Oil Systems Modeling for an Operators' Training Combined Cycle Plant Simulator

Yadira Mendoza-Alegría, Edgardo J. Roldán-Villasana, Iván F. Galindo-García, and Jorge Zorrilla-Arena

Abstract— In this paper, the bases of the models of the oil systems of a full scope simulator of a 450 MW combined cycle power plant are presented. The simulator is executed in real time and was designed as support for the training of the operators.

Here, the modeling methodology used to develop the referred models and the mathematical principles used to obtain the main equations are summarized. The tendencies of selected variables during transients and malfunctions are presented and analyzed in order to prove the validity of the simulator.

Index Terms—Combined Cycle Power Plant, Oil System, Process Modeling, Real Time Training Simulator.

I. Introduction

In 1975 the Mexican Electric Research Institute (IIE [1], http://www.iie.org.mx) was established. Since then, it has been the R&D right hand of the Mexican Electric Utility Company (CFE) offering technical solutions and innovations. The Simulation Department (GS) of the IIE is a technical group specialized in training simulators. The group design and implement tools and methodologies to support the development and exploitation of simulators. The GS has constructed several training simulators for the CFE devoted to train fossil-fuel power plants operators. To satisfy their training requirements, CFE has acquired simulators based on control panels, classroom simulators, portable simulators and, recently, simulators based on multi-window man machine interfaces (MMI) as control screens.

The use of real time full scope simulators has proven through the years to be one of the most effective and reliable ways for training power plant operators. Using simulators, the operators can learn to operate the power plant more efficiently in transients or maneuvers such as lowering the heat rate or reducing the power required by auxiliary equipment [1]. Even not full scope simulators are being used successfully for operators' training [2]. Most often, the justification for acquiring an operator training simulator is based on estimating the reduction in economic losses [3].

In 2000 the CFE initiated the operation of a 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. It was decided to develop the new simulator in two stages: the gas-turbine part in 2007 and the steam-heat recovery part in 2009 [4]. In this paper the description of the oil systems models of the combined cycle simulator (CCS) is presented.

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[1] Some acronyms are after the name or phrase spelling in Spanish

II. General Description of the Simulator

A. Simulation Session

The simulator is operated from its own console by an instructor. Operators are trained using control stations, replica of the real ones. A simulation session starts when an initial condition is established (cold start up, 100% of load, etc.), and a task is imposed to the operator. The instructor follows the simulation session and, without the awareness of the operator, introduces malfunctions to evaluate the operator response. A malfunction is a simulated failure of plant equipment, for example: pumps trips, heat exchangers tube ruptures, valves obstruction, etc. The instructor has the option to define the malfunction start time, permanence time, severity, and evolution time. Also, using remote functions, the instructor can simulate the operation of equipment operated in the plant by auxiliary local operators. The instructor may modify the external conditions: atmospheric pressure and temperature (dry and wet bulb), voltage and frequency of the external system, fuel composition, etc.

The "ANSI/ISA S77.20-1993 Fossil-Fuel Power Plant Simulators Functional Requirements" norm was adopted as a design specification, including the real time execution.

B. Hardware

The CCS is constituted by four Personal Computers interconnected through a fast Ethernet Local Area Network. Each PC has a Pentium D processor with 3.6 GHz, 1GB of RAM, 40GB HD, and Windows XP as operating system. Fig.1 shows a schematic of this architecture.

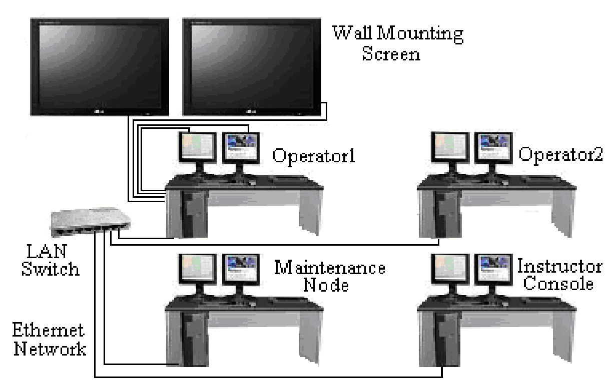

Fig. 1 Hardware architecture

C. Software

The SCC has Windows XP as operating system, and was programmed in MS Visual Studio 2005: Fortran Intel was used for the mathematical models, Flash and VisSim for the gas turbine screens. The steam turbine screens were duplicated from the real plant control, and C# was the basis for the modules of the simulation environment called *MAS* (proprietary software of the IIE), where the instructor guides the simulation sessions, Fig. 2.

