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UPGRADE OF A FULL-SCOPE SIMULATOR FOR FOSSIL-FUEL POWER PLANTS

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ABSTRACT

The upgrade of a full-scope simulator for fossil-fuel power plants is presented. The mathematical models of a control board simulator have been re-hosted on a new simulation environment based on Windows XP. In order to improve the simulator capacities, the turbine model and the turbine control model are replaced by models with a wider scope. The turbine model is based on physical laws and has an application range from cold iron up to full-load generation and shutdown operations. On the other hand, the turbine control model is based on the main features of modern electrohydraulic controls and has a full application range too. This simulator has been extensively tested during steadies and transient states and its response has been validated with regard to data plant by the instructors of a training center for power plant operators.

1 INTRODUCTION

Full-scope simulators incorporate detailed modeling of those systems of the referenced plant with which the operator interfaces in the actual control room environment. Usually, replica control room operating consoles are included. In these simulators, the responses of the simulated unit are identical in time and indication to the responses received in the actual plant control room under similar conditions. A significant portion of the expense encountered with this type of simulator is the high fidelity simulation software that must be developed to drive it. The completeness of training using a full-scope simulator is obviously much greater than that available on other simulator types since the operator is performing in an environment that is identical to that of the control room. Experienced operators can be effectively retrained on this simulators because the variety of conditions, malfunctions, and situations offered do not cause the operator to become bored with the training or to learn it by rote (Instrument Society of America 1993).

Currently, full-scope simulators are recognized worldwide as the only realistic method to provide real time and hand-on training of operators. Also the simulators are utilized to validate the normal operating procedures, to conduct engineering studies and to train plant technical supporting personnel (International Atomic Energy Agency 2004). Outstanding topics on simulation methodologies and mathematical modeling related with power plants are shown by Flynn (2003).

In 1998, as a part of a project supported by the Mexican Federal Commission of Electricity (CFE), the Mexican Electric Research Institute (IIE) re-hosted a 300 MW fossil power plant simulator, from its platform *Gould* to a *Compaq* Work Station. This real time and full-scope simulator has a replica of a power plant control boards, and it has helped to cover the training requirements of the CFE, but due to the last changes carried out in the power plants, where the control boards have been replaced by personal computers with interactive process diagrams, the Ixtapantongo National Training Center for Operators (CNCAOI) detected the necessity of having a simulator with a new operator Human Machine Interface (HMI). This necessity gave as a result a new simulator based on personal computers and using *Windows XP* as operating system (Tavira et al. 2008). In this simulator the HMI for the operators is based on computers monitors, where the operators control and supervise the simulated process.

As a complement of this project, the CNCAOI asked to the IIE to replace the turbine and turbine control former models. The main requirements for this substitution were: 1) the turbine control model must have speed and acceleration automatic controls; 2) the turbine control must have a wide scope for operation with full/partial arc; 3) the turbine model requires to improve its precision throughout transients tests; 4) the substitution of these mathematical models must be done with no detriment of other processes.

Additionally for expanding the training courses scope, the CNCAOI requires a mathematical model for evaluating the boiler efficiency in the same way as it is done in actual power plants.

This paper presents the results of upgrading a fuel fossil power plant simulator, where the majority of the mathematical models of a former simulator are re-hosted in a new platform based on *Windows XP*, and where the turbine and turbine control models are replaced by new ones, and a boiler efficiency model is added to the simulator.

The next sections show the main features of the current simulator models, a description of the new turbine and turbine control models, and finally are shown the simulator results for steady and transient states.

2 SIMULATOR ARCHITECTURE

The computer platform consists of five PCs interconnected through a Fast Ethernet local area network. Each PC has a 3.8GHz Pentium 4 processor, 1 GB memory and *Windows XP* operating system. The Figure 1 shows a diagram of this architecture. The IC station is an instructor console with two 19 in. monitors, the OC1, OC2 are the operator consoles, each one with two 19 in. monitors; the AC is an auxiliary operator console with four 50 in. monitors; the AD is a station for watching the flames of boiler simulated and customized digital displays, this station has two 14 in. monitors. The operator can use anyone of the OC1, OC2 and AC for supervising and controlling any process of the power plant simulated.

