar substances. The validity range is for low pressure to 80 bars. There are 20 components considered that possibly may be form a mixture: nitrogen, oxygen, methane, ethane, propane, n-butane, i-butane, n-pentane, n-hexane, n-heptane, n-octane, n-nonane, ndecane, carbon dioxide, carbon monoxide, hydrogen sulphide, sulphur dioxide, nitrogen monoxide, nitrogen dioxide, and water.

The cubical equations have the following general form (Reid *et al.*, 1987):

$$P = \frac{RT}{\hat{v} - b} - \frac{a}{\hat{v}^2 + u\hat{v}b + wb^2} \quad (5)$$

where  $R$  is the ideal gas constant,  $\hat{v}$  is molar volume, and  $a, b, u, w$ , are constants that in fact determine the precise cubic equation that may be used: Van der Waals, Redlich-Kwong, Soave, Peng-Robinson, Lee-Kesler, Racket (for saturated liquid only), Hankinson-Brost-Thompson (for liquid only), and Ideal Gas. Also may be used the corresponding states equation Lee Kesler:

$$Z^{(0)} = 1 + \frac{B}{V_r^{(0)}} + \frac{C}{(V_r^{(0)})^2} + \frac{D}{(V_r^{(0)})^5} + \frac{C4}{T_r^3 (V_r^{(0)})^2} \left[ \beta + \frac{\gamma}{(V_r^{(0)})^2} \right] \exp \left[ \frac{-\gamma}{(V_r^{(0)})^2} \right] \quad (6)$$

$$Z^{(0)} = \frac{P_r V_r^{(0)}}{T_r}; \quad Z^{(R)} = \frac{P_r V_r^{(R)}}{T_r}; \quad Z = Z^{(0)} + \frac{\Omega}{\Omega_R} (Z^{(R)} - Z^{(0)}) \quad (7)$$

where  $B, C, D, C4, \beta$ , and  $\gamma$  are characteristics (constants), and  $\Omega$  is Pitzer's acentric factor.

For the solution of any of the equations for a gas mixture, the Newton-Raphson method is used.

#### Flows and Pressures Networks

This model simulates any hydraulic network in order to know the values of the flows and the pressures along the system. A convenient approach to represent the network (easy to solve and sufficiently exact for training purposes) is considering that a hydraulic network is formed by accessories (fittings), nodes (junctions and splitters) and lines (or pipes). The accessories are those devices in lines that drop or arise the pressure and/or enthalpy of the fluid (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 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 ( $w$ ):

$$\Sigma w_i - \Sigma w_o = 0 \quad (8)$$

Also, the momentum equation may be applied on each accessory on the flow direction  $x$ :

$$\rho \frac{\partial v}{\partial t} = - \frac{\partial P}{\partial x} - \frac{\partial \tau_{xx}}{\partial x} - \rho v_x \frac{\partial v_x}{\partial x} + \rho g_x \quad (9)$$

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:

$$\Delta P = -L \Delta \tau + \rho g h \quad (10)$$

where the viscous stress tensor term may be evaluated using empirical expressions for any kind of accessories. For example, for a valve, the flowrate pressure drop ( $\Delta P$ ) relationship is:

$$w^2 = k' \rho A p^\zeta (\Delta P + \rho g \Delta z) \quad (11)$$

where the flow resistance is a function of the valve aperture  $A p$  and a constant  $k'$  that depends on the valve itself (size, type, etc.). The exponent  $\zeta$  represents the characteristic behaviour of a valve in order to simulate the effect of 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 a fitting with constant resistance the term  $A p^\zeta$  does not exist. For a pump (or a compressor), this relationship may be expressed as:

$$\Delta P = k_1' w^2 + k_2' w \omega + k_3' \omega^2 - \rho g h \quad (12)$$

where  $\omega$  is the pump speed and where  $k'_i$  (for  $i=1,2,3$ ) are constants that fit the pump behaviour. Note that the density  $\rho$  has a much more influence on a compressor than a pump. Similar equations may be obtained for any other fitting (turbines, filters, piping, etc.).

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:

$$w^2 = k_a \Delta P + k_b \quad (13)$$

Applying equation (8) on each node and equation (13) on each accessory a set of equations is obtained to be solved simultaneously. However, a more efficient way to get a solution is achieved if equation (13) is linearised. To exemplify the linearization approach, equation (13) is selected for the case of a pump with arbitrary numerical values (but the same result may be obtained for any other accessory and any numerical scale). Figure 14 presents the quadratic curve of flowrate  $w$  on the  $x$  axis and  $\Delta P$  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 dismisses 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). This line is represented as:

$$\Delta P = m' w + b' \quad (14)$$

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:

$$\Delta P = m w + b \quad (15)$$

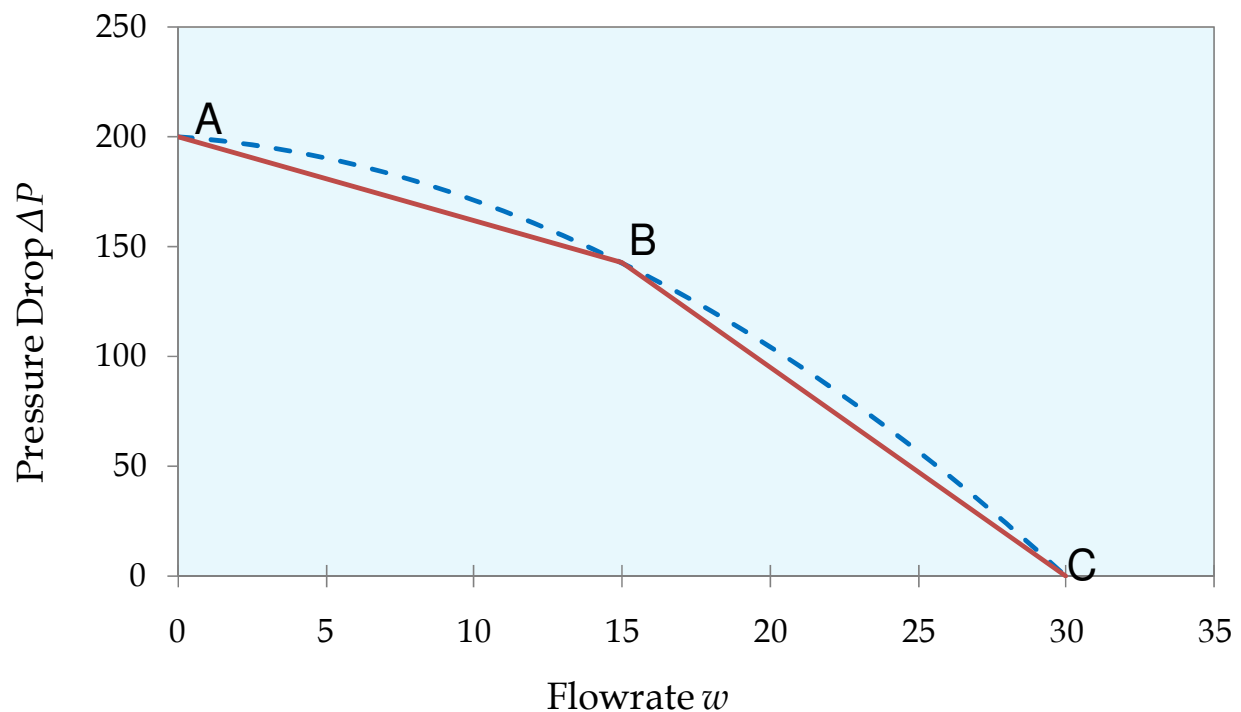


Fig. 14. Linearization of the curve that represent a fitting.

This equation may be arranged as:

$$w = C \Delta P + Z \quad (16)$$

Substituting equation (16) on (8), for each flow stream, a linear equations system is obtained where pressures are the unknowns. The order of the matrix that represents the equations system is equal to the number of internal nodes of the network. Flows are calculated by equation (16) once the pressures were solved.

