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SIMULATION AND CONTROL OF THE CONDENSATE CIRCUIT IN A NUCLEAR POWER STATION

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Abstract

In this paper the simulation of the condenser circuit of a nuclear power plant is presented, as well as the design of its control system. The model used is based on first principles and experimental data. The closed loop system was tested in simulation and then applied to the process, where it is working successfully.

1 Introduction

This presentation deals with the simulation and design of the level control system of a condenser in a nuclear power station in Spain. This unit is an important one in the process, so that on-line tuning and test are not recommended. Instead, the methodology we applied was based in the use of a mathematical representation of the plant in a computer. The design was made using this representation and, after tested, we moved the resulting system to the process.

To follow this path, a non-linear dynamic model of the process was established using a mix of equations based on first principles and experimental data. The model includes not only the condenser but other relevant part of the circuit that affects its dynamic. The simulation was made using the simulation language ACSL, and incorporated two regulators and two manipulated variables operating in a switching mode. For the purpose of the design of the regulators, simpler models were obtained by linearization, which were used for tuning with specific MATLAB functions. Then the whole system, non-linear model and control system, was tested in simulation and, after that, the control parameters were applied to the local controllers of the real plant.

In order to show the main points and results, the paper is organized as follows: Paragraph 2 describes the process as well as the estructure and aims of its control system. In paragraph 3 we develop the mathematical model of the plant and in paragraph 4 some details of the simulation using the ACSL language. Finally in paragraph 5 we deal with the tuning of the regulators and we present some results.

2 Process description

In a power plant, the role of the condensate circuit is is to condensate continuously the steam coming from the turbines and to sent it back to the steam generators. A simplified schematic of the plant we have been dealing with, can be seen in Fig.1. We can distinguish in the upper left corner a steam generator (SG) connected to a turbine (TB) which sends a lower pressure steam flow F_0 Kg/s to the condenser. Here, with the help of a refrigerant flow, this flow is converted into water which accumulates in three interconnected sections.

From the condenser the water is pumped by two parallel pumps (PB) to a set of heaters (DBP), then filtered in another set of filters (FUB) and finally arrives as flux F_{26} to a huge tank, the accumulator (TA). This tank is used to supply a flow Ft to the steam generators, closing the loop in this way.