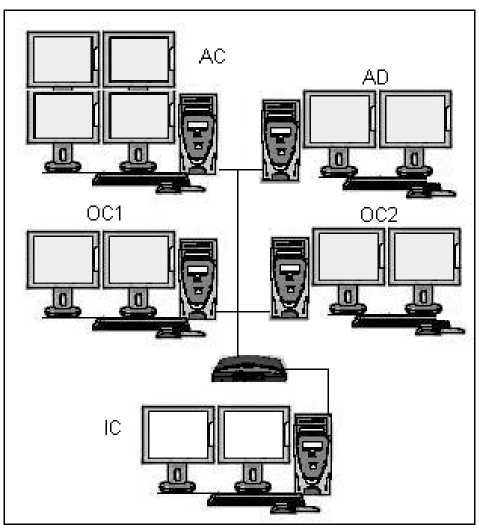

Figure 1: Simulator Architecture

The HMI operator is completely graphical and based on a multi-window environment, the operation diagrams are organized in hierarchical levels, following the power plant organization, i.e. boiler, turbine, etc. There are two main types of diagrams: information diagrams and operation diagrams. The formers show to the operator values of selected variables by him, or a predefined set of variables, the values are presented as bar or trend graphs. The operator uses the operation diagrams for controlling and monitoring the whole process. This HMI is especially suitable for training operators of modern power plants where the operators do not use control boards any longer.

The software architecture of the simulation environment has three main parts - the real time executive, the operator module, and the instructor console module. Each one of these modules is hosted in a different PC, and they are connected through the TCP/IP protocol. All these modules are programmed in C#. This software architecture is described in detail by Tavira et al. (2008).

3 MATHEMATICAL MODELING

In a full-scope simulator, the models must be able to reproduce, in a dynamic way, the behavior of the power plant in any feasible operation, this means any steady state from cold iron up to full-load generation, and transients states, as a part of operation itself or because of malfunctions.

The simulator mathematical models are divided in three groups: electrical, process and control. In the first group are the models of electric generator and electric network, their mathematical formulation is based on Park theory and Kirchof's law, the main variables calculated for these models are: power generation; turbine-generator speed and power plant voltages. The process models consist of the water cycle and its auxiliary services, their main components are: boiler; combustion process, main and reheated steam; turbine; condenser and feedwater heaters; all these models are formulated on the basis of momentum, heat and mass conservation principles. Some of the main variables calculated for these models are: flow rate, pressure and temperature of steam; flow rate, pressure and temperature of feedwater; and main condenser pressure. For customizing the models to the actual power plant, each one of the equipment (tanks, valves, pumps, fans, heat exchangers, etc.), are characterized with design information and operation data.

Finally, the control models simulate the digital and analog control loops of the actual plant. The digital loops deals with all the required conditions for turning on/off any equipment as: pumps, fans, valves. On the other hand, the analog control is devoted to maintain process variables (pressures, temperatures, etc.) in pre-set values. Examples of the major control loops simulated are: boiler level, main steam temperature and combustion control.

Depending of their complexity, the mathematical models are constituted by linear algebraic equations, nonlinear algebraic equations, differential equations or a combination of them. Linear equations are solved with LU decomposition methods. Newton-Raphson methods are utilized for solving the algebraic nonlinear equations. The differential equations are solved with fixed step-size integration methods.

The mathematical models described previously were developed at the IIE as a part of the original control board simulator and all of them are programmed in Fortran, therefore, they were migrated from Fortran Unix to Fortran Intel 9.1, and re-hosted in the new simulation environment. These tasks were done for all the models with the exception of the turbine and turbine control models, which were replaced by new models.

The modular sequential approach is conserved in the new simulator architecture; consequently the models are still using the same step-size integration methods.