An active topology of a network is a particular arrangement of the grid that allows flow through their elements. The active topology may change, for instance, if a stream is “created” or “eliminated” of 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 active 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 and that helps the understanding and development of models of simulators for training purposes. In the flows and pressures GM an algorithm to detect the active topology is detected 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) in detail. The procedure seeks the system of equations to identify the sub-systems that can be solved independently.

The valves are considered with an isenthalpic behaviour and the compressor and turbine are calculated as an isentropic expansion and corrected with an 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  $T_e^*$  is calculated at the exhaust pressure  $P_e$  with the entropy inlet  $s_i$ ):

$$f(T_e^*) = s_i(T_i, P_i, c) - s_e^*(T_e^*, P_e, c) = 0$$

(17)

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

$$h_e = \frac{(h_e^* - h_i)}{\eta} + h_i$$

(18)

All other exhaust properties are computed with the real enthalpy and pressure. The efficiency  $\eta$  is a function of the flow through the turbine. The properties at the turbine exit were formulated like the compressor but considering that the work is produced instead of consumed.

To exemplify a flows and pressures network, in Figure 15 the control screen from the OS for the water cooling system of the generator and the hydrogen supply is reproduced. Figures 16 and 17 present the simplified diagrams of the flows and pressures networks of the generator’s cooling water and hydrogen supply, respectively. These simplified diagrams are the basis to parameterise the flows and pressures GM according the methodology developed by the IIE.

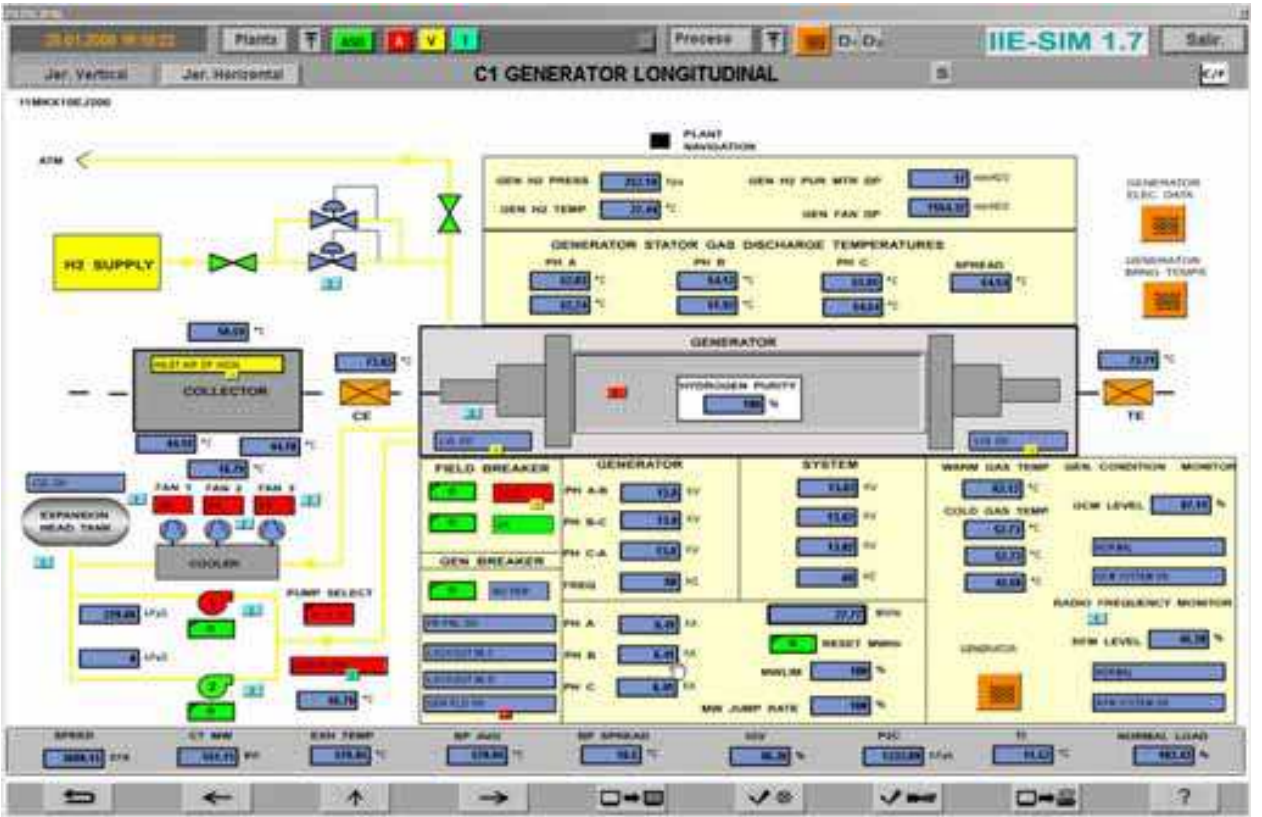


Fig. 15. Control and display screen of the generator cooling water and hydrogen supply.

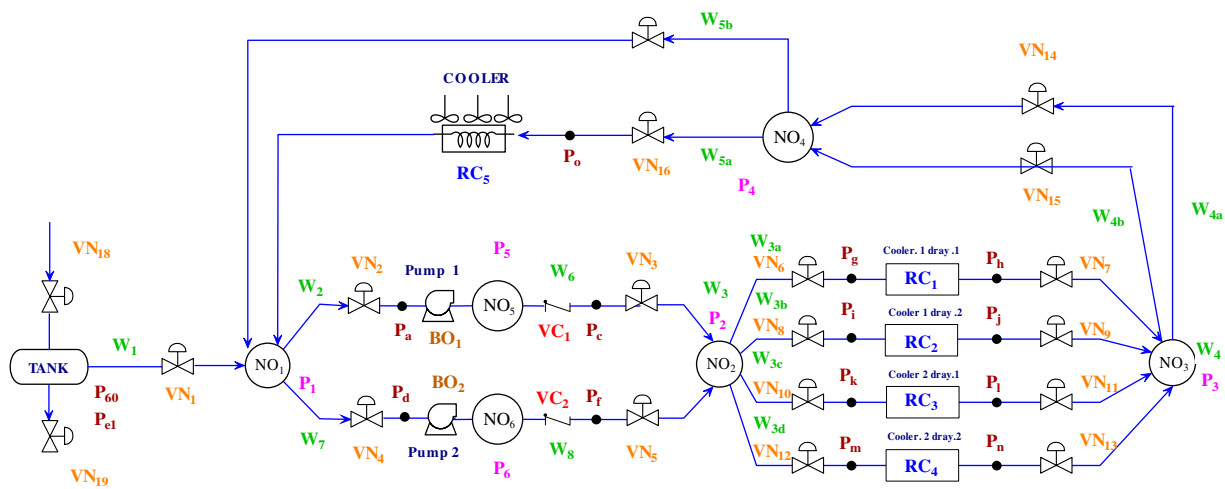


Fig. 16. Simplified diagram of the generator cooling water system.