III. Modeling Methodology

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

A. Process

The models are a set of algebraic and differential equations obtained from the application of basic principles (energy, momentum and mass balances and well-known and proved relations). The models were developed applying a methodology developed by the IIE. This methodology may be summarized in the following steps: a) Information of the process is obtained and classified, b) The information is analyzed and a conceptual model is stated, c) Simplifications of the system are made and a simplified diagram is obtained, d) Main assumptions are stated and justified, e) The configuration of the flows and pressures network is obtained, f) Energy balances are programmed using generic models, g) The equipment representing capacitive nodes are parameterized considering the available generic models in the simulator's libraries or, eventually, an appropriate model is developed, h) Local tests are performed and, if necessary, the models are adjusted, i) All systems and their controls are integrated, j) Global tests are made (with the needed adjustments), k) Final acceptance tests are performed by the final user according to their own procedures.

B. Control

The actions the operators perform on the simulator screens are registered and processed by the control models. The control models are a reproduction of the actual logic of the plant.

IV. Systems Description

A. Lube Oil Systems

The components of the gas turbine lube oil system (GTLOS) and the steam turbine lube oil system (STLOS) are: AC motor pumps, emergency DC motor pumps, a lubrication oil tank, an electric oil heater, an oil cooler, mist eliminators (extractors), oil filters, and valves.

The GTLOS additionally has a pressure control valve located upstream the lubricated parts (the turbine and generator bearings).

The STLOS has a main pump mounted on the turbine shaft, oil ejectors and an oil conditioner.

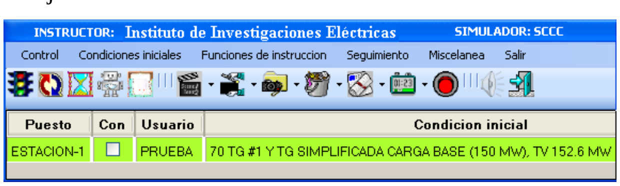

Fig. 2. Main display of the instructor console (partial view)

The systems provide a continuous supply of filtered oil at a temperature and pressure as required for lubrication. In normal operation conditions of the GTLOS, the oil is supplied from the lube oil tank to the bearings through the main pump; the backup pump operates when the main cannot keep operating requirements. An emergency DC pump is used only as a reserve for the main pump. It ensures that the gas turbine slows down safely when a loss of pressure in the oil system, indicated by the pressure in the bearings header, occurs.

During start up and shut down periods, the steam turbine lube oil is supplied by the auxiliary pump and when the turbine is at rated speed the main oil pump supplies the oil. For both systems the oil is taken from the main oil tank; it flows through a water operated cooler, it enters the turbine where it lubricates the bearings and returns to the main oil tank.

B. Gas Turbine Seal Oil System

The components of the Gas Turbine Seal Oil System (GTSOS) include the seal oil tank, the drain regulator tank, the emergency pump, and valves.

The main function of the GTSOS is to prevent the leaking of hydrogen in the generator and to lubricate the seals.

The GTSOS is connected to the GTLOS through a tube that connects both of the tanks (to equal the oil levels) and through a valve which supplies seal oil to the generator when the seals pump fails.

C. Gas Turbine Control Oil System

The components of the Gas Turbine Control Oil System (GTCOS) include the control oil tank, pumps, filters and a heat exchanger.

The main function of the GTCOS is to provide a continuous supply of pressurized oil for the operation of the gas fuel control valves and the compressor inlet guide valves. The oil is filtered and chilled in a parallel circuit by an air/water heat exchanger.

A backup pump is turned on automatically if the main pump trips. The oil is returned to the tank after the activation of the valve mechanisms.

