

U-TUBE STEAM GENERATOR - UTSG, A MATLAB DYNAMIC SIMULATION APPLICATION

Lamartine Nogueira Frutuoso Guimarães

Institute for Advanced Studies, Rodovia dos Tamoios km 5,5, Torrão de Ouro, São José dos Campos, SP, 12228-840
guimarae@ieav.cta.br
And Universidade Braz Cubas, Mogi da Cruzes, SP

Nilton da Silva Oliveira Jr.

Universidade Braz Cubas, Mogi da Cruzes, SP

Eduardo Madeira Borges

Institute for Advanced Studies, Rodovia dos Tamoios km 5,5, Torrão de Ouro, São José dos Campos, SP, 12228-840
eduardo@ieav.cta.br

***Abstract.** In this work a U-Tube Steam Generator - UTSG model is presented. This model was developed as test bed to build complete power plant simulators. The UTSG is an ordinary component of most of the Pressurized Water Reactors - PWR. A proportional-integral three element controller was also coupled with the UTSG model. Also a user-graphical interface was developed to allow a good visualization of the dynamical behavior of the UTSG during steady state and transient modes. This model is part of a library called SIMODIS - Simulation MODeling Integrated System ("Sistema MODular Integrado de Simulação"). Some transient analysis results will be presented as well. The developed simulation program together with the graphical interface was developed in MATLAB.*

***Keywords.** Steam generator, simulation, UTSG, PWR*

1. Introduction

Steam generators are very important components in nuclear power reactors. They have basically three functions: generate steam for the power turbine to produce power, be a separating boundary between the primary and secondary water coolant and with the reactor shut down remove the residual reactor heat. The separating boundary function is of special relevance because it isolates the cooling water that goes through the reactor, and therefore carries irradiated products, from the water that is transformed into steam for power production.

A special interest is raised in Brazil about steam generators of the type U-Tube Steam Generator - UTSG. This interest comes from the fact that the UTSGs are used in the Pressurized Water Reactor - PWR, which is the line of power producing reactors adopted in Brazil. Nowadays, Brazil has two operating nuclear reactors: Angra I and Angra II. These two reactors have the UTSG as components of their steam cycle. The UTSG model presented here is part of the "Sistema MODular Integrado de Simulação - SIMODIS" (Guimarães et al, 2000) set, which is a library of power plant component models (Guimarães et al, 1998a, Guimarães et al, 1998b, and Guimarães et al, 2002). The UTSG model presented here was also described in detail at (Oliveira Jr., 2000). The description presented here is a short one for the UTSG model with 9 state variables, plus 6 state variables for the three-element PI controller, which comes to a total of 15 state variables.

This work is organized as follows: a section with a brief description of the UTSG, a section describing the 15 state variable model, a section presenting the GUI developed for the simulator, a section with results and explanations on how to use the model, and finally some conclusions. An APPENDIX is included with the internal parameters for models and the names and description of the variable nomenclature used.

2. The U-tube steam generator description

Figure (1) shows a schematic diagram of the UTSG. Several variations on the design may be found depending on the manufacturer. Figure (1) collects the most used features. The name of the equipment comes from the characteristically U shaped inverted tubes, represented by (2) in the Fig. (1).

The UTSG is one of many components in a PWR. A brief description is provided in order to understand how the energy is generated and transferred up to the point where electricity is produced. More details may be found at (Ali, 1976, Etherington, 1958, and Rust, 1979).

In a nuclear reactor, heat is generated by sustained nuclear fission reaction inside the fuel pellet. The heat is transferred by heat conduction and convection to the water flowing through the reactor core. It is important to emphasize that the pellets are contained inside metal tubes and the water flowing through the reactor core does not enter in direct contact with the pellets. The temperature difference between water entering and exiting the reactor core is in general 30°C.

The PWR is composed of three water loops from the heat source (reactor core) to the heat sink (environment, usually a river, a lake or the sea). Two of the loops are closed-loops, the third one is an open loop. The UTSG is the connecting interface between the first and second closed-loop, respectively called primary and secondary. The primary water coming from the reactor core enters the UTSG through (1), refer to Fig. (1). From there the water follows the metallic U-tubes up and down, exiting in (3). The heat contained in the primary water is transferred (convection-conduction-convection) to the secondary water. The primary water exit the steam generator, going back to the reactor core, at a lower temperature (around 30°C lower). Conditions maintained at all times: the primary and secondary water do not mix, the primary water is at subcooled condition at all times and the pressure is kept constant, around 15 MPa.