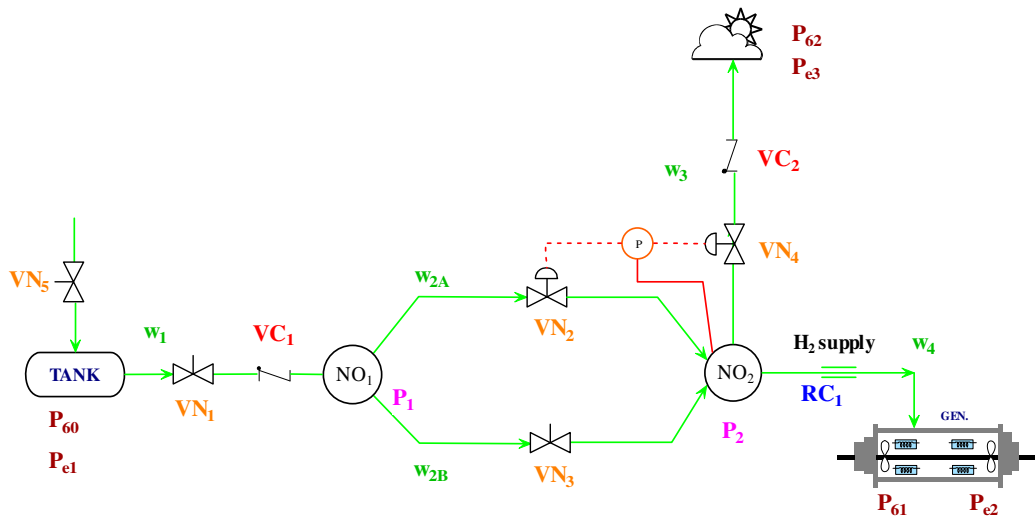


Fig. 17. Simplified diagram of the generator hydrogen supply.

Electric Phenomena Model

The generator model is not discussed here but it was simulated considering a sixth order model and equations related to the magnetic saturation of the air gap, the residual magnetism and the effect of the speed variations on the voltage. The control screen of the electric network is presented in Figure 18.

The model to simulate electrical grids was adapted from the generic model for hydraulic networks (Roldán-Villasana & Mendoza-Alegría, 2004). Basically, equations (8) and (16) may represent an electrical network in a permanent sinusoidal state by substituting flows ( $w$ ) by currents ( $I$ ), pressures ( $P$ ) by voltages ( $V$ ), conductances ( $C$ ) by admittances ( $Y$ ), pumping terms ( $Z$ ) by voltage source increase ( $VT$ ) when they exist and considering that the gravitational term does not exist in electrical phenomena, and valve apertures ( $Ap$ ) by a parameter to represent the variation of a resistance or impedance ( $Ps$ ). No linearization was necessary because the electric equations are linear. Although the model was designed to represent alternate current grids, it is able to represent direct current circuits. The first adaptation was made considering that it was necessary to handle complex numbers. The





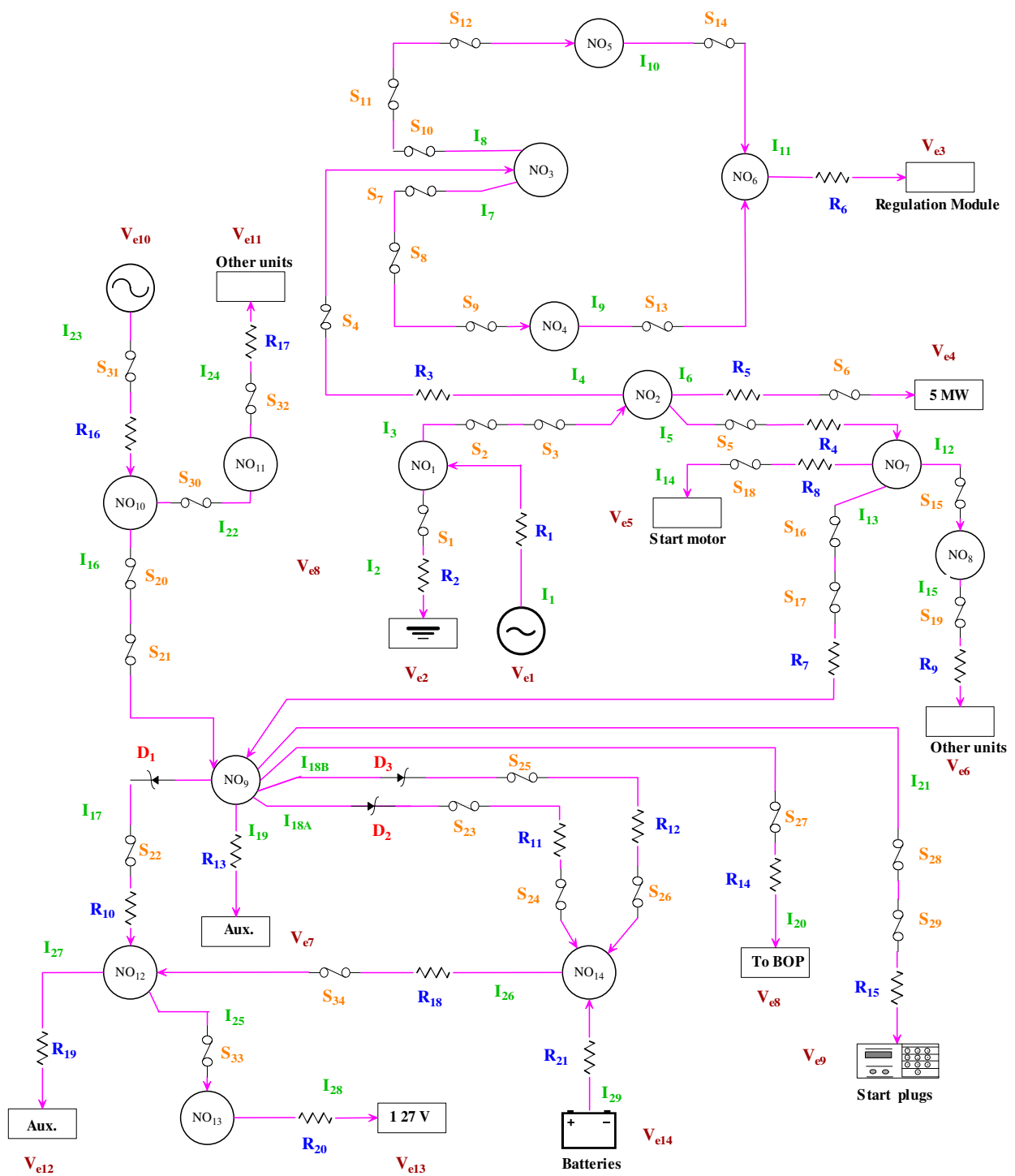


Fig. 19. Simplified diagram of the electric network as used for parameterisation.

$$\frac{d\omega}{dt} = (\omega_{nom} - \omega) k_{iii}$$

(20)

The variable  $\omega_{nom}$  is nominal speed if the motor is on and is zero if the motor is off. The constant  $k_{iii}$  has two values one for the motor starting up and other value for the coast down. The heat gained by the fluid due the pumping  $\Delta h_{pump}$  when goes trough a pump (turned on) is:

$$\Delta h_{pump} = \left( \frac{\eta \Delta P}{\rho} \right) \quad (21)$$

where  $\eta$  is the efficiency. The temperature at the exit of the pump  $T_o$  is (being  $T_i$  the inlet temperature):

$$T_o = T_i + \frac{\Delta h_{pump}}{C_p} \quad (22)$$

#### Capacitive Nodes

There are two kinds of capacitive nodes.

The first one is a node that is part of the flows and pressures network whose pressure is calculated as explained before. An energy balance on the flows and pressures network is made where heat exchangers exist and in the nodes where a temperature or enthalpy is required to be displayed or to be used in further calculations.

In this case, the inertial 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:

$$\frac{dh}{dt} = \frac{\sum w_i (h_i - h) - q_{atm}}{m} \quad (23)$$

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 is a single or a two phase one (for the case of water/steam). The state variable could be the temperature if no phase change is expected and if the specific heat  $C_p$  divides the  $q_{atm}$  term.

All the steam 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:

$$\frac{dm_j}{dt} = \sum w_i c_{i,j} - \sum w_o c_j \quad (24)$$

The second kind of node is those that is a frontier of the flows and pressures network. Here, the state variables depend on each particular case.