D. Steam Turbine Control Oil System

The steam turbine control oil system (STCOS) shares with the STLOS the main oil tank and the main and auxiliary pumps. Also, it has all the pipelines to direct the oil to the EHC valves.

The STCOS is a high pressure system to operate: the pistons that move the main servomotor valve, the low pressure reheater stop valve, the governor servomotor valve, the interceptor valve, and the servomotors of the low pressure control valves. The oil pressure is controlled at three different levels, according to the required force to move each piston. Besides, STCOS is used to periodically test the valves during the normal operation of the plant.

This system is especially important when a unit trip occurs because it has the responsibility to close the valves immediately to avoid turbine damage.

V. General Systems Modeling

A modeled system is a mathematical representation of the behavior of the variables of the real systems of the power plant. The models, from the point of view of power plant

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operation training, and specially the oil systems models, are not frequently reported in the literature because they belong to the companies that provide the training or develop simulators, and therefore, it is proprietary information [5]. Design and analysis simulation approaches for oil systems may be found in [6]-[9].

In training simulators, the model of a system should respond to the operator actions in the same way the real systems would (in tendency and time). Typically, the equations for each model system are stated in such a way that the set of equations of one model is mathematically independent of the set of equations of another. The IIE has adapted different solution methods for both, linear and non-linear equations (Newton-Raphson, Gaussian elimination and bisection partition search) and they are used depending on the structure of each particular model.

The differential equations are numerically solved with one of various available methods (e.g. Euler, trapezoidal rule with one or two corrections).

For the modeling, fundamental conservation principles were used considering a lumped parameter approach and widely available and accepted empirical relations. The independent variables are associated with the operator actions on valves, pumps, etc., and with the control signals from the distributed control system (DCS).

The design of generic models (GM) as developing tools allows reducing the time used to develop a simulator. 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. The main tools are a simulation environment (*MAS*); a generic configurable model (*flupre*) to simulate flow and pressure networks [10]; a generic configurable model (*redele*) to simulate electrical networks [11]; a generic program to simulate direct contact condensers with non-condensable gases (*gecoin*); a generic model to simulate a combustion chamber (*gecomb*); thermodynamic properties for water and steam and for mixtures of hydrocarbon components; generic models to simulate particular equipment (atmospheric open tanks, pressurized tanks, air or gas containments, electrical response of induction motors, combustors, condensers, heat transfer equipment); PID control modules; energy (temperature or enthalpy) balance in mixing nodes; mixing of streams with hydrocarbon components; mathematical packages to solve linear and non-linear algebraic equations systems; methods for numerical integration of differential equations.

In this paper, a summary of the main GMs used by the oil systems is presented.

A. Flows and Pressures

The *flupre* model is derived applying the momentum equation to each flow stream and the continuity equation to each node.

Neglecting the terms of temporal acceleration and considering that the forces acting on the fluid are instantly balanced, a model may be stated integrating the momentum equation along a stream:

$$\Delta P = -X\ \Delta\tau + \rho\, g\, z \qquad (1)$$

Here, P is the pressure, X the length, ρ the density, g the gravity acceleration, z the height, and τ the viscous stress tensor that may be evaluated using empirical expressions for any kind of element. For example, for pumps it may be assumed that:

$$\Delta P = K_1^{'}\, w^2 + K_2^{'}\, w\, \omega + K_3^{'}\, \omega^2 - \rho\, g\, z \qquad (2)$$

where K'_i are constants, w the mass flow, and ω the angular speed of the pump.

For non rotating elements the equation may be stated as:

$$w^2 = K'\, \rho\, Ap^{\gamma}\left(\Delta P + \rho g z\right) \qquad (3)$$

where Ap is the aperture of the valves, but it may represent a variable resistance factor to the flow. The exponent of the aperture γ represents the characteristic behavior of a valve. *Flupre* has a set of typical equations to represent some other components (like turbines).

Thus, applying the proper momentum equation on each element and the mass balance on each node, a system of equations is stated where the flows and pressures are the unknown variables to be solved. *Flupre* may solve any hydraulic network by automatically detecting the topology and setting the appropriate set of equations.