3.1 Specifications for the New Models

In a previous section was established the CNCAOI necessity of improving the response of the current turbine and turbine control models. The requirements for these new models were established by the CNCAOI, and they can be summarized as:

1) The high pressure turbine must be simulated with its eleven stages; each one of the two intermediate pressure turbines must be simulated with their four stages and the low pressure section must be simulated with its six stages.
2) The turbines must have seven steam extractions and a 300 MWatts capacity at a speed of 3600 rev/min.
3) The pressure and temperature for main and reheated steam must be the same as they are in the control board simulator.
4) The turbines steam valves must contain: two main throttling valves, eight governing valves, two stop reheated valves and two intercept valves.
5) The turbine metal temperature profiles during transients and steady states must be similar to plant data.
6) The turbine control must contain:
   a. Speed and acceleration controls.
   b. Steam flow unit for carrying out full/partial arc operations.
   c. Power control with variable rate.
   d. Protection interlocks.
   e. Devices for habitual tests of valves.

For accomplishing these requirements the turbine and turbine control models are divided in three parts, turbine-steam side (TS), turbine-metal side (TM) and electrohydraulic control (EC). In order to identify the interaction variables among the current simulator models and the new ones, a causality diagram was done. The Figure 2 shows this diagram in a simplified way, the arrows signify the information flow, the ellipses are the models and the communication symbols (p, w, Ω, etc.) represent one o more interaction variables, e.g., the models TS and FW exchange information for each one of the turbine steam extractions with their corresponding feedwater heaters. The TS model is closely related with all the major components of the steam cycle, as main steam (MS), reheated steam (RH), feedwater system (FW) and main condenser (CO). The lower part of the diagram shows the causality among the models TM and EC with the TS model and with the electric generator (EG).

In the following sections the main features of the TS, TM and EC models are described.

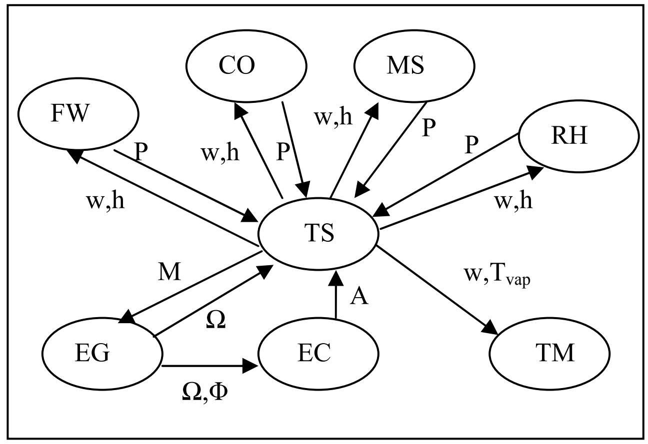

Figure 2: Causality Diagram.

3.2 Turbine Model

The turbine model of the control board simulator has limitations due to the methodology adopted for its development, because of this, in some cases the metal temperatures were calculated in an isolated way, with a weak dependence of the pressure and temperature of its steam. Therefore the metal temperatures have each one its own warming dynamic, which in transient operation causes an abnormal behavior of the thermal expansion.

For modeling purposes, the new turbine model is divided in two parts, the steam side and the metal side.

The aim of the turbine-steam side model is to calculate the inlet flow rates to the turbine and evaluate its outlet flow rates and produced mechanical power. The inlet flow rates come from the main and reheated steam headers, and the outlet flow rates go to the feedwater heaters and main condenser.

The TS model has an inertial part and a resistive part. The former solves in a dynamic way the variation of steam composition as a part of the air-steam mixture. This composition is modified by operation actions like opening the vacuum-breaker valve, or because of the turbine warming process.

The static part of the TS model is based on the methodology shown by Tavira and Arjona (2001), which supposes that turbine is working in steady state in each one of the time intervals defined by the integration step; the solution is obtained by solving the momentum equations in steady state for the valves and turbine stages, and the continuity equation for the points where the flows are joined or split. The main equations of this solution are described below.