In this category are the boilers, condenser, deaerators, and other equipments related with different phenomena involving water/steam operations. These equipments were not used in this simulator and their formulations are not explained here. However, regarding gas processes, two approaches are used: the simplified model used for capacitive junction nodes or gas contained in close recipients (no phase change is considered in this discussion but indeed a generic model is available), and complex gas processes like a combustion chamber. For the simplified model, the pressure is calculated using next equation obtained with basis in an ideal gas behaviour (only the pressure change is calculated as an ideal gas, not the other properties):

$$P = \frac{nRT}{V} \quad (25)$$

The change in the moles  $n$  of the nodes is obtained correcting the change of the mass, being this a state variable too as indicated in equation (24) with the molecular weight. Equation (23) for the enthalpy is used too.

For complex processes where a possible change of phase occurs, the model considers to calculate the internal energy  $u$  in the node and its pressure. The derivative of the internal energy is evaluated as:

$$\frac{du}{dt} = \frac{\sum w_i h_i - \sum w_o h - u \frac{dm}{dt} - q_{atm}}{m} \quad (26)$$

The derivative of the total mass is the sum of the derivatives of each species as equation (24). Here, the internal energy and density are known (this later by dividing the total mass and the volume of the node). The thermodynamic properties are a function of pressure and temperature, so all the properties are calculated with a double Newton-Raphson iterative method. When two phases are present, some extra calculations are made to know the liquid and vapour volumes, but this is not treated here.

A last category of capacity nodes are tanks that are open to the atmosphere and filled with liquid. Equation (23) applies for temperature (or enthalpy) variations and a mass balance is used to calculate the derivative of the liquid mass:

$$\frac{dm}{dt} = \sum w_i - \sum w_o \quad (27)$$

Where the liquid volume is:

$$V_l = \frac{m}{\rho} \quad (28)$$

The liquid level is calculated with an adequate correlation depending on the tank's geometry.

#### Heat Exchangers

In the simulated plant, three varieties of heat exchangers were included: fluid (gas or water) cooled by air; metals cooled with hydrogen, air or oil; and water-water exchangers.

The fluid-air exchangers were modelled considering a heat flow  $q$  between the fluid and air:

$$q = U A \Delta T \quad (29)$$

The heat transfer coefficient  $U$  depends on the fluids properties, flowrates, and the construction parameters of the equipment.  $A$  is the heat transfer area.

The representative temperature difference between hot ( $h$ ) and cold ( $c$ ) streams is, generally, the logarithmic mean temperature difference calculated as (for countercurrent arrangements):

$$\Delta T = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\text{Log} \left( \frac{T_{h,i} - T_{c,o}}{T_{h,o} - T_{c,i}} \right)} \quad (30)$$

and for each fluid, a energy balance may be stated (with a constant  $C_p$ ) to calculate the exit temperature (exit enthalpy also may be used if a constant  $C_p$  is not considered)

$$T_o = T_i - \left( \frac{q}{wC_p} \right) \quad (31)$$

Besides, it is necessary to accomplish the thermodynamics' second law by avoiding the crossing of the temperatures in the exchanger, considering a minimal temperature differences (defined by the user) between the hot and cold streams: the outlet temperature of the cold stream does not be warmer than the inlet temperature of the hot stream and the outlet temperature of the hot stream does not be colder than the inlet temperature of the cold stream. If a crossing of temperatures is detected, clearly the heat calculated by equation (29) is too high and the limiting stream is identified, depending of which is the cold and the hot streams and the maximum heat allowed by each stream to no violate the second law. So, the heat is calculated arranging the equation (31). With the new heat, the outlet temperatures are calculated again. Clearly, an iterative procedure may be established in order to converge the last three equations with this procedure.

The model for the metals cooled with hydrogen, air or oil, was based on the fact that the metal is heated by friction (turbines, compressors, motors, etc.), electric current (generators and motors), or another fluid (radiators).

This approach is used instead equations (29) to (31). The generated temperature  $T_g$ , when the metal is heated by a fluid, is equivalent to the cooler temperature  $T_f$  and the exchanger is a fluid-fluid one, when the dynamics is relatively slow. When the metal is heated by friction or electrical current,  $T_g$  is represented by virtual temperatures ( $T_I$  for the current and  $T_\omega$  for the speed) that are calculated in order to simulate theses heating effects (a scheme of the heat transfer process is shown in Figure 20):

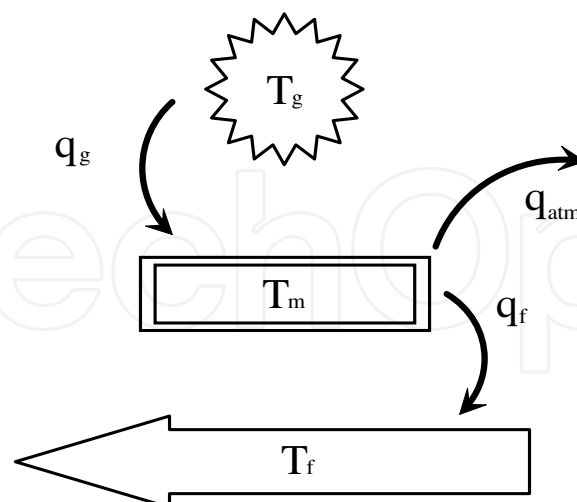


Fig. 20. Schematic representation of a generic metal-fluid heat exchange.

$$T_I = T_{amb} + k'_I I \quad (32)$$

$$T_\omega = T_{amb} + k'_\omega \omega \quad (33)$$



Thus, it is possible to calculate the total generated heat  $q_g$  by speed  $q_\omega$  and current  $q_I$  to the metal using a proper correlation for the heat transfer coefficients (Pasquantonio & Macchi, 1976):

$$q_g = q_\omega + q_I = k_\omega(T_\omega - T_m)\omega^{0.4} + k_I(T_I - T_m)I^2 \quad (34)$$

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

$$\frac{dT_m}{dt} = \frac{q_g - q_f - q_{atm}}{Cp_m m_m} \quad (35)$$

$q_f$  is calculated using equation (29) but the temperature difference  $\Delta T$  is:

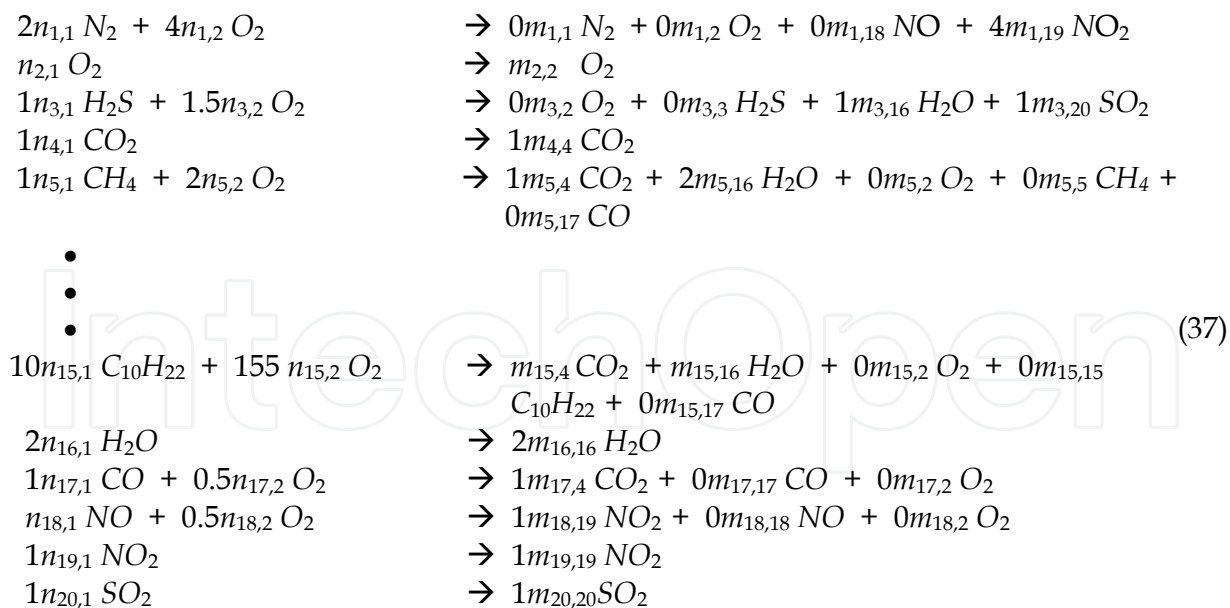
$$\Delta T = T_m - T_f \quad (36)$$

With this approaches any heat exchanger may be simulated, including the generator cooling with hydrogen that contains several heat exchanging stages.