B. Energy Balances

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 the oil models, two varieties of heat exchangers were included: fluid-fluid exchangers and metals cooled with oil. The fluid-fluid (water-air) exchangers were modeled considering the heat flow q between them as:

$$q = U\, A \Delta T \qquad (4)$$

where q is the heat flow, A the area, T the temperature, and U the heat transfer coefficient which depends on the fluids properties, the flow rates, and the construction parameters of the equipment.

The characteristic temperature difference between hot and cold streams ΔT is, generally, the logarithmic mean temperature difference calculated for countercurrent arrangements. So, for each fluid, an energy balance may be stated (considering the heat capacity C_p as a constant) to calculate the exit temperature:

$$T_o = T_i - \left(\frac{q}{wCp}\right) \qquad (5)$$

where the subindices o and i are for output and input values, respectively. In order to avoid the crossing of temperatures in the exchanger a minimal temperature difference between the hot and cold streams is defined by the user. If a crossing of temperatures is detected, the heat calculated by (4) is too high and the limiting heat, depending on the cold and the hot streams, and the maximum heat permitted by the second law of thermodynamics, would be imposed. So, the heat is calculated arranging (5). With the new value of heat, the outlet temperatures are calculated again. Clearly, an iterative procedure may be established in order to obtain a converged solution.

The model for the metals cooled with oil was based on the fact that the turbine and generator metals are heated by friction and electric current. In Fig. 3, the generated temperature T_g is represented by virtual temperatures (T_I for the current and T_ω for the speed) that are calculated in order to simulate theses heating effects. With the generated temperature T_g, the heat q_g represents the transferred energy due the frictional forces and/or the generated electric current [12]:

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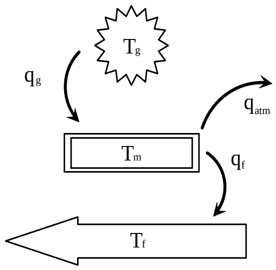

Fig. 3. Schematic metal temperature model

$$q_g = q_\omega + q_I = k_\omega (T_\omega - T_m)\,\omega^{0.4} + k_I (T_I - T_m) I^2 \qquad (6)$$

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

$$\frac{dT_m}{dt} = \frac{q_g - q_f - q_{atm}}{m\,Cp} \qquad (7)$$

Being t the time, m the mass, and f and atm the subindices for the fluid and atmosphere, respectively. In all cases the heat flow is calculated with the temperature difference, an equivalent area and a heat transfer coefficient.

C. 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. In this case, because no phase change is simulated for the oil, the temperature is calculated by integrating next equation:

$$\frac{dT}{dt} = \frac{\sum w_i T_i - w_o T}{m} - \frac{q_{atm}}{m\,Cp} \qquad (8)$$

In this expression, m is the mass of the node, and q_{atm} the heat lost to the atmosphere. The state variable could be the enthalpy, especially if a phase change is expected.

The mass of the oil is obtained from a mass balance on the liquid phase:

$$\frac{dm}{dt} = \sum w_i - \sum w_o \qquad (9)$$

where the volume of the liquid V_l is:

$$V_l = \frac{m}{\rho} \qquad (10)$$

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

The second kind of node is one 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 equipment related with phenomena involving water/steam operations. This equipment was not used in the oil systems. In this case closed tanks with oil and air were modeled. For the modeling, the tank is considered to have two separated phases with interfacial contact with heat transfer between them. The air pressure is calculated with the next equation, which is obtained based on an ideal gas behavior:

$$P_a = \frac{m_a\, R\, T_a}{M_a\, V_a} \qquad (11)$$

being M_a the air molecular mass. Expressions (8) and (9) apply for the air phase. The humidity flashed into the air is neglected. The extractors (vacuum pumps) that maintain the vacuity in the tanks are formulated with (2).

VI. Modeled Systems

The oil systems were modeled using the generic models described above. In this section some particular considerations of each model are presented. The common simplifications are those included in the generic models (for example, density and heat capacity are constant). In all the cases the control model associated with the systems were modeled in an independent way (the activation of the automatic actions and the alarms behavior were included in these models).

Additional GMs are employed to solve for the angular speed and current of the pump motors.