In a general way, for liquids and gases, the flow rate through valves is calculates as:

$$W = K \; Y \sqrt{X \rho P_i} \tag{1}$$

where, K is a the valve conductance, $X=1- P_o / P_i$, and Y is the expansion factor. This factor compensates the changes in fluid properties due to expansion of the fluid through the network (Crane, 1988). For liquids $Y=1$, and for gases the choking flow condition is verified as:

$$Y = 1 - \frac{X}{3G\beta} \; ; \; X = G \; \beta \Leftrightarrow G \; \beta \leq X$$

where G is the ratio of specific heats factor. The standard uses $G_T = \gamma / 1.4$. Additionally, β is the rated pressure drop ratio factor and it is characteristic of the valve type.

The calculation of the flow through the turbine stages is better approximated by :

$$W = J \sqrt{2 \frac{m}{m-1} P_i \rho_i} \sqrt{p^{2/m} - p^{(m+1)/m}} \tag{2}$$

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

$$p = \frac{P_i - \frac{P_i - P_o}{\delta}}{P_i} \quad ; \delta \geq 1$$

δ is the stages number where the flow rate is being evaluated.

The Figure 3 shows a typical arrangement of a turbine tandem. This tandem has turbines of high, intermediate (2), low pressure, and all the steam valves described in the section 3.1. We define a flow-node as a point in a flow-pressure network where the steam lines are joined or split; so the flow-nodes are related with headers and steam extractions.

In steady state, the continuity equation in any flow-node satisfies:

$$\sum W_i - \sum W_o = 0$$

In a general approach, the application of equations (1) and (2) to all network flow-nodes yields a system of simultaneous nonlinear equations:

$$F \left[\sum W_i - \sum W_o \right]_{k=1,nd} = 0 \tag{3}$$

This system is solved by the Newton-Raphson method. The construction of the Jacobian matrix is made with the analytical or numerical first-order partial derivatives with respect to the flow-nodes pressures P_k.

The steam enthalpy of the flow-nodes related with valves are calculated from the isenthalpic flow assumption, while for turbine stages, their efficiency definition is utilized

$$h_j = h_{j-1} - \eta_j \left(h_{j-1} - h_{ideal.j} \right) \tag{4}$$

η_j is the stage efficiency and it is calculated with actual plant operation data. $h_{ideal,j}$ is the isentropic enthalpy for the stage. With these enthalpies, the mechanical power is evaluated as:

$$M = \sum w_j \left(h_{j-1} - h_j \right)$$

Finally, the steam temperature in each one of the flow-nodes is evaluated with correlations like:

$$T_{vap,k} = A_1 + A_2 \sqrt{P_k} \tag{5}$$

A1 and A2 are quadratic polynomials depending of the enthalpy. The solution of equations (3), (1) and (2), and equations (4) and (5) yields a discrete profile of temperature, flow rate and pressure of steam, which serves as base information for the TM model.

The turbine-metal side model evaluates the warming and cooling processes of the turbine metals according to the flow rate, pressure and temperature of steam in any feasible operation.

For this goal, the turbine is assumed like two infinitely long concentric hollow cylinders, where the steam is flowing inside the annulus. The heat transfer for the metal surface is defined as:

$$Q = H \left[T(r,t) - T_{vap}(t) \right]$$

where $T(r, t)$ represents the metal temperature in the radio r at the time t; T_{vap} is the steam temperature at any time, and H is the heat transfer coefficient.

The differential equation for heat conduction in one dimension for an infinitely-long hollow cylinder, is given by:

$$\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r,t)}{\partial r} = \frac{1}{\alpha} \frac{\partial T(r,t)}{\partial t} \tag{6}$$

where

$$\alpha = \frac{k}{\rho \, Cp}$$

The values of heat capacity Cp, density ρ and thermal conductivity k, are evaluated to the fluid bulk temperature.