#### Combustor

A GM for the combustor was developed by the IIE. The objective is to calculate flame temperature and the composition of the burned gases. It is possible simulate a mixture up to the same 20 components of the thermodynamic properties for the air, gas fuel and combustion products.

To calculate the flame temperature the stoichiometric coefficients are needed, thus, some of the reactions for the combustion process are:



Water should be considered joining external flow to control the chamber temperature (to prevent emissions) and the humidity contained in the fuel. The excess of oxygen may be calculated from the flowrates of the reactive components. The total combustion efficiency  $\alpha_{i,1}$  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

$\text{CO}_2$  and 0 if none of the products of a reaction is completely oxidized). The partial combustion efficiency  $\alpha_{i,2}$  is defined as the fraction of the theoretically amount of oxygen that is consumed for a partial total 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

$$\alpha_{i,1} + \alpha_{i,2} \leq 1 \quad (38)$$

must be satisfied at any moment.

Although no kinetics is taken into account, 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:

$$\begin{aligned} N : 2 n_{1,1} &= 2 m_{1,1} + m_{1,18} + m_{1,19} \\ O_2 : n_{1,2} &= 0.5 m_{1,18} + m_{1,19} ; m_{1,2} = 0.0 \\ \text{If excess of oxygen} &\geq 200\% \quad \alpha_{1,1} = 0.1 ; \alpha_{1,2} = 0.0 \\ \text{If excess of oxygen} &= 100\% \quad \alpha_{1,1} = 0.0 ; \alpha_{1,2} = 0.1 \\ \text{If excess of oxygen} &\leq 50\% \quad \alpha_{1,1} = 0.0 ; \alpha_{1,2} = 0.0 \end{aligned} \quad (39)$$

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:

$$\begin{aligned} m_{1,19} &= 2 \alpha_{1,1} n_{1,1} \\ m_{1,18} &= 2 \alpha_{1,2} n_{1,1} \\ m_{1,1} &= 0.5 (2 n_{1,1} - m_{1,18} - m_{1,19}) \\ n_{1,2} &= 0.5 m_{1,18} + 1 m_{1,19} \end{aligned} \quad (40)$$

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 (automatically calculated from the component's formation heats), reactive and product sensitive heat, and heat losses by radiation and convection.

The combustor is considered to be a capacitive node and equations (24) and (26) applies for the calculation of the combustor variables considering that the product of the combustion is the inlet to the capacitive node equations and the concentration in the combustor are associated to the exit flowrate, as presented in Figure 21.

#### Local Controls

During the off line tests, the models run without the DCS (see Section 9), thus, independent local controls applied on valves were simulated in a simplified way to avoid the problem of

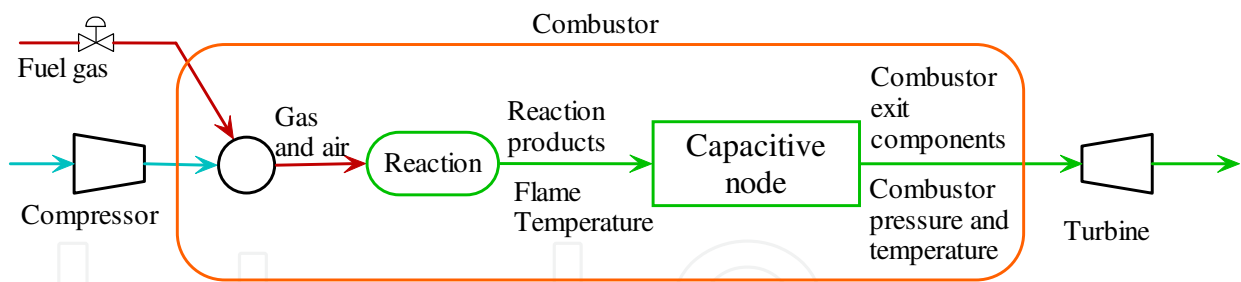


Fig. 21. Conceptual model of the combustor.

a variable increased or diminished because it is not being controlled. The model for the aperture demand  $dm$  is:

$$dm = Ap \pm k_p \frac{Sp - Va}{Sp} \tag{41}$$

Where  $Sp$  is the desired set point,  $Va$  the value of the variable to be controlled, and.  $K_p$  is a proportional constant whose value depends on the dynamics of the controlled variable. The aperture of the valve tends to the value of the demand with a lag ( $k_t$ ) as:

$$Ap = Ap + (dm - Ap) k_t \tag{42}$$

Although the control model is not a conventional one and there does not exit an integral value, in all cases worked with enough precision for the tests purposes (in fact, the model has been applied on the final version of other full scope training simulators).

*Final Remarks*

There were not included in this revision the generic models developed by the IIE that were not utilised in this simulator as ejectors, air cooled condensers, deaerators, boilers, cooling tower, separators of hydrocarbon mixtures, etc.

Although first principle and well known tested and approved correlations are used as the modelling basis, some assumptions and simplifications are involved in the final models. Inevitably, differences between the model results and the plant behaviour are presented. To fit the model in order to minimize the difference to accomplish with the ANSI/ISA norm, the parameters have to be adjusted.

The simulator resulted with 1500 parameters, 8800 global variables including 33 analogical malfunctions, 65 logical malfunctions, 55 analogical remote functions and 151 binary remote functions

**8.3 Malfunctions, remote functions and external parameters**

*Malfunctions.*

The malfunctions included in the simulator were defined according the ANSI/ISA norm and the particular interest of the CENAC. They may be classified in the types generic and specials.

*Generic malfunctions:* problems in the pressure, temperature and flow transmitters; valves failure (open, close or stuck); filters and flow resistances fouling; heat exchanger fouling (to decrease the heat transfer coefficient); alteration of the turbine and generator vibrations;

| System             | Subsystem                     | Number of malfunctions | Number of remote functions |
|--------------------|-------------------------------|------------------------|----------------------------|
| C1 Control System  | Generator and Electric System | 13                     | 64                         |
|                    | Gas Turbine                   | 7                      | 7                          |
| Supervisory System | Ready to Start/Trips          | 1                      | 5                          |
|                    | C1 Gen Vibrat Analysis        | 4                      | 0                          |
|                    | C1 Combustion Flash back      | 3                      | 0                          |
|                    | C1 Blade Path Exhaust         | 36                     | 0                          |
| Auxiliary Systems  | Fuel Gas System               | 7                      | 4                          |
|                    | C1 Lube Oil System            | 5                      | 35                         |
|                    | C1 Hydr Ctl Oil System        | 2                      | 18                         |
|                    | C1 Generator Longitudinal     | 2                      | 32                         |
|                    | C1 Gen Seal Oil System        | 2                      | 15                         |
|                    | C1 Turbine Cooling System     | 16                     | 26                         |

Table 7. Number of malfunctions and remote functions for each system in the simulator.

variation of the metal temperatures in the turbine-generator metals; motors trips (for pumps, fans, compressors etc.); heat exchanger tubes breaking; and closed tanks gas leaking. *Special Malfunctions.* They are the malfunctions specifically designed to cover the CENAC’s necessities: malfunctions of electric components (black out, charge of generation rejection, etc.); fault of the control components (turbine overspeed, no detection of the combustor flame, etc.); problems in the combustor (low combustion efficiency, exhaust thermocouples); low pressure of fuel gas supply; and turbine low efficiency.