A. Gas Turbine Lube and Seal Oil Systems Model

The GTLOS and GTSSO were simulated into a single module. This model includes the pumps, valves, filters and associated pipelines. For the tanks the extractors were included. Also, the bearing metals and the heat exchangers were considered. The oscillation tanks were not included and the dragging of the hydrogen into the oil was neglected.

At a first attempt the model included both oil networks in one equations system. However mathematical instabilities appeared because the magnitude order of the flow rates were very different. To avoid the numerical problems, two independent sets of equations were solved, one for each system. In Fig. 4 a schematic diagram of the networks is presented. The dotted lines represent the common flow rates calculated without using the *flupre* models. In Fig. 5 the control screen of the GTLOS is presented.

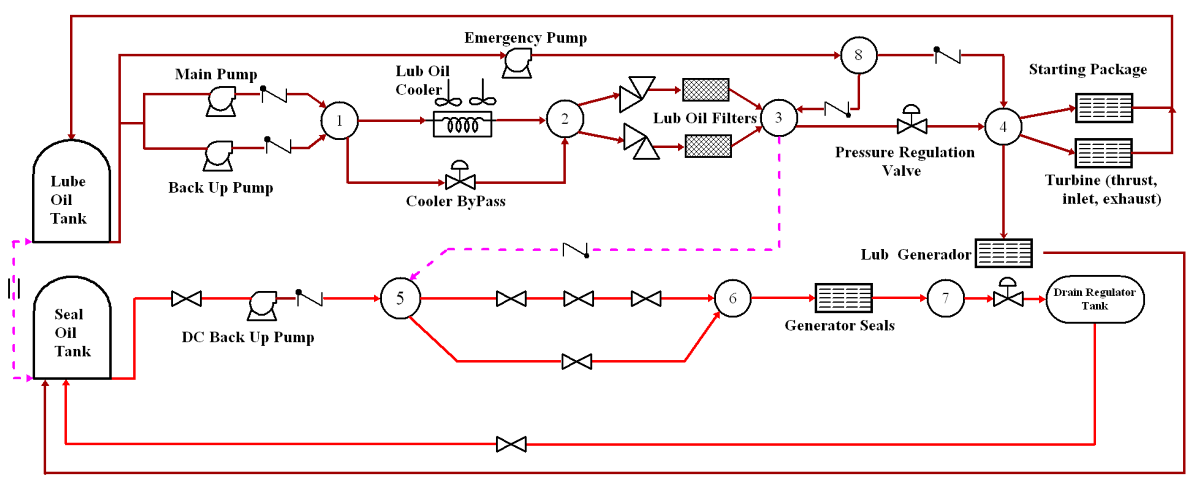

Fig. 4 Gas turbine lube and seal oil systems flows and pressures network

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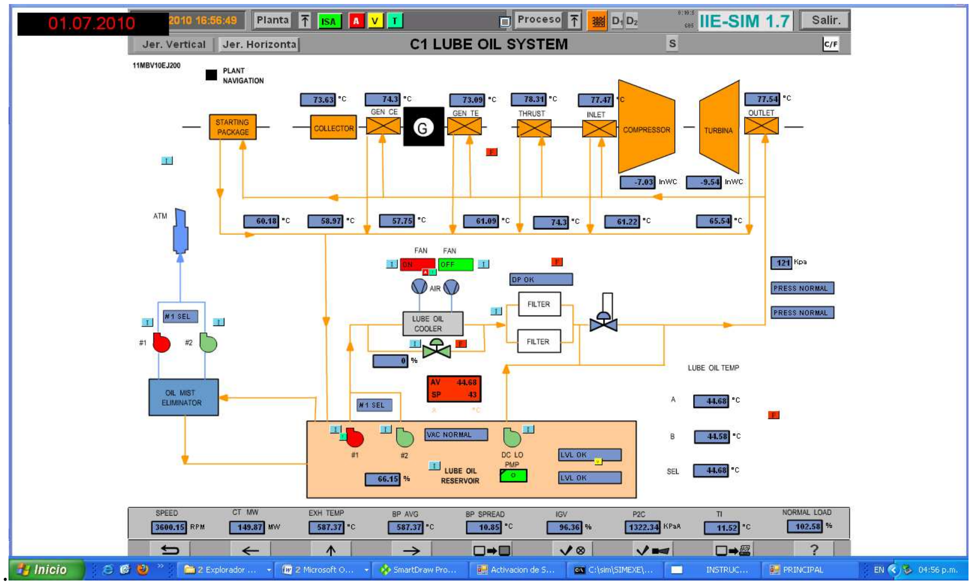