On the secondary side, water comes through (4) as it is shown in Fig. (1). After, the secondary water is sprayed by the distribution ring downwards, and it follows the arrows path, depicted in Fig. 1, through an annular region, turns 180° and goes upwards among the U-tubes. The heat transferred to the U-tubes by the primary water, is now transferred to the secondary water. The secondary water enters the UTSG in a subcooled state, and starts to receive the heat as it contacts the U-tubes. In general, the secondary water reaches the saturation point between 1/3 to 2/3 of the height of the U-tubes. The boiling process, started then, continues and at the top of the U-tube structure quality reaches a value of about 20%, in general. From there on, the mixture water/steam goes through a series of structures called dryers, where the water is separated from the steam. The water is returned to the distribution ring region and mixed with the incoming water. The steam exits at (8) and goes to the turbine, where its thermal energy is transformed into kinetic energy and latter into electric energy. After that, the steam is then condensed, pre-heated and the resulting water is conducted back to the UTSG entrance in (4).

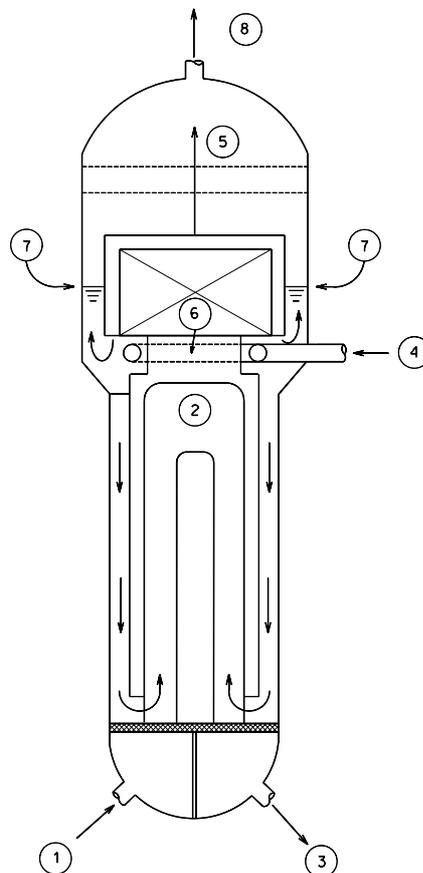


Figure 1. Simplified diagram for a U-tube steam generator. Numbering significance: (1) primary water entrance (coming from reactor core), (2) inverted metallic U tube set, (3) primary water exit (going back to the reactor core), (4) secondary water entrance, (5) steam exit after going through the steam dryers, (6) secondary water distribution ring, (7) secondary water level and (8) high quality steam exit to the turbine.

3. The U-tube steam generator model equations set

The fundamental UTSG equations and nodalization scheme were initially developed in (Ali, 1976). Ali developed a series of UTSG models in order to study its dynamic behavior. At that time, Ali linearized all the equations, which was a standard procedure to save computer time. In this new model derivation it was preserved, from Ali's work, the nodalization scheme and most of the fundamental equations. The final obtained equations are completely different from the ones presented in Ali's. First, because of the desired final form, and secondly because the new derivation includes all the original non-linearities, no linearization step is performed.

$$A = \begin{bmatrix} a_{1,1} & 0 & a_{1,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{2,1} & a_{2,2} & 0 & a_{2,4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{3,1} & 0 & a_{3,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{4,2} & 0 & a_{4,4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_{5,3} & a_{5,4} & 0 & 0 & a_{5,8} & a_{5,9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_{6,3} & a_{6,4} & 0 & 0 & a_{6,8} & a_{6,9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{7,7} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{8,8} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{9,8} & a_{9,9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{10,7} & 0 & 0 & a_{10,10} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{11,7} & 0 & 0 & a_{11,10} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{12,7} & 0 & 0 & a_{12,10} & a_{12,11} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{13,15} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{14,12} & a_{14,13} & a_{14,14} & a_{14,15} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{15,14} & 0 \end{bmatrix}. \quad (03)$$

$$\bar{b}^T = [b_1 \ 0 \ b_3 \ b_4 \ b_5 \ b_6 \ b_7 \ b_8 \ 0 \ b_{10} \ b_{11} \ b_{12} \ b_{13} \ b_{14} \ b_{15}] \quad (04)$$

$$a_{1,1} = -\left(\frac{W_{pi}}{M_p} + \frac{U_{pm} * A_{pm}}{M_p * C_p}\right). \quad (05)$$