*Remote functions* The remote functions included in the simulator were defined according the ANSI/ISA norm and the particular interest of the CENAC. The main remote functions are: opening and closing of manual valves, opening and closing of switches and relays; automatic and manual position switching; and start up and trip of equipments; selection of the equipment; and set point modification.

In Table 7 the number of malfunctions and remote functions are listed according the system-subsystem classification defined by the customer to be presented in the respective simulator pop-up menu.

*External parameters.*

The external parameters allow modifying the environment conditions that do not depend on the operators control as: temperature (dry and wet bulbs), atmospheric pressure, gas supply pressure, combustion factor and variation in the voltage and frequency of the external system; and both methane and nitrogen molar fraction in the gas.

9. Off line testing and coupling of the systems models

During the models development, a very important task is to define the causal relation of the models, *i.e.* to specify for each model all the variables (inputs and outputs) between the models, controls, operator console, and instructor console, and assure that all the models

have congruency. The variables (global variables) are classified and added into a data base. This data base contains the variables declaration for the C and FORTRAN programs, parameters values, malfunctions, instruments ranges, remote functions, unit conversions, etc.

Each MSS, developed independently, is tested off line without controls (open loop). In this stage it is convenient to have some simplified controls to avoid problems of process instabilities; for example in a tank model it is necessary to control the level to avoid it becomes empty or shedding. The idea of the tests is to reproduce the design data, normally data plant working at 100% of capacity. The global input variables must have an initial values registered in an ASCII format file (initial condition).

For the coupling process, the DCS models are integrated into the MAS without the process models and tested to verify its dynamics, including the control screens. The models are added one by one according the defined sequence matrix. With each model the initial condition file is actualised and some tests are performed to assure the coupling is successful. In this stage adjustments are done, to avoid mathematical instabilities.

When the last model has been added and the 100% initial condition is ready, by operating the plant there are obtained all the other initial conditions up to get the cold start initial condition.

Fabric tests are applied (the same mentioned in the following section) to the integrated simulator before it is translated to its final site in the customer's facilities.

## 10. Validation and results

The simulator validation was carried out proving its response against the 16 very detailed operation procedures elaborated by CFE specialised personnel, ("Acceptance Simulator Test Procedures"). The tests included all the normal operation range, from cold start conditions to full charge, including the response under malfunctions and abnormal operation procedures. In all cases the response satisfied the ANSI/ISA norm.

The customer provided the plant data for an automatic start up procedure (with a total of 302 variables). The simulator results were compared with these data. No data for other transients were considered as design data.

To selected results presented here are an automatic start-up followed by a coupling of malfunctions. During these transients no actions of the operator were allowed. The plotted variables were chosen to verify the effect of the malfunctions. In Table 8 a list of the events and the time they happen is presented.

For all the graphs, excepting Figure 22, a comparison between the real plant values and the simulator results during the first 2780 s are presented, then no plant data are available and only the simulator results are displayed up to the end of the simulation. In all the tests may be appreciated the good agreement between the real plant data and the simulation results. No further commentaries are necessary at this respect.

In Figure 22 a comparison between the expected and simulator turbine speed is presented during the turbine speed up during 830 s when the speed reaches its nominal value of 3600 rpm.

In Figure 23, the combustor pressure is presented on the left *y* axis and the gas delivery pressure (an external parameter where the operator has no control) is presented on the right *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.



| Time (s) | Time (hh:mm:ss) | Event   |
|----------|-----------------|---|
| 0        | 00:00:00        | Simulation is initiated.  |
| 5        | 00:00:05        | Turbine is turned on in automatic mode.   |
| 120      | 00:02:00        | Ignition in the combustor is triggered.   |
| 830      | 00:13:50        | Turbine reaches its nominal speed (3600 rpm).   |
| 2790     | 00:46:30        | The plant produces its nominal charge (150 MW).   |
| 2970     | 00:49:30        | Initiates malfunction of low efficiency in the combustor.                                       |
| 3000     | 00:50:00        | Malfunction of low efficiency in the combustor takes its final value (50% of severity).         |
| 3500     | 00:58:20        | Initiates malfunction of pressure loss in the delivery line of gas fuel.                        |
| 3680     | 01:01:20        | Malfunction of pressure loss in the delivery line of gas fuel takes its final value (4082 kPa). |
| 4200     | 01:10:00        | End of the simulation.  |

Table 8. Times of the transients’ events

The graph of the gas delivery pressure (Figure 23) shows how the pressure changed with a ramp between the 3500 s and 3680 s. The behaviour of the combustor pressure is explained in Table 9.

In Figure 24, the fuel gas flowrate is plotted on the left *y* axis and the apertures of two (A and C) of the gas control valve apertures are presented on the right *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.

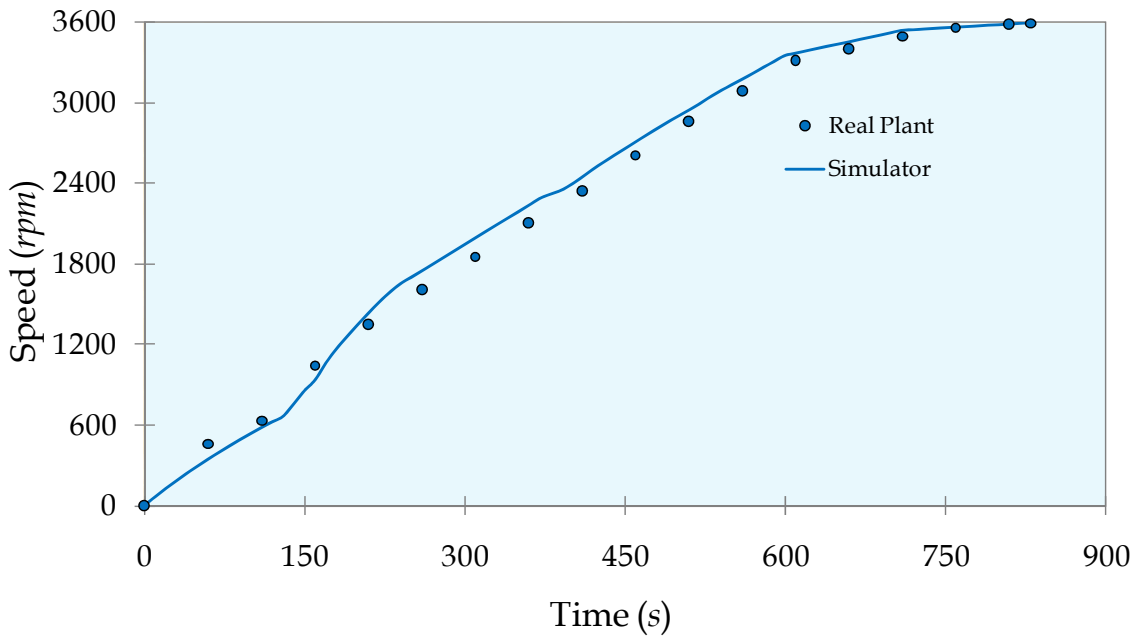


Fig. 22. Turbine speed comparison for the real plant and the simulation.