For solving the equation (6), this is replaced by a linear equation via implicit finite differences method and dividing the rotor in concentric cylinders of constant thickness a. In a series expansion, the time-temperature dependence is expressed as:

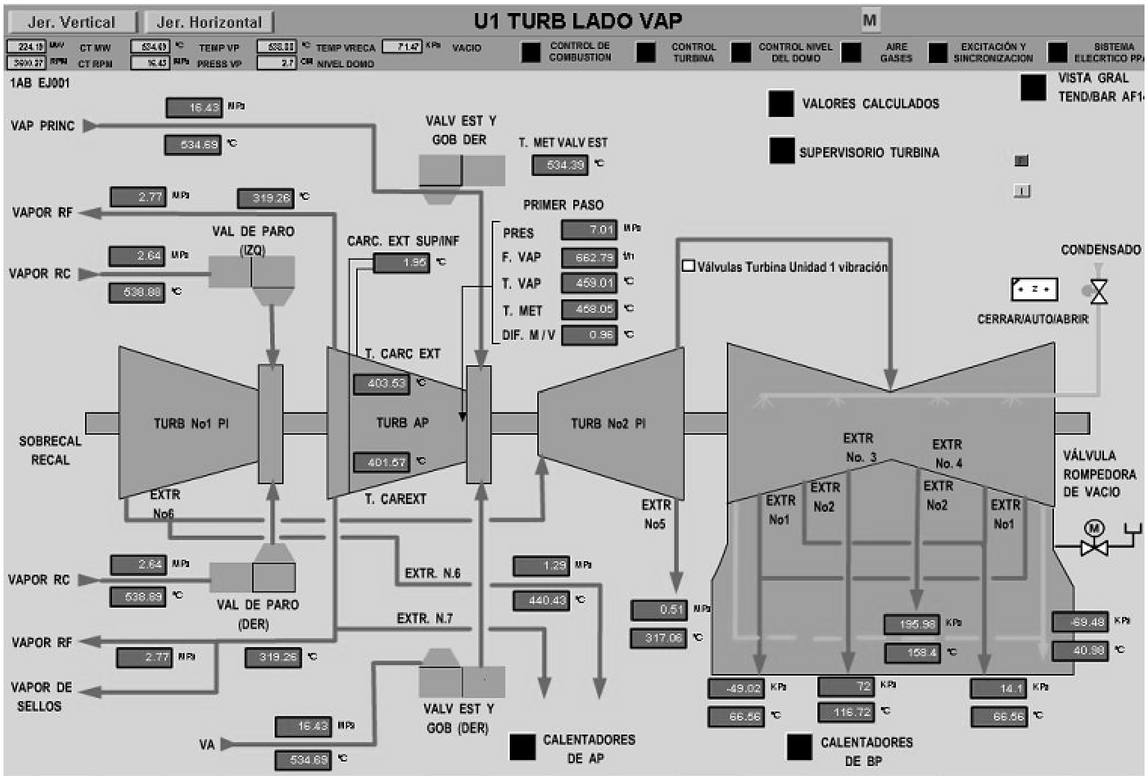

Figure 3: Turbine Arrangement

$$\left(\frac{\partial T}{\partial t}\right)=\frac{T_n^*-T_n}{\Delta t}$$

where:

T_n - Temperature in the n element at time t.

T_n^* - Temperature in the n element at time $t+\Delta t$.

The equation to evaluate the temperature in the internal elements, is given by:

$$T_n^*=T_n+\frac{\alpha\Delta t}{a^2}\left[\left(1+\frac{a}{2r_n}\right)T_{n+1}-2T_n+\left(1-\frac{a}{2r_n}\right)T_{n-1}\right]$$

In the same way, for the elements in contact with steam:

Rotor:

$$T_{n+1}^*=\frac{4\,T_n^*-T_{n-1}^*+2a\,\dfrac{H^*}{k}\,T_{vap}^*}{3+2a\,\dfrac{H^*}{k}}$$