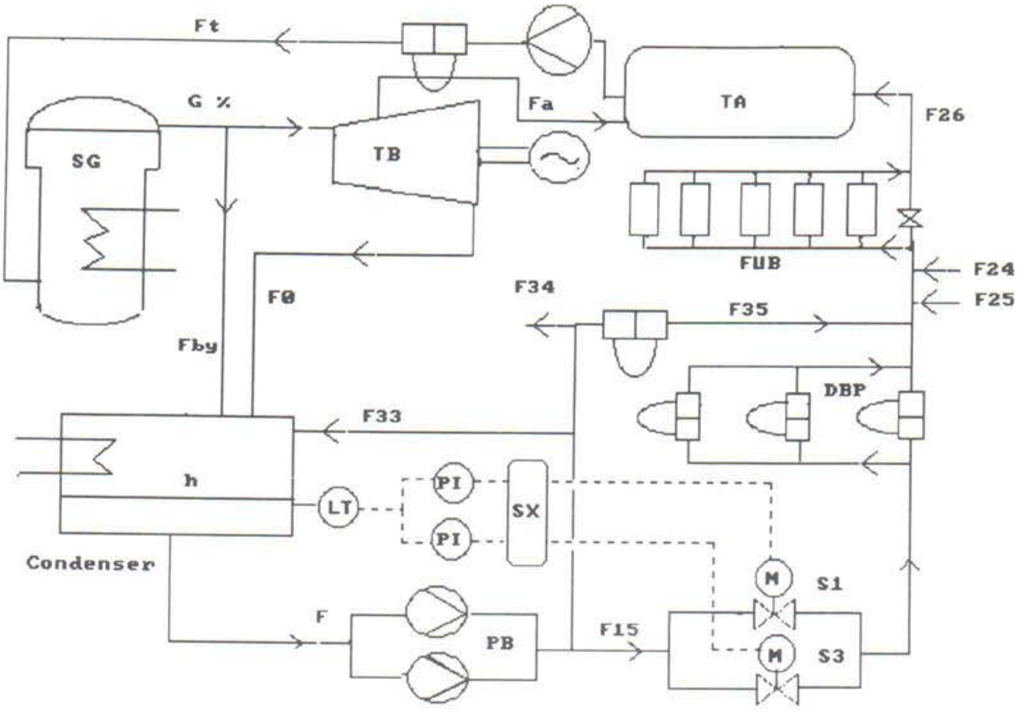

Fig.1 Plant schematic

The two pumps (PB) operate according to a switching policy with a histeresis reflected in Fig.2, where the flow of a pump F_b is plotted against total flow F. A minimum flow is maintained by a recirculating circuit. In the same way, the filters (FUB) have a bypass line that opens if the differential pressure in one of them rises above a certain limit, and that it it used to maintain the pressure drop of the group.

In the schematic we can distinguish also a bypass line of the turbines which sends a flow F_{by} to the condenser. When there is equilibrium between the power that a certain amount of steam generated G is able to produce, and the electrical power actually obtained E, then $F_{by}=0$, but in transients or under other circumstances in which there are not such an equilibrium, F_{by} is not zero. Then, an additional flow of water, F_{33}, is sent to the condenser to compensate for this fact.

Fig.1 shows some other flows like F_{35}, etc and a couple of electrical valves S1 and S3 that can modify the flow F. The main aim of the control system is to maintain the level h of water in the condenser closely around a prescribed set point. The openings of these valves are used as manipulated variables of two PID regulators operating in a split range mode (SX). When the control signal of one of the regulators reach an upper limit, it remains in this position and the regulatory action is taken by the other controller. At the same time, if the error between the control signal and the actual position of the stem of the valve is greater than a limit, the controller is switched to manual.

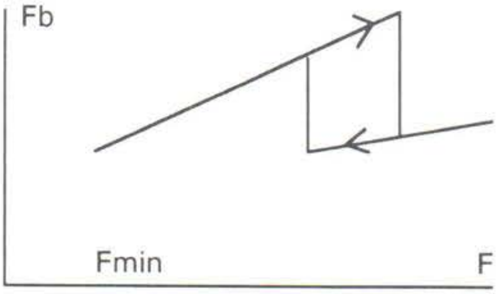

Fig.2 Pump operation

Each regulator is represented schematicaly in Fig.3. As we can see the internal set point is obtained as a non linear function of the electrical power E, the flow F and an external set point w. It incorporates an antiwindup system as