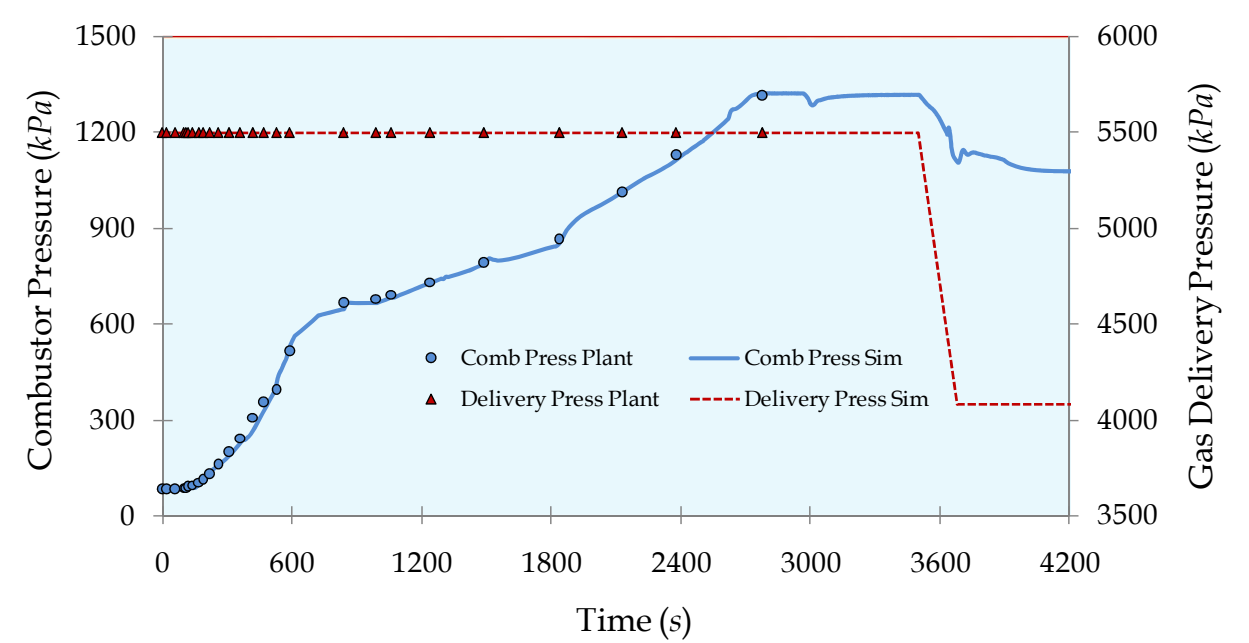


Fig. 23. Combustor pressure and gas delivery pressure

| Time period (s) | Event Id                                       | Description of the results for the combustor pressure, Fig. 23   |
|-----------------|--|--|
| 2790 - 2970     | Nominal charge - Low efficiency initiates      | The pressure stabilises.   |
| 2970 - 3000     | Low efficiency initiates - Low efficiency ends | The pressure drops because the combustion is affected and the temperature in the combustor descents too.   |
| 3000 - 3500     | Low efficiency ends - Pressure loss initiates  | Pressure arises due the effect of the gas control valves that treats to keep the charge of the plant by allowing more gas flowrate to the combustor.   |
| 3500 - 3680     | Pressure loss initiates - Pressure loss ends   | 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 charge. At about 3660 s the pressure increases and then descents because the aperture of the gas oscillate due the control algorithm. |
| 3680 - 4200     | Pressure loss ends - Simulation Ends           | The pressure decreases lightly trying to reach a new (and final) steady state because the gas control valves tend to stabilise their aperture.   |

Table 9. Description of the results for the combustor pressure, according Fig. 23

The behaviour of the gas control valves dynamics during the malfunctions transients are explained in table 10.

The changes of the fuel gas flowrate variable for the test are explained in table 11.

The exhaust temperature is measured in the gas phase on the exit of the combustor. Some comments on the behaviour of the exhaust temperature during the malfunctions transients are given in table 12.

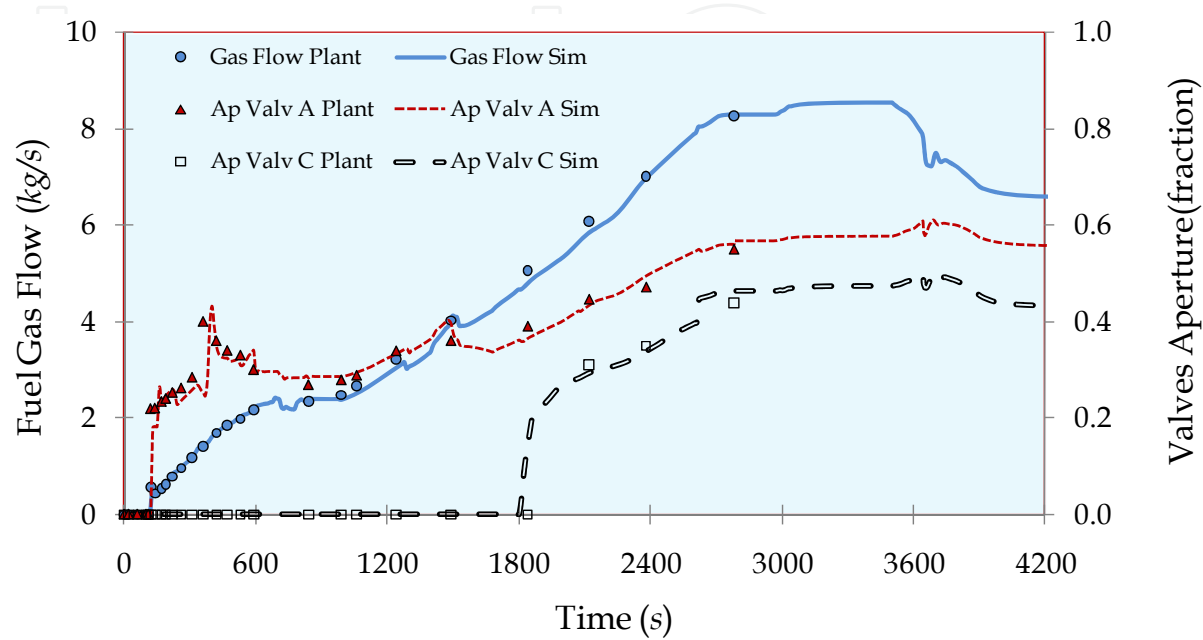


Fig. 24. Gas flowrate and apertures of gas control valves A and C.

| Time period (s) | Event Id                                       | Description of the results for the fuel gas control valves, Fig. 24   |
|-----------------|--|---|
| 2790 - 2970     | Nominal charge - Low efficiency initiates      | The apertures are stable.   |
| 2970 - 3000     | Low efficiency initiates - Low efficiency ends | The apertures increase their value trying to compensate the charge descending due to the loss of combustion efficiency.   |
| 3000 - 3500     | Low efficiency ends - Pressure loss initiates  | The gas control valves adjust their value and control the charge.   |
| 3500 - 3680     | Pressure loss initiates - Pressure loss ends   | The gas control valves treat to keep the charge. At about 3660 s the gas control valves have a transient because open suddenly but the control detects this abrupt change and limits the valve apertures producing a slight transient in the apertures. |
| 3680 - 4200     | Pressure loss ends - Simulation Ends           | The control algorithm allows decreasing the charge and stabilise the apertures and the plant in a new steady state.   |

Table 10. Description of the results for the fuel gas control valves apertures, according Fig. 24.

| Time period (s) | Event Id                                       | Description of the results for the fuel gas flowrate, Fig. 24  |
|-----------------|--|--|
| 2790 - 2970     | Nominal charge - Low efficiency initiates      | The fuel gas flow remains stable.  |
| 2970 - 3000     | Low efficiency initiates - Low efficiency ends | The gas flowrate increases following the aperture of the gas control valves trying to compensate the losing of electrical power due the malfunction.   |
| 3000 - 3500     | Low efficiency ends - Pressure loss initiates  | The gas flowrate adjusts its value (grows slightly) according the gas control valves aperture to adjust the charge.  |
| 3500 - 3680     | Pressure loss initiates - Pressure loss ends   | The gas flowrate descents because the gas control valves are not able to keep the charge. The malfunction is too severe. At about 3660 s the gas flow has a transient because the valves open and then close (not totally) suddenly. |
| 3680 - 4200     | Pressure loss ends - Simulation Ends           | The gas flow tends to stabilise reflecting the control valves apertures behaviour.   |

Table 11. Description of the results for the fuel gas flowrate, according Fig. 24.