$$a_{1,3} = \frac{U_{pm} * A_{pm}}{M_p * C_p}. \quad (06)$$

$$a_{2,1} = \frac{W_{pi}}{M_p}. \quad (07)$$

$$a_{2,2} = -\left(\frac{W_{pi}}{M_p} + \frac{U_{pm} * A_{pm}}{M_p * C_p}\right). \quad (08)$$

$$a_{2,4} = \frac{U_{pm} * A_{pm}}{M_p * C_p}. \quad (09)$$

$$a_{3,1} = \frac{U_{pm} * A_{pm}}{M_m * C_m}. \quad (10)$$

$$a_{3,3} = -\frac{(U_{pm} * A_{pm} + U_{ms} * A_{ms})}{M_m * C_m}. \quad (11)$$

$$a_{4,2} = \frac{U_{pm} * A_{pm}}{M_m * C_m}. \quad (12)$$

$$a_{4,4} = -\frac{(U_{pm} * A_{pm} + U_{ms} * A_{ms})}{M_m * C_m}. \quad (13)$$

$$a_{5,3} = a_{5,4} = \frac{trcl2 * U_{ms} * A_{ms}}{\det}. \quad (14)$$

$$a_{5,8} = -\frac{trcl2 * trc4}{\det}. \quad (15)$$

$$a_{5,9} = \frac{trcl2 * trcl1}{\det}. \quad (16)$$

$$a_{6,3} = a_{6,4} = \frac{trcl1 * U_{ms} * A_{ms}}{\det}. \quad (17)$$

$$a_{6,8} = -\frac{trc4 * trcl1}{\det}. \quad (18)$$

$$a_{6,9} = \frac{trcl1 * trcl1}{\det}. \quad (19)$$

$$a_{7,7} = -\frac{1}{\rho_f} * \frac{d\rho_f}{dP} * \frac{dP_{sat}}{dt}. \quad (20)$$

$$a_{8,8} = -\frac{W_{fi} + (1 - x_e) * W_3}{\rho_f * A_{dw} * L_{dw}}. \quad (21)$$

$$a_{9,8} = \frac{W_1}{M_d}. \quad (22)$$

$$a_{9,9} = -\frac{W_1}{M_d}. \quad (23)$$

$$a_{10,7} = -\frac{1}{\tau}. \quad (24)$$

$$a_{10,10} = -\frac{1}{\tau}. \quad (25)$$

$$a_{11,7} = -\frac{G_1}{\tau}. \quad (26)$$

$$a_{11,10} = -\frac{G_1}{\tau} + \frac{1}{\tau_1}. \quad (27)$$

$$a_{12,7} = -\frac{G_1 * G_2}{\tau}. \quad (28)$$

$$a_{12,10} = G_2 * \left(\frac{1}{\tau_1} - \frac{G_1}{\tau}\right). \quad (29)$$

$$a_{12,11} = \frac{1}{\tau_2}. \quad (30)$$

$$a_{13,15} = -1. \quad (31)$$

$$a_{14,12} = G_v * w_{nv}^2. \quad (32)$$

$$a_{14,13} = \frac{G_v * w_{nv}^2}{\tau_2}. \quad (33)$$

$$a_{14,14} = -2 * Z_{nv} * w_{nv}. \quad (34)$$

$$a_{14,15} = -w_{nv}^2 * (1 - G_v * G_2). \quad (35)$$

$$a_{15,14} = 1. \quad (36)$$

$$b_1 = \frac{W_{pi}}{M_p} * T_{pi}. \quad (37)$$

$$b_4 = \frac{U_{ms} * A_{ms}}{M_m * C_m} * T_s. \quad (39)$$

$$b_6 = -\frac{(trc2 * trc13 - trc5 * trc11)}{\det} + trc15. \quad (41)$$

$$b_8 = \frac{W_{fi}}{A_{dw} * L_{dw} * \rho_f} * T_{fi} + \frac{(1 - x_e) * W_3}{A_{dw} * L_{dw} * \rho_f} * T_{sat}. \quad (43)$$

$$b_{10} = \frac{L_{dw0}}{\tau}. \quad (44)$$

$$b_{12} = \frac{G_1 * G_2 * L_{dw0}}{\tau}. \quad (46)$$

$$b_{14} = 2 * z_{rv} * w_{nv} * r_0 + w_{nv}^2 * W_{fi0} + G_v * G_2 * w_{nv}^2 * W_{so}. \quad (48)$$

$$b_{15} = -r_0. \quad (49)$$

$$U_{pm} = \frac{1}{\frac{1}{h_i} + \frac{D_{in}}{2 * K_{th}} * \log\left(\frac{D_{avg}}{D_{in}}\right)}. \quad (50)$$

$$D_{avg} = \frac{(D_{in} + D_{out})}{2}. \quad (52)$$

$$W_1 = C_1 * \frac{\sqrt{\rho_d * (L_d + L_{dw}) - \rho_s * L_d - \rho_f * L_{dw}}}{12}. \quad (54)$$

$$W_2 = cfdr4 * \frac{dP_{sat}}{dt} - cfdr5 * \frac{dx_e}{dt} - \frac{1}{x_e} * \frac{\rho_g}{\rho_f} * \frac{(W_{fi} - W_1)}{cfdr2} + \frac{1}{x_e} * \frac{W_{so}}{cfdr2}. \quad (55)$$

$$W_3 = \frac{1}{x_e} * \left(\frac{cfdr3}{cfdr2} * \frac{dP_{sat}}{dt} - \frac{\rho_g}{\rho_f} * \frac{(W_{fi} - W_1)}{cfdr2} + \frac{W_{so}}{cfdr2} \right). \quad (56)$$

$$\det = trc11 * trc3 + trc12 * trc2. \quad (57)$$

$$cfdr1 = \frac{(1 - x_e)}{x_e} * \frac{(V_{dr} - A_{dw} * L_{dw})}{\rho_f * A_{dw}} * \frac{d\rho_g}{dP} - \frac{L_{dw}}{\rho_f} * \frac{d\rho_f}{dP}. \quad (58)$$

$$cfdr2 = 1 + \frac{(1 - x_e)}{x_e} * \frac{\rho_g}{\rho_f}. \quad (59)$$

$$cfdr3 = (V_{dr} - A_{dw} * L_{dw}) * \frac{d\rho_g}{dP} + \frac{\rho_g}{\rho_f} * A_{dw} * L_{dw} * \frac{d\rho_f}{dP}. \quad (60)$$

$$cfdr4 = \frac{1}{x_e} * \frac{cfdr3}{cfdr2} - \frac{V_r * \left(\frac{dv_f}{dP} + x_e * \frac{dv_{fg}}{dP} \right)}{(v_f + x_e * v_{fg})^2}. \quad (61)$$

$$cfdr5 = \frac{V_r * v_{fg}}{(v_f + x_e * v_{fg})^2}. \quad (62)$$

$$\frac{dP_{sat}}{dt} = a_{5,3} * T_{m1} + a_{5,4} * T_{m2} + a_{5,8} * T_{dw} + a_{5,9} * T_d + b_5. \quad (63)$$

$$\frac{dx_e}{dt} = a_{6,3} * T_{m1} + a_{6,4} * T_{m2} + a_{6,8} * T_{dw} + a_{6,9} * T_d + b_6. \quad (64)$$

$$trc1 = W_1 * C_{ps} + V_s * \rho_s * trc6 * \frac{W_1}{M_d} - U_{ms} * A_{ms} * \frac{L_{sb}}{L}. \quad (65)$$

$$trc2 = V_s * (\rho_s * trc7 + h_s * trc9) + h_e * cfdr4. \quad (66)$$

$$trc3 = V_s * (\rho_s * trc8 - h_s * trc10) - h_e * cfdr5. \quad (67)$$

$$trc4 = \frac{V_s * \rho_s * trc6 * W_1}{M_d}. \quad (68)$$

$$trc5 = \left(\frac{h_e}{x_e} * \frac{\rho_g}{\rho_f} * \frac{(W_{fi} - W_1)}{cfdr2} - 2 * U_{ms} * A_{ms} * \left(\frac{L_{sb}}{2 * L} + \frac{L_b}{L} \right) \right) * T_{sat}. \quad (69)$$

$$trc6 = \frac{C_{ps} * L_{sb}}{2 * L}. \quad (70)$$

$$b_3 = \frac{U_{ms} * A_{ms}}{M_m * C_m} * T_s. \quad (38)$$

$$b_5 = \frac{(trc3 * trc13 + trc5 * trc12)}{\det} + trc14. \quad (40)$$

$$b_7 = \frac{1}{\rho_f * A_{dw}} * (W_{fi} + (1 - x_e) * W_3 - W_1). \quad (42)$$

$$b_{11} = \frac{G_1 * L_{dw0}}{\tau}. \quad (45)$$

$$b_{13} = W_{so}. \quad (47)$$

$$U_{ms} = \frac{1}{\frac{1}{h_d} + \frac{D_{out}}{2 * K_{th}} * \log\left(\frac{D_{out}}{D_{avg}}\right)}. \quad (51)$$