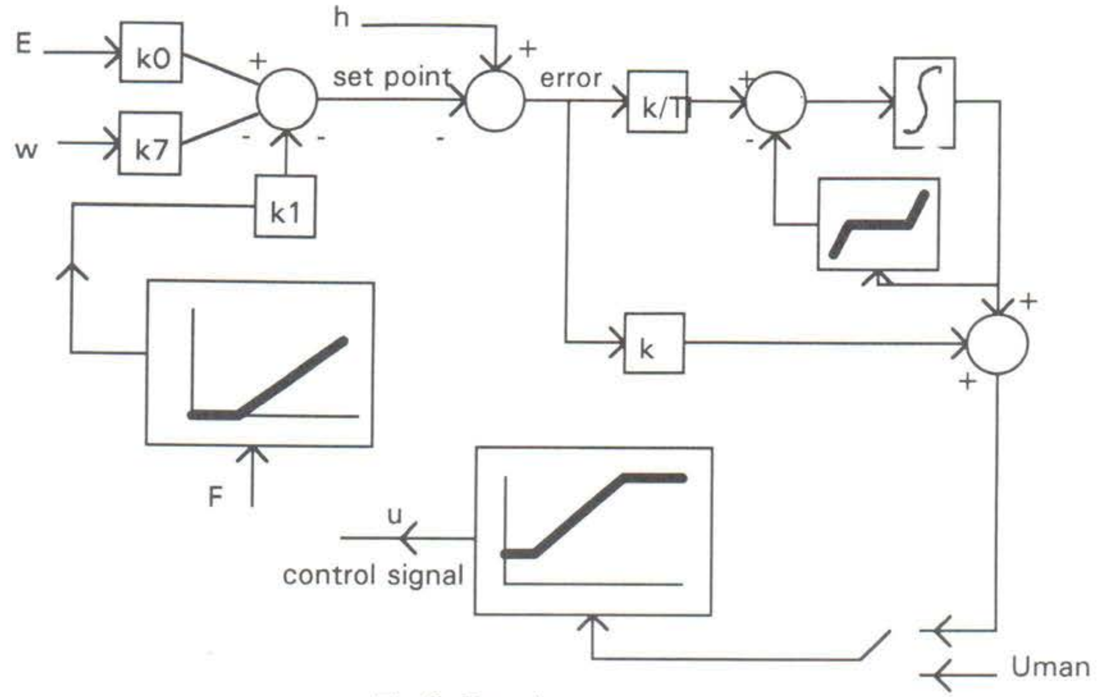

Fig.3 Regulator structure

well as limits in the control signal.

An additional aim is not to disturb the level of the accumulation tank (TA).

3 Mathematical Model

A mathematical model of any process is always based in a set of hyphotesis. On the other hand the goodness of a model is linked to the aim for which it has been built. In our case the goal was to design and test a control system, so the level of complexity has been fitted to this purpose. In particular we have modeled:

- the level in the condensator
- the level in the tank TA
- the condensate flow
- the regulation system

as well as all those elements which dynamic were significant either to the above mentioned elements or to the testing experiments.

Whenever possible, we wrote first principles models. So, with reference to Fig.1, the accumulation of mass in the condenser per unit time leads to:

$$\alpha \frac{dh}{dt} = F_0 + F_{by} + F_{33} - F \qquad (1)$$

where α is a constant, h the level in the condenser and the meaning of the F's has been explained above.

In the same way, in the case of the acccumulation tank we can write:

$$1000 \frac{dV_a}{dt} = F_{26} + F_a - F_t \qquad (2)$$

the relation between the volumen V_a and its associated level h_a is given by the implicit equation:

$$V_a = \gamma((h_a - R)\sqrt{h_a(2R^2 - 1)} + \\ + R^2(\arcsin\frac{h_a - R}{R} + \pi/2) \qquad (3)$$

with R and γ two parameters.

The dynamical behaviour of the flow F can be writen in terms of the pressure drop along the line from the condenser to the accumulation tank. However, due to the branches, added flows, etc we cannot talk of a flow but a set of them, and each should be modeled by a similar equation. Nevertheless, taking into account that the flow in the main branch is far more larger than the others, and defining equivalents cross seccion A and lenght L of the circuit, we have:

$$\frac{L}{10^5 A}\frac{dF}{dt} = p_c + 0.098h_c + p_b - \,.\,. \qquad (4)$$
$$-pp - p_{UB} - p_a - p_h$$

Here p_c is the pressure in the condenser, p_b the increase of pressure given by the pumps, p_v the pressure drop in the valves, p_{UB} the pressure drop in the filters (FUB) and pp in the rest of the line. p_a is the pressure in the accumulacion tank (TA) and finally p_h takes into account differencies in height in the line.

In order to solve these equations we need to compute the values of the flows and pressures of the right hand side of the set (1),(2),(4). In general, these are complex functions of the electrical power E, the generated steam G or the flows. In some cases an equation based in the knowledge of the physical laws of the process can be derived, but, in most of the times it is better to use mathematical relations obtained from experimental data.

F_0, is linked directly to the electrical power E generated by the turbines, and its response is fast enough in relation to the variables of interest, as to assume a non-linear static relation $F_0(E)$ between these variables. From experiments, we had values of E and F_0 in several working points corresponding to 0, 25, 30, 50, 75 and 100% of E. Intermediate values were obtained by interpolation. The same technique was applied to some other variables like $F_{24}(E)$, $F_{33}(F_{by})$, $p_c(E)$, or $pp(F_{15},F_{26})$. $p_{UB}(F_{UB})$ was obtained also by the same procedure, but, here, F_{UB} is the flow throught a filter (FUB in Fig.1), given by:

$$F_{UB} = F_{26}/n_f \qquad (5)$$

being n_f the number of filters in operation, which can change if the bypass line opens due to a pressure drop too high in a filter. In like manner, p_b is given as $p_b(F_b)$ by the characteristics of the pump, being F_b the flow of condensate through a single pump which is linked to F by Fig.2.

By the contrary, in the case of other variables we cannot drop its dynamic. For instance F_{by} can be computed as the difference between G, the flow of steam from the steam generators (SG), and the one to the turbines G_t. This can be obtained as $G_t(E)$, but G has a second order dynamic linking changes in % in steam demand G_v. to changes in G. In order to obtain this relation, first its static gain was determined as before from tables of stationary values and interpolation, giving $G_{ss}(G_v)$. Next, using experimental data from transiets, the coefficents a and b of the second order transfer function

$$G = \frac{1}{as^2 + bs + 1} G_{ss}(G_v) \qquad (6)$$

were adjusted by a least squares procedure to fit the model response to experimental data.

The same procedure allows us to obtain a similar expresion for F_t:

$$F_t = \frac{1}{cs^2 + ds + 1} G_{ss}(G_v) \qquad (7)$$

and for p_a:

$$p_a = \frac{1}{fs + 1} p_{ss}(E) \qquad (8)$$

Finally, p_v, the pressure drop in the valves S1, S3, is related to the flow F_{15} by a known expression:

$$F_{15}^2 = p_v\left(\frac{a_1 C_v}{\sqrt{17.439 + J_1 a_1^2 C_v^2}} + \right. \qquad (9)$$
$$\left. + \frac{a_3 C_v}{\sqrt{17.439 + J_3 a_3^2 C_v^2}}\right)$$

where C_v is the valve coefficient, J's are loss coefficients in each branch and the a's are the percentage openings of every valve. These a's can be obtained from the stem positions m, via the static characteristics $a_1(m_1)$, $a_3(m_3)$ of the valves. The stem positions are determined by the control signals from the regulators and the switching SX, u_1 and u_3, taking into account the dynamic of the actuators, that in our case is given by:

$$\frac{dm_1}{dt} = \beta \text{sign}(u_1 - m_1)$$
$$m \,\varepsilon\, [0,100] \quad (10)$$
$$\frac{dm_3}{dt} = \beta \text{sign}(u_3 - m_3)$$

beeing β a coefficent.

4 Simulation and validation

The mathematical model as well as the control system of Fig.3 and the switching policies, were simulated using the simulation language ACSL. The program was organized so that, initially it was possible to obtain, for a given operation point given by E and G_V in equilibrium, the control signals that maintained the process in a stationary state. In this way, the response to any action was due to that action only. The simulation gives us the time evolution of the variables of interest in the process, according to the programmed experiences and process parameters. These where obtained in most cases from the documentation available, but some of them, L/A, J_1, J_3, had to be estimated. The procedure used was to minimize an error function between the flow and level responses of the model (which depend on these parameters) and a set of experimental data in response to the same action: a ramp change in electrical power. After that, another set of data was taken to validate the model.

Two kind of experiments were performed for this purpose. Fisrt we validate equation (4) by writing another simulation program in which E evolved according to a positive ramp pattern and the experimental values of E, h_C, m_1 and m_3 where given to the same variables in this equation. Fig.4 shows the time evolution of E and the stem position m_3 and, in the bottom picture, two graphs corresponding to F given by the experiment and by the model. As we can see there is a good agreement between both.

In a second kind of tests, the whole circuit was involved. In this case the upper graph of Fig.5 gives the values of level in the condenser from the model and from the experiment for the same test as

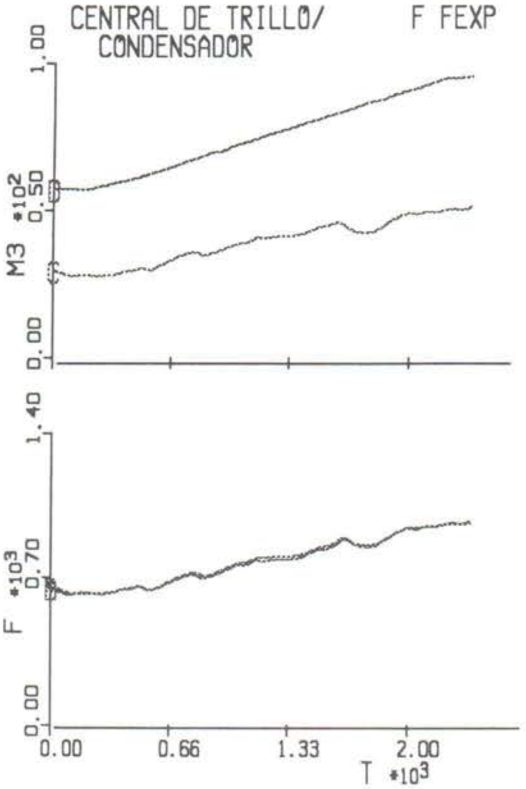

Fig.4

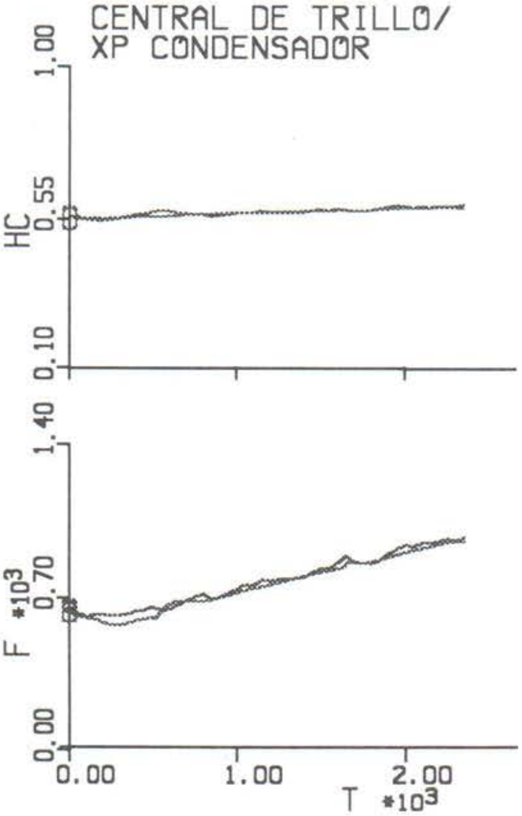

Fig.5

before:a positive ramp input in E. In the bottom we can see the values of the main flow F, again from the simulation and field data. As a result of these test, an others that were performed, we concluded that the model was good enough as to be used for the design of the control system.

5 Control system design and implementation

One of the aims of this project was to retune the existing control system for a new situation in which the valves S1, S3, had been changed for new ones. Besides computing the new values of the controllers parameters, this includes the switching network and and extensive set of tests to assure that the new system will respond well in a wide set of situations.

The control policy was to operate with a valve until its opening reached a maximun, and from this point to start working with the other. The tuning was made using a linear model computed with the facilities offered by ACSL. Then the controllers were tested with the non-linear model. Some results are presented in Figs 6 and 7. In this experiment a jump from 100% of electrical power down to 40% was simulated. The first graph shows the level inthe condenser, that it is keep quite well by the control system. Bellow we can see the action of one of the controllers and the evolution of F. In Fig.7 The jump in E is seen as well as the values of G and F_{33} and the bypass flow during the transients. After testing the design, it was applied to the process and has been working with sucess from then.

References

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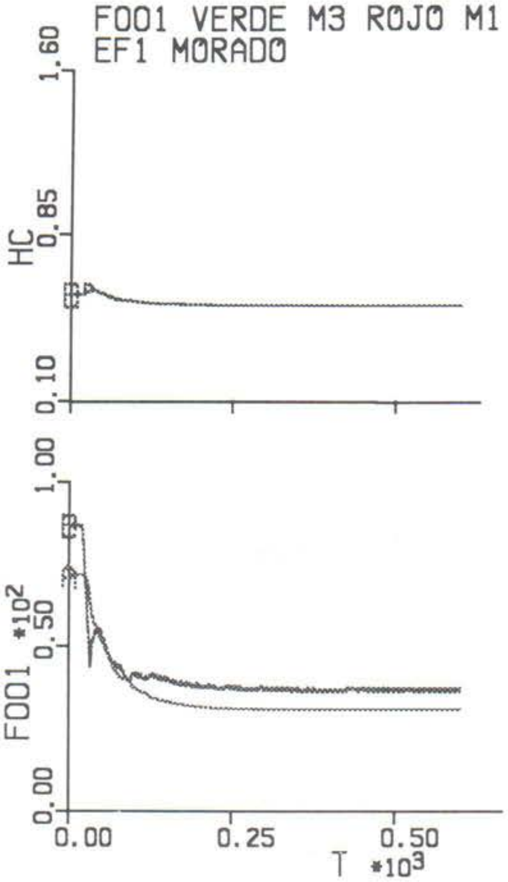

Fig.6