Fig. 5 Gas turbine lube and seal oil systems control screen

B. Gas Turbine Control Oil System Model

The GTCOS model includes the tank, pumps, pipelines, filters, and the heat exchanger. It was modeled with two independent oil networks. The oscillation tanks were not simulated. In Fig. 6 the real control screen of the GTCOS is presented.

C. Steam Turbine Lube Oil Model

The STLOS model includes pipelines, pumps, heat exchangers, rotor bearings and valves. A modeling simplification is the exclusion of oil ejectors at the suction of the main oil pump resulting in taking suction directly from the main oil tank and including their pressure effects in the main oil pump operation curve. The STLOS model is shown schematically in Fig. 7. The flows and pressures network consists of two internal nodes and two external pressure nodes (the lube oil tank simulated in the STCOS and the drain oil tank, both assumed to be at constant pressure). The operator monitoring and control screen is shown in Fig. 8.

D. Steam Turbine Control Oil System

The STCOS was simulated including the lube oil tank with the vapor extractor and the electric heater. The oil conditioner was not simulated.

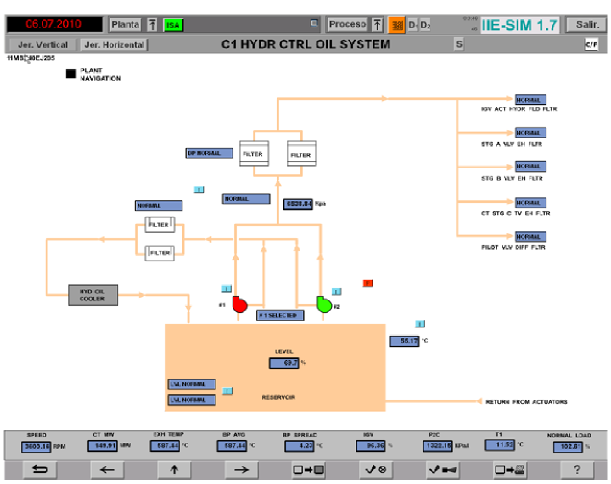

Fig. 6 Control screen gas turbine control oil system

No flows and pressures network was considered; instead simple logic equations were developed for the display of the pressure indicators. The pressures depend on the status of the oil network of the STLOS and the position of the valves controlled by the STCOS. Fig. 9 presents the control screen of the STCOS.