Casing:

$$T_0^*=\frac{4\,T_1^*-T_2^*+2a\,\dfrac{H^*}{k}\,T_{vap}^*}{3+2a\,\dfrac{H^*}{k}}$$

and for the elements with no heat flux across (large drill rotor):

$$T_0^*=\frac{4\,T_1^*-T_2^*}{3}$$

On the other hand, under combined conditions of turbulent flow, rotation and eventually condensation. The heat transfer coefficient is evaluated according to Pasquantonio (1976), Manrique (1998) and Pioro et al. (2004), so:

$$H=0.023\frac{k}{D}\left(\frac{D\nu\rho}{\mu}\right)^{0.8}\left(\frac{Cp\mu}{k}\right)^{0.4}$$

Because of this approach, a complete thermal behavior of the turbine metals is evaluated. In this model, the metallic surfaces are in direct contact with the steam, so the absorbed heat by the metal is dependent of the steam conditions, rotor geometry, casings, valves chest, etc. In this way, the heat is transferred from the steam to the metal entrails until its temperature becomes uniform. Therefore if the steam temperature increases suddenly, the metal undergoes an abrupt warming, this bring as a consequence a differential thermal dilatation between rotary and stationary turbine parts, in this case the rotor is heated faster and consequently it dilates before than the casing. The dilatation or contraction is simulated only in the axial direction, because it is the biggest of the three dimensional problem.

As a complement of the turbine model, it is included a program for evaluating the rotor vibration amplitude. This part of the model is constituted by a system of partial differential equations in the space-time dominion; the equations are based on: linear elasticity theory, linear momentum balances, and the equilibrium inside of the body boundaries. The system is solved by finite element method, this one yields a discrete numerical model of the rotor deformation. The vibration problem of the rotor is related to the elastic body in movement, so that:

$$\mathbf{u}(x,t) = \mathbf{q}(x) \bullet \alpha_i cos(\omega t + \upsilon)\hat{\mathbf{e}}_i = \mathbf{r}(x)cos(\omega t + \upsilon)$$

$$\mathbf{E}(x,t) = \mathbf{E}(x)cos(\omega t + \upsilon)$$

$$\mathbf{S}(x,t) = \mathbf{S}(x)cos(\omega t + \upsilon)$$

where: $\mathbf{u}(x, t)$, $\mathbf{r}(x)$ are displacement fields (vibration amplitude), $\mathbf{E}(x,t)$, $\mathbf{E}(x)$ are tensor fields of deformation, $\mathbf{S}(x, t)$, $\mathbf{S}(x)$ are tensor stresses, $\mathbf{q}$ are the base functions of approximation space, x is any point of the geometric dominion, t is the time, ω is the vibration frequency, υ is the phase angle of the vibration and α are the coordinate vectors relative to the space base of approach.

3.3 Turbine Control Model

The control board simulator has turbine control model with a simplified mechanical-hydraulic governor, where the operator carries out the regulation process in almost a manual way, so it has a rough regulation of the speed and main steam flow rate. The main elements of the governor are: main governor, auxiliary governor, load limiter and the load rejection anticipator. Due to this, the operations for increasing the speed of the turbine and the power generation were actions very dependent of the operator skills.

With the aim of having a simulator with a modern turbine control, a new control model based in one with electro-hydraulic technology was developed and implanted in the new simulator.

The actual control utilized as a reference is an electro-hydraulic control with digital processing. This control has three main components:

1). Digital processing. It is devoted to solve the equations for carrying out the functions of control and protection.

2). Electro-hydraulic interfaces. They convert control signals from electric current to control oil pressure.

3). Hydraulic actuators. They are the final control elements and they are constituted for two main throttling valves, eight governing valves, two stop reheated valves and two intercept valves.

The new turbine control model simulates these elements with generic control elements as: proportional and proportional-integral controllers; linear functions; arithmetic operators, Boolean operators, etc. The model has the next features: closed loop of speed control, open loop of power control, acceleration control, manual power limiter, thermal stress limiter, pressure regulator, vacuum unloader, full/partial arc transfer, automatic acceleration during critical speeds, over speed protection control, over speed mechanical trip, electrical over speed trip, and devices for testing valves.