$$W_{so} = C_{so} * P_{sat}. \quad (53)$$

$$trc7 = \frac{C_{ps} * L_{sb}}{2 * L} * \frac{dT_{sat}}{dP} + \frac{L_b}{L} * \left(\frac{dh_f}{dP} + \frac{x_e}{2} * \frac{dh_{fg}}{dP} \right). \quad (71)$$

$$trc8 = \frac{L_b}{2 * L} * h_{fg}. \quad (72)$$

$$trc10 = \frac{L_b}{L} * \frac{\frac{v_{fg}}{2}}{\left(v_f + \frac{x_e}{2} * v_{fg} \right)^2}. \quad (74)$$

$$trc12 = V_s * trc10 + cfdr5. \quad (76)$$

$$trc14 = -\frac{(trc3 + h_e * trc12)}{\det * x_e * cfdr2} * W_{so}. \quad (78)$$

$$\rho_s = \frac{(\rho_d + \rho_f) * L_{sb}}{2 * L} + \frac{1}{v_f + \frac{x_e}{2} * v_{fg}} * \frac{L_b}{L}. \quad (81)$$

$$h_s = C_{ps} * \frac{(T_d + T_{sat}) * L_{sb}}{2 * L} + \left(h_f + \frac{x_e}{2} * h_{fg} \right) * \frac{L_b}{L}. \quad (81)$$

$$T_s = \frac{(T_d + T_{sat}) * L_{sb}}{2 * L} + T_{sat} * \frac{L_b}{L}. \quad (83)$$

$$trc9 = \frac{L_{sb}}{2 * L} * \frac{d\rho_f}{dP} - \frac{L_b}{L} * \frac{\left(\frac{dv_f}{dP} + \frac{x_e}{2} * \frac{dv_{fg}}{dP} \right)}{\left(v_f + \frac{x_e}{2} * v_{fg} \right)^2}. \quad (73)$$

$$trc11 = V_s * trc9 + cfdr4. \quad (75)$$

$$trc13 = W_1 + \frac{1}{x_e} * \frac{\rho_g}{\rho_f} * \frac{(W_{fi} - W_1)}{cfdr2}. \quad (77)$$

$$trc15 = \frac{(trc2 - h_e * trc11)}{\det * x_e * cfdr2} * W_{so}. \quad (79)$$

$$\quad (80)$$

$$h_e = h_f + x_e * h_{fg}. \quad (82)$$

$$L = L_{sb} + L_b. \quad (84)$$

4. The U-tube steam generator simulator GUI

As stated previously two versions of the UTSG program were developed, a MATLAB m-file and a C-file. The m-file was developed to take advantage of the easy programming and prototyping provided by the MATLAB environment. Once the development and correction of the programming errors phases are over, what is desired is processing speed.

The MATLAB m-file is interpreted and, as though it facilitates the development and debugging it contributes negatively for speed. That is the reason for the C-file version of the UTSG model. It is compiled and runs at much higher speed. This C-file version was also coupled with a Graphical User Interface – GUI (Oliveira et al, 2000, and Oliveira et al, 2001) to allow easy visualization of the dynamical behavior. It also allows the visualization of the initial conditions and input conditions before the simulation processes starts. The input conditions maybe modified by the user simulating an impulse change in one of the inputs. Also, three different transient types are provided to be chosen by the user: a straight ramp, a step change and a more smooth variation on the form of a sine wave. The user may inform the transient initial and final times and if it is increasing or decreasing in time.

Figure (3) shows the main simulation interface window, where a static representation of the UTSG is shown. This window has internal boxes with the measured state variables and some input conditions values shown. The bars, underneath the boxes, move as the dynamical simulation is performed. This translates into a visual sensation of the dynamics. Also at the top right hand corner an indication of the running time is presented. There are two more windows that can be displayed. This is done in order not to saturate one window with too much information. These other windows are not shown here due to space limitations. For the demonstration purposes, it is believed that the main window is sufficient enough.

After the simulation is completed, plotting maybe realized by activating the proper option at the main window menu. The user may choose which state variable to plot. Also a help window is provided to explain what the meaning of the state variables is.

5. Results

Tables (1) and (2) present the state variable values before and after a specified transient. As may be seen from both tables, the state variable values are in the vertical columns for both tables. The first column refers to either steady state or which transient is applied. The letters SS stands for steady state, therefore the values presented at that line are the steady state values. The next line shows the symbol $1.1 * C_{so}$ which means an increase of 10% in the steam valve aperture. Respectively, after this transient, it follows 10% reduction in the steam valve aperture, 10% in increase and decrease in the inlet primary water temperature, 10% decrease in the inlet feedwater temperature and 10% decrease in the primary water flow. All the shown transients are of the ramp type. The model is let run for 300 s, the respective transient is applied between 300 and 700 s, the system is let run for another 500 s in the new conditions.

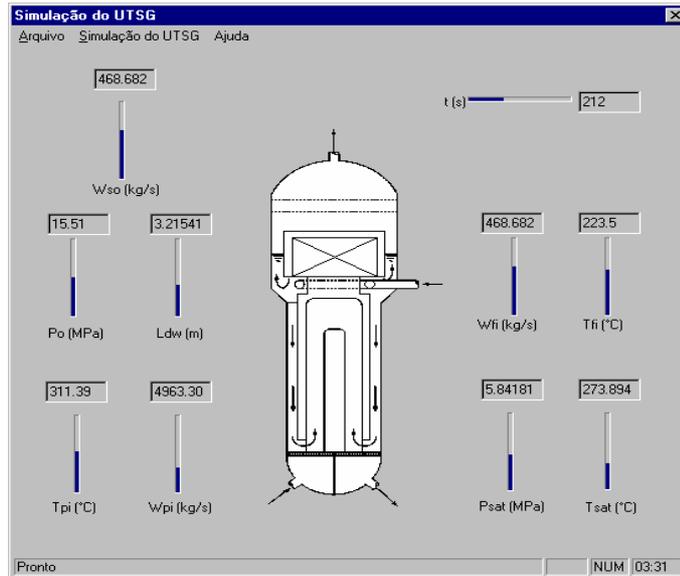


Figure 3. Main simulation interface window for the UTSG.

Table 1. Values for the state variables T_{p1} , T_{p2} , T_{m1} , and T_{m2} in the steady state (SS) and after the imposed transients on the UTSG.

	T_{p1} (°C)	T_{p2} (°C)	T_{m1} (°C)	T_{m2} (°C)
SS	302.9	296.4	297.5	292.2
$1.1 \cdot C_{so}$	301.8	294.5	295.8	289.8
$0.9 \cdot C_{so}$	304.1	298.5	299.5	294.9
$1.1 \cdot T_{pi}$	336.0	330.6	330.0	325.6
$0.9 \cdot T_{pi}$	272.8	267.3	268.7	264.2
$0.9 \cdot T_{fi}$	302.2	295.1	296.4	290.6
$0.9 \cdot W_{pi}$	302.0	294.8	296.6	290.8

Table 2. Values for the state variables P_{sat} , x_e , L_{dw} , T_{dw} , and T_d in the steady state and after the imposed transients on the UTSG.

	P_{sat} (MPa)	x_e (adim)	L_{dw} (m)	T_{dw} (°C)	T_d (°C)
SS	5.892	0.233	3.22	262.6	262.6
$1.1 \cdot C_{so}$	5.474	0.235	3.22	258.9	258.9
$0.9 \cdot C_{so}$	6.405	0.232	3.21	266.8	266.8
$1.1 \cdot T_{pi}$	9.210	0.367	3.21	275.1	275.1
$0.9 \cdot T_{pi}$	4.036	0.157	3.22	246.6	246.6
$0.9 \cdot T_{fi}$	5.636	0.221	3.22	256.0	256.0
$0.9 \cdot W_{pi}$	5.804	0.230	3.22	262.0	262.0

In Tab. (1) and Tab. (2) the results presented are before and after the transient, during the transient only a few of the responses maybe shown, due to lack of space. Figure (4) presents the response of the drum water level due to a 10% increase at the steam valve aperture. As the valve opens more steam is sent to the turbine. That causes a reduction in the pressure drum and a subsequent increase in the water level. This phenomenon is known as “swell”. It happens the other way around if one closes the steam valve, where it is called “shrink.” The “shrink and swell” phenomena are the main reason for the use of a three-element PI controller on the UTSG. As may be seen from Fig. (4), the phenomenon is reproduced and the proper response is obtained. Figure (5) presents the steam quality response during the same transient. Note that the steam quality increases, reaching a maximum and than stabilizes in a lower value than that of the maximum, but higher than the initial steady state one. This transient response is also in accordance with what was expected. Once the steam demand is increased more steam should be supplied in order to match the demand.

All the above transients agree in behavior with the responses previously shown by (Ali, 1976, and Naghedolfeizi, 1990), where in Ali’s case some experimental data is presented. The new model does not use linearization. In this sense the new model does not include the limitations presented at the one developed by Ali. Naghedolfeizi derivation tried to avoid linearization, but his derivation lacks the elegance of the one presented here. Besides, his implementation was made in a simulation environment called ACSL, which is not so well known and used in Brazil. It is believed that an MATLAB implementation has a much wider reach. There is an important observation about Naghedolfeizi’s work. He

has implemented what is called Ali's fourth model. This specific model includes an effect called moving boundary between the subcooled and boiling secondary water regions. The model presented here includes this feature. However, an analogous derivation was performed by the authors of this work and will be presented in the future.

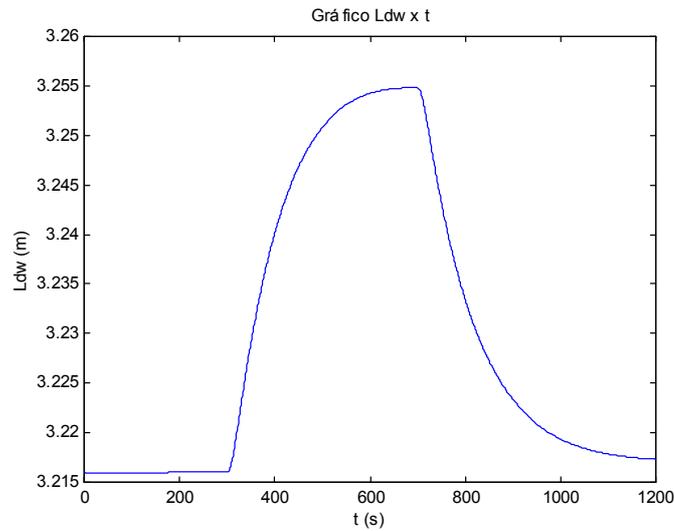


Figure 4. Drum water level response due to a 10% increase in the steam valve aperture.

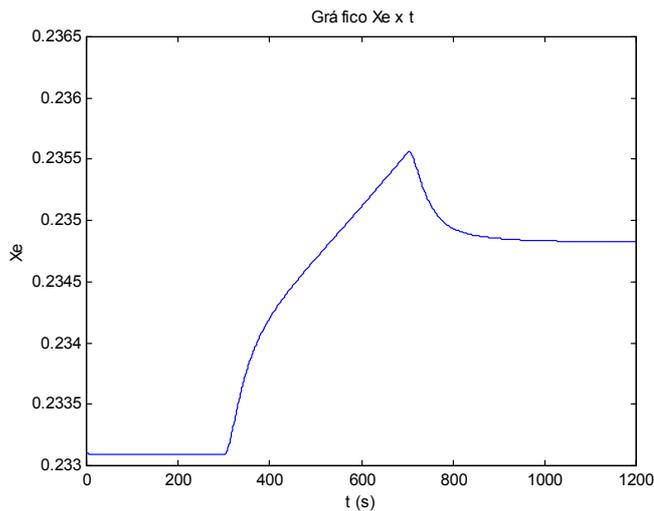


Figure 5. Steam quality response due to a 10% increase in the steam valve aperture.

6. Conclusions

The model presented here is not intended for design. It is intended for dynamic behavior studies and training. It could be used to show the dynamic behavior, to students or operation personal, without the costs of running the real equipment. At least three types of standard transients are pre-programmed in the GUI.

The model was tested with 10% variation transients. However, once the model is not limited by linearization process higher values of transient variation are also accepted.

Together with the UTSG model a three-element PI controller was used. That choice was made for practicality reasons, or, that was the controller available at the time. The same model maybe used as an advanced control test bed, as for instance, a fuzzy logic controller could be developed to work with this model. As a matter of fact that is one of the next steps of this reach.

The results presented with this model are very satisfactory. It reproduces well the “shrink and swell” phenomena and the controller takes the proper action to control the UTSG. Unfortunately, this model does not include the moving boundary effect that exists between the secondary subcooled and boiling water interface. A model with this effect is already available and it will be published elsewhere.

The UTSG model presented here is part of the SIMODIS set, which includes a series of models, not only from steam generators, but from other internal plant equipments. The idea is, in the near future, be able to connect these

models and assemble power plants to study new concepts, such as, control strategies, safety features, some economic aspects of the workings of power plants, etc.

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8. References

- Ali, M.R.A., 1976, "Lumped Parameter, State Variable Dynamic Models for U-Tube Recirculation Type Nuclear Steam Generator," PhD Dissertation, The University of Tennessee, Knoxville, TN, USA.
- Etherington, H., 1958, "Nuclear Engineering Handbook", McGraw-Hill Book Company.
- Garland, Wm.J., 1991, "Water and Steam Properties - V1.03," Department of Engineering Physics, McMaster University, 1280 Main St. W., Hamilton, Ontario, Canada, 18S 4m1.
- Guimarães, L.N.F., Oliveira Jr., N.S., and Flores, P.T., 1998a, "Simplified Steam Generator Model as a Teaching Tool", IVth Conference on Computer Simulation and Artificial Intelligence, Ciudad de México, v.1, p. 30-36.
- Guimarães, L.N.F., Flores, P.T., 1998b, "Modelos Dinâmicos Simplificados de Gerador de Vapor como Ferramenta de Ensino", Revista Brasileira de Ensino de Física, v. 20-3, p. 189-200.
- Guimarães, L.N.F., Oliveira Jr., N.S., da Silva, G.A.S., Bueno, M., and Borges, E.M., 2000, "SIMODIS – A Software Package for Simulating Nuclear Reactor Components", Proceedings of the XII Meeting on Reactor Physics and Thermal Hydraulics - ENFIR, CDROM, Rio de Janeiro, Brazil, cta08r03.01-05 pp.
- Guimarães, L.N.F., da Silva, G.A.S., and Borges, E.M., 2002, "Simulador Iterativo de um Gerador de Vapor de Tubo Reto", 9th Brazilian Congress of Thermal Engineering and Sciences, Caxambú – MG, Associação Brasileira de Ciências Mecânicas, v. 1, p. 1-12.
- Haar, L., Gallager, J.S., and Kell, G.S., 1984, "Steam Tables Thermodynamic and Transport Properties and Computer Programs for Vapor and Liquid States of Water in SI Units," Hemisphere Publishing Corporation, New York.
- MATLAB, 1995, The Math Works Inc., "The Student Edition of MATLAB, The Ultimate Computing Environment for Technical Education," Prentice Hall, Englewood Cliffs, NJ 07632, 1995.
- Naghdolfeizi, M., 1990, "Dynamic Modeling of a Pressurized Water Reactor Plant for Diagnostics and Control," Knoxville, TN, USA. Master Thesis (Master of Science Degree in Nuclear Engineering) - The University of Tennessee.
- Oliveira Jr., N.S., 2000, "Simuladores Iterativos de Geradores de Vapor de Tubo em "U"", Trabalho de Graduação Interdisciplinar, Universidade Braz Cubas, Mogi da Cruzes, SP.
- Oliveira Jr., N.S., da Silva, G.A.S., Bueno, M.F., and Guimarães, L.N.F., 2001, "Desenvolvimento de Interfaces Gráficas para Manipulação de Modelos Dinâmicos do Conjunto SIMODIS", I Encontro de Pós-Graduação, Universidade do Vale do Paraíba, v. 2, p. 246-251.
- Rust, J.H., 1979, "Nuclear Power Plant Engineering," S. W. Holland Company, P. O. Box 250254, Atlanta GA, 30325, USA.

9. APPENDIX – Identification for Symbols, Variables, for the set of equations presented in this paper.

Water/steam physical properties. Symbol; function; dimension.

$$C_{p1}; \text{cpfsub}(P0, Tp1); \frac{kJ}{kg \cdot ^\circ C} \cdot C_{p2}; \text{cpfsub}(P0, Tp2); \frac{kJ}{kg \cdot ^\circ C} \cdot C_{ps}; \text{cpf}(Psat); \frac{kJ}{kg \cdot ^\circ C} \cdot$$

$$\frac{dh_f}{dP}; \text{dhfdp}(Psat); \frac{kJ}{kg \cdot MPa} \cdot \frac{dh_g}{dP}; \text{dhgdp}(Psat); \frac{kJ}{kg \cdot MPa} \cdot \frac{d\rho_f}{dP}; \text{drfdp}(Psat); \frac{kg}{m^3 \cdot MPa} \cdot$$

$$\frac{d\rho_g}{dP}; \text{drgdp}(Psat); \frac{kg}{m^3 \cdot MPa} \cdot \frac{dv_f}{dP}; \text{dvfdp}(Psat); \frac{m^3}{kg \cdot MPa} \cdot \frac{dv_g}{dP}; \text{dvgdP}(Psat); \frac{