In Figure 25, the generated electrical power is graphed on the left *y* axis and the exhaust temperature on the right *y* axis.

The graph of the generated electrical power in Figure 25 shows how the charge evolutes depending on the malfunctions. The behaviour of the charge is explained in table 13.

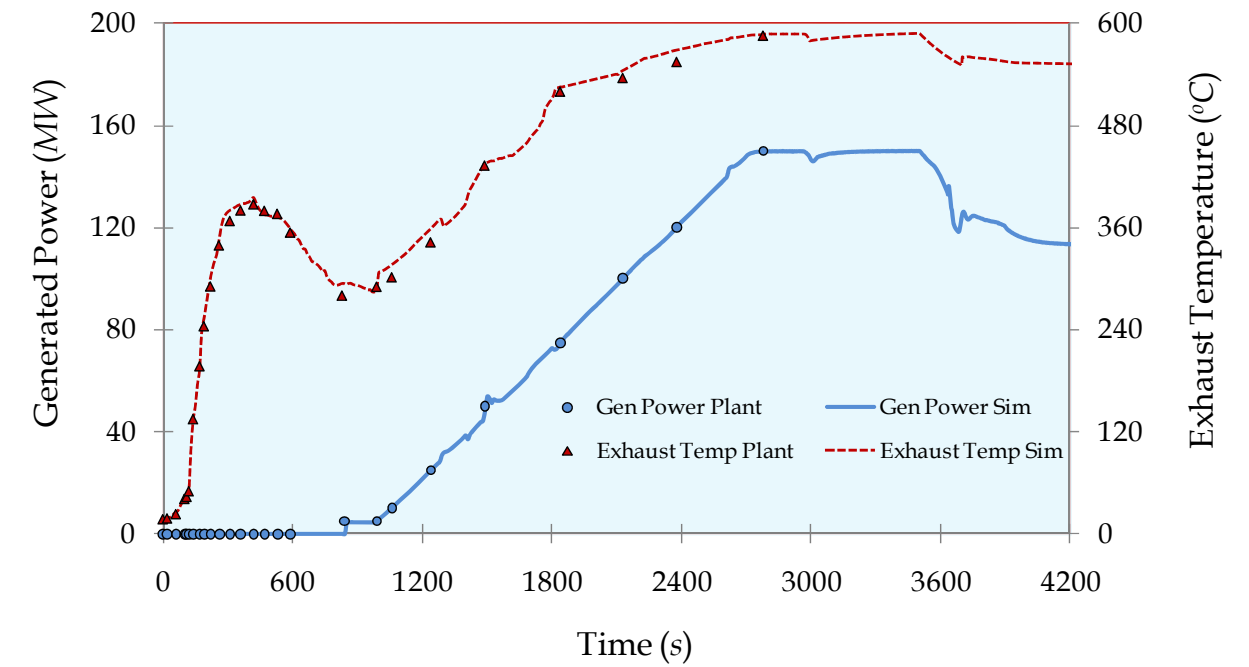


Fig. 25. Generated electrical power and exhaust temperature.

| Time period (s) | Event Id                                       | Description of the results for the exhaust temperature, Fig. 25  |
|-----------------|--|--|
| 2790 - 2970     | Nominal charge - Low efficiency initiates      | The exhaust temperature stabilises.  |
| 2970 - 3000     | Low efficiency initiates - Low efficiency ends | The exhaust temperature drops because the combustion is affected and the gas control valves do not respond immediately.  |
| 3000 - 3500     | Low efficiency ends - Pressure loss initiates  | The exhaust temperature arises 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.  |
| 3500 - 3680     | Pressure loss initiates - Pressure loss ends   | 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. |
| 3680 - 4200     | Pressure loss ends - Simulation Ends           | The exhaust temperature decreases tending to stabilise according the gas control valves position.  |

Table 12. Description of the results for the fuel gas flowrate, according Fig. 25.

| Time period (s) | Event Id                                       | Description of the results for the exhaust temperature, Fig. 25   |
|-----------------|--|---|
| 2790 - 2970     | Nominal charge - Low efficiency initiates      | The charge is in steady state.  |
| 2970 - 3000     | Low efficiency initiates - Low efficiency ends | The charge drops because the combustion malfunction and the gas control valves do not compensate the effect that soon.  |
| 3000 - 3500     | Low efficiency ends - Pressure loss initiates  | The charge recovers its original nominal value due the control by the gas control valves, allowing more gas flowrate into the combustor.  |
| 3500 - 3680     | Pressure loss initiates - Pressure loss ends   | The charge drops because the malfunction of losing delivery pressure that cannot be nullified by the gas control valves. At about 3660 s the charge oscillates due the gas control valves aperture behaviour. |
| 3680 - 4200     | Pressure loss ends - Simulation Ends           | The charge tends to stabilise for the steady state defined by the control algorithm.  |

Table 13. Description of the results for the fuel gas flowrate, according Fig. 25.



Although they are not presented in this work, must be mentioned that all the expected alarms were presented in the precise time.

The CENAC endorsed and accepted as correct the results of the tests in accordance with the testing acceptance procedures.

## 11. Conclusion

A complete model of a gas turbine generation plant for operators' training has been presented. The validation of the simulator was carried out by CENAC specialised personnel under rigorous acceptance simulator testing procedures, and with reliable experience in the use of simulators. The simulator was tested in all the operation range from cold start to 100% of load and fulfils the performance specified by CENAC including a comparison of its results with plant data. The results demonstrate that the simulator is a replica, high-fidelity, plant specific simulator for operator training. Realism is provided by the use of DCS screens emulation. Now, the CENAC has one more useful tool to train the future generation of operators of the gas turbine power plants.

The robustness of the models is due, in an important part, to the generic models approach, the software tools, and the methodology that supports the development of the simulator.

From the literature review, considering that the modelling basis of the IIE has less constraints and thus a more wide scope, it may be concluded that the present models could be used for other purposes like that reported.

This simulator had several adjustments during its development to fit its dynamic behaviour to that obtained in the real plant.

An additional aspect that gives certitude and robustness to the simulator behaviour is that this has practically the same DCS that the plant which means that the process models that were obtained by the SD engineers reproduce correctly the real behaviour of the reference plant.

Presently, training scenarios were defined and used in the simulator to achieve the training program that is proving to be a successful one.

## 12. Acknowledgment

The simulators developed by the SD of the IIE have been projects carried out thanks to the effort, enthusiastic and very professional hard work of researchers and technicians of the IIE as well as very good coordination of the co-operation of operators, trainers and support personnel of CENAC. This project was carried out thanks to the financial support of CFE.

## 13. Acronyms

The list of acronyms used in this chapter is:

|       |  |
|-------|--|
| CFE   | - The National Utility Company in Mexico   |
| CENAC | - National Centre of Training Ixtapantongo |
| DCS   | - Distributed Control System               |
| GM    | - Generic Model                            |
| IC    | - Instructor Console                       |
| ICO   | - Initial Conditions                       |

|       |   |
|-------|---|
| IIE   | - Electrical Research Institute           |
| IPD   | - Interactive Process Diagrams            |
| MAS   | - Simulation Environment                  |
| MMI   | - Man Machine Interface                   |
| MN    | - Maintenance Node                        |
| MSS   | - Model of a Simulated System             |
| OS    | - Operators' Station                      |
| PC    | - Personal Computer                       |
| PEMEX | - Mexican Oil Company                     |
| SAMA  | - Scientific Apparatus Makers Association |
| SD    | - Simulation Department                   |
| SN    | - Simulation Node                         |
| TP    | - Thermodynamic Properties                |

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