Because of the high automation degree of this control, it is possible to carries out operations for increasing the turbine speed with a variable set point; this can be done with three different rates: 90, 180 and 360 rev/min^2. The full and partial arc actions have a wider scope, so the operator can switch from full to partial arc before or after the synchronization process. The power generation is too enhanced due to the power control with variable rate from 0 to 35 MWatt/min.

3.4 Efficiency of the Steam Generator

The methodology for evaluating the boiler efficiency is based on the looses method defined by the CNCAOI. This method calculates all the additions and looses of heat related with the steam generator. The most important input data required for the model are: flow rate, temperature, composition and higher heating value of fuel; temperature and composition of flue gas; temperature and moisture of the air. The main heat additions are due to: fuel oil, combustion temperature and air moisture. The main heat looses calculated are due to: heat contained in the flue gas to the stack, hydrogen combustion and radiation.

With this information, the algorithm calculates the steam generator efficiency and also includes the evaluation of the air leaks from the regenerative heaters and their corresponding efficiencies.

All the mathematical models are programmed in Fortran with a similar methodology to the others simulator models.

Before incorporating each one of the new models to the simulator, they were tested and validated in an independent way, and their corresponding step-size integration methods were defined. After that, they were introduced into the modular sequential solver according to their causality.

A summary of the main features of the simulator models is shown in the Table 1.

4 RESULTS

The Table 2 shows the absolute value of calculated errors for some of the most important variables of the simulated process for three power generation steady states. These errors are evaluated with regard to actual power plant values. The first seven variables are very important because they are directly related with the generation capacity of the power plant, for these variables the CNCAOI asks for a maximum error of 2 %, this criterion is satisfied with the exception of the pressure and flow rate of reheat steam at 225 MW, where there are lightly bigger errors (2.38 % and 2.42% respectively), these little discrepancies should not affect the training courses quality. For the other variables in Table 2, the CNCAOI asks for a maximum error of 10%, and this criterion is satisfied too.

Table 1: Simulator Models

Topic	Value
Number of Process and Electric Models	26
Number of Control Models	16
Numerical Method for Linear Algebraic Equations	LU Decomposition
Numerical Method for Nonlinear Algebraic Equations	Newton-Raphson
Numerical Methods for Differential Equations	Euler and Second Order Runge-Kutta
Integration steps	From 0.125 to 1 sec.
Other Numerical Methods Utilized	Finite Element Method
Analog Variables Simulated (e.g. pressure, temperature, valve position)	730
Digital Variables Simulated (e.g. indicating leds, alarms, push buttons)	1194

Table 2: Error percent of main variables

VARIABLE	Power Generation (MWatt)		
	150	225	300
Output power	0.31	0.11	0.29
Main steam pressure	0.44	0.28	0.40
Main steam temperature	0.15	0.12	0.58
Main steam flow rate	1.01	0.52	0.08
Reheat steam pressure	0.64	2.38	0.60
Reheat steam temperature	0.22	0.25	0.20
Reheat steam flow rate	0.01	2.42	1.46
Pressure of steam extraction 7	5.61	3.29	5.03
Temperature of steam extraction 7	6.39	4.99	1.16
Pressure of steam extraction 6	5.38	2.98	3.34
Temperature of steam extraction 6	0.18	0.41	0.64
Pressure of steam extraction 5	2.40	2.22	1.42
Temperature of steam extraction 5	1.89	4.23	0.98
Pressure of steam extraction 4	3.45	4.37	5.87
Temperature of steam extraction 4	5.23	9.13	1.82
Pressure of steam extraction 3	6.62	3.79	3.16
Temperature of steam extraction 3	5.97	0.37	7.43
Pressure of steam extraction 2	4.94	8.49	9.22
Temperature of steam extraction 2	3.66	8.01	4.77
Pressure of steam extraction 1	1.72	1.08	2.29
Temperature of steam extraction	2.69	1.69	0.24
Steam flow rate to the escape	1.46	2.56	1.56

The Figure 4 shows a comparison between the simulator and the actual power plant during the operation of increasing the turbine speed from 0 to 3600 rev/min. The simulated temperatures of steam and metal in the turbine first stage have good precision with regard to actual plant. The speed control also has a good response and therefore has a suitable behavior. About the main steam temperature, the shown differences are due to the operation actions, where the steam temperature can be modified by the operator utilizing more fuel or increasing the steam flow rate through the superheaters.