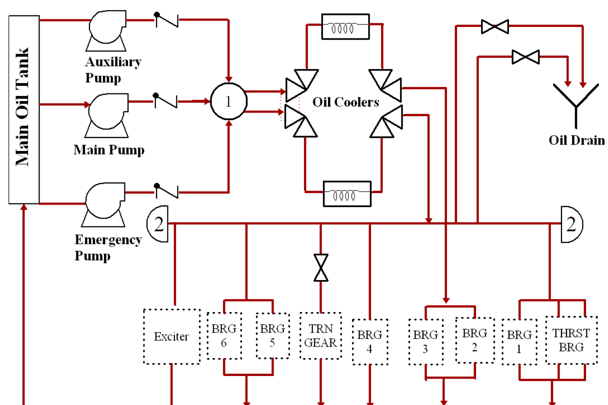

Fig. 7. Schematic diagram steam turbine lube oil system

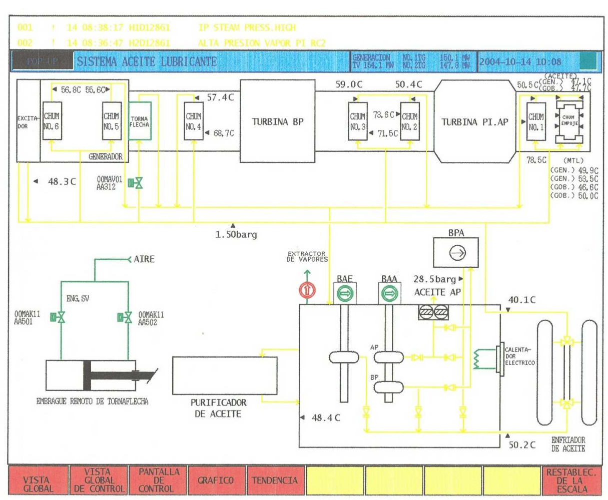

Fig. 8 Control screen of the steam turbine lube oil system

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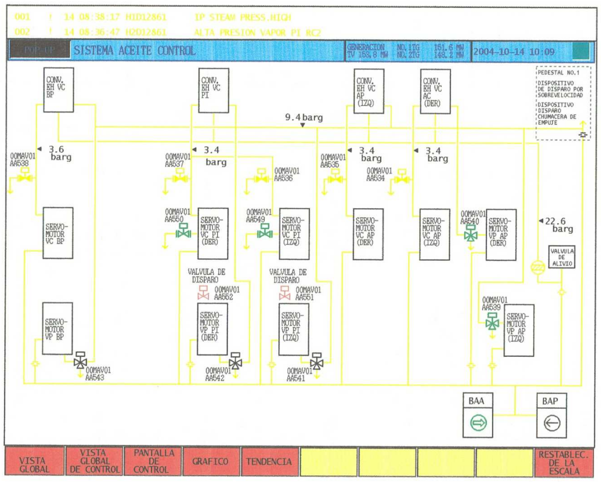

Fig 9 Control screen of the steam control lube oil system

VII. Coupling and Testing

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) that connect the mathematical models, the controls, the operator console, and the instructor console. The goal is to assure that all models have congruency. The global variables are classified and added into a data base. This data base contains the variables declaration for all the simulator programs, parameters values, malfunctions, instruments ranges, remote functions, unit conversions, etc.

Each model, developed independently, is tested off line without the DCS. In this stage it is convenient to have some simplified local 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 sheds. The idea of the tests is to reproduce the design data, normally data of the plant working at 100% of capacity. The global input variables must have an initial value stored in an ASCII format file that may be used as initial condition. For the coupling process, the control models are integrated into the *MAS* without the process models and they are tested to verify its dynamics, including the control screens.

The models are added one by one according to a predefined order, considering the best sequence to avoid mathematical problems as much as possible. An algorithm was developed to minimize the delayed information (global variables) from other models [13].

In each model the initial condition file is updated and tests are performed to assure the coupling is successful. At this stage adjustments are done to avoid mathematical problems and to fix differences between the simulator and the real plant values. When the last model has been added and the 100% initial condition is ready, all the other initial conditions, up to the cold start initial condition, are obtained by operating the plant.

Full factory tests, developed by the final user, are applied to the integrated simulator before it is delivered and installed in its final site.

VIII. Results

To exemplify the results of the oil models, a couple of scenarios are presented. Both were executed with the entire simulator coupled in closed loop. No corrective action by the operator was made during the transients.

The first one is related to the gas turbine. The customer provided plant data for an automatic start up procedure. The simulator results were compared with these data. No data for other transients were available. In Fig.10 a comparison between the expected and simulator speed is presented. The *x* axis is the sum of the gas turbine speed and the load of the gas turbine generator (note that the load is zero while the speed reaches its nominal speed of 377 *rad/s*). The selected variables were the temperatures of the control oil tank and the thrust bearing metal and oil at the exit. The agreement between the simulated results and the plant data is evident.

The second transient consists in testing the steam turbine oil models under the actions reported in Table 1. The reported variables in Fig. 11 are the temperatures in the lube oil tank, at the exit of the cooler, of the metal of the third bearing, and the oil at the exit of the third bearing; and the aperture of the cooler control valve (simulated in the cooling water circuit system).

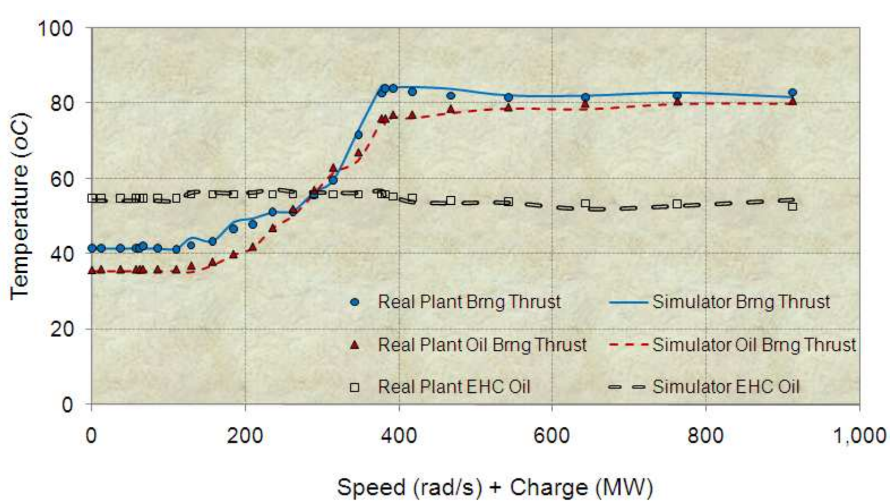

Fig. 10 Gas turbine oil models results

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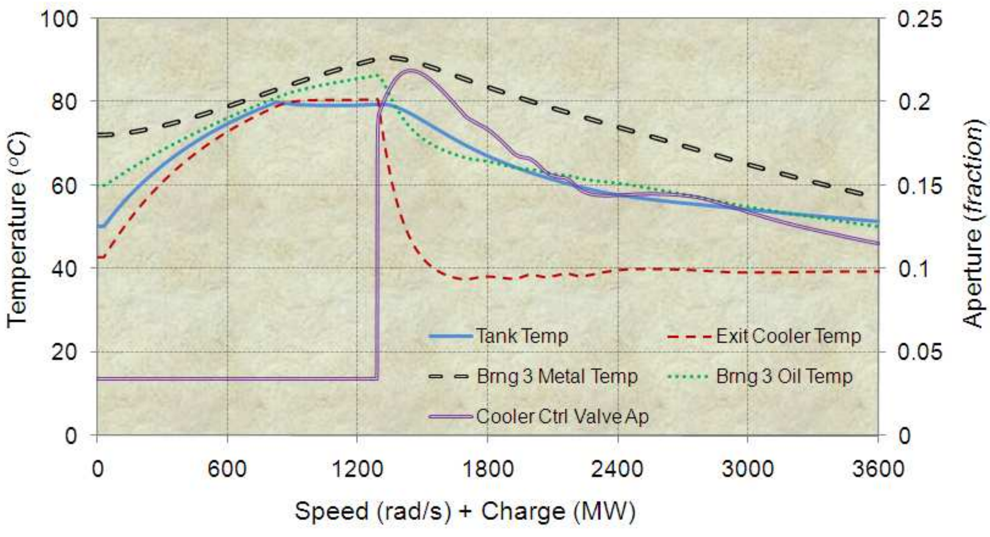

Fig. 11 Steam turbine oil models results

Table I. Test events of the steam turbine oil models

Time (*s*)	Event
0	Simulation starts at 100% of load in steady sate with the lube oil cooler control valve stuck at a position of 33% (a malfunction)
30	The electric oil heater is turned on. The temperatures of the system (oil and metals) increase.
830	The electric oil heater trips automatically when the oil temperature in the tank reaches 80 ^{o}C. The temperatures in the tank and at the exit of the cooler stop augmenting The metal and oil temperatures at the exit of the bearing keep raising until an inflexion point is reached at 830 *s*.
1200	The steam unit trips due to high temperature in the turbine metals (the 3rd bearing metal temperature reaches 89 ^{o}C). The metal and oil temperatures continue increasing because the turbine speed, although lowering, continues with a high value.
1290	The cooler control valve is released from its malfunction. The valve opens quickly trying to control the oil temperature (at 40 ^{o}C). All the metal and oil temperatures descend.

From a qualitative point of view, the simulator results are in agreement with the expected behavior the plant would have if the same transients were applied on the real plant.

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