4.1 Acceptance Tests

In order to test and validate the dynamic response of the simulator, the instructors of the CNCAOI developed a group of acceptance tests procedures. The aims of these procedures are:

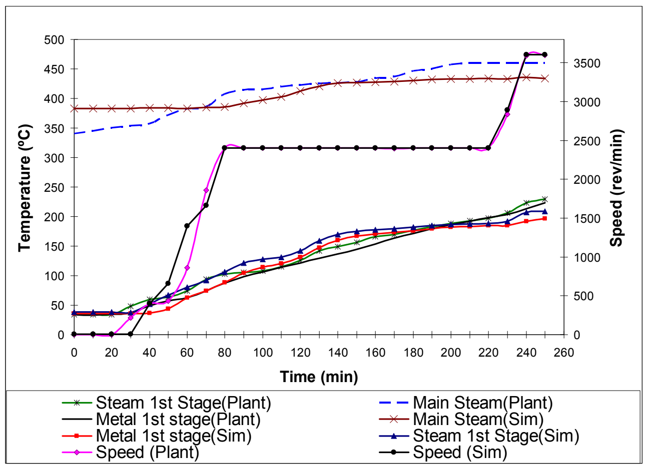

Figure 4: Speed increase from 0 to 3600 rev/min

1) Verifying the simulator response in any feasible operation, e.g., from cold state up to full-load generation, from warm startup up to full-load generation, or shutdown operations.
2) Validating the simulator response when a malfunction is introduced. The malfunction can be introduced in different initial conditions, but in any case, the simulator trends must be agree with the physic phenomena expected.
3) Testing the HMI operator, and their correct interaction with the mathematical models of process and control.

Currently, the simulator is utilized for the operators training courses at the CNCAOI.

5 CONCLUSIONS

With the aim of improving and updating a power plant simulator, the mathematical models of boiler, main steam, feedwater, electric generator and auxiliary services, of a former simulator, are re-hosted in a new simulation environment. The turbine and turbine control former models are replaced by new ones, according to the CNCAOI training requirements.

The new simulator static and dynamic response has been extensively tested and validated with regard to plant data. This simulator has full-scope and real time features, and provides an HMI suitable for the operators of modern power plants, where they have an HMI based on computers monitors.

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NOMENCLATURE

a	Constant thickness
A	Valve position
Cp	Heat capacity
D	Cylinder diameter
E	Tensor field
F	Matrix of the nonlinear equation system
G	Ratio of specific heats factor
h	Enthalpy
H	Heat transfer coefficient
J	Turbine conductance
k	Thermal conductivity
K	Valve conductance
m	Polytrophic coefficient
M	Mechanical torque
Q	Heat transfer
P	Pressure
q	Base functions of approximation space
r	Radius
r	Displacement field
S	Tensor stress
t	Time
T	Metal temperature
T_n	Metal temperature in the *n* element at time *t*.
T_n^*	Metal temperature in the *n* element at time $t+\Delta t$.
T_{vap}	Steam temperature
u	Displacement field at the time
v	Steam velocity
W	Flow rate
x	Any point of the geometric dominion
Y	Expansion factor

Greek letters

α	Coordinate vectors relative to the space base of approach.
β	Rated pressure drop ratio factor
γ	Ratio of specific heats
δ	Number of stages
Δ	Increment
η	Stage efficiency
μ	Viscosity
ρ	Density
υ	Phase angle of the vibration
Φ	Acceleration
ω	Vibration frequency
Ω	Speed

Subscripts

i	Input
$ideal$	Ideal condition
j	Stage
k	Flow-node
nd	Total number of flow-nodes
o	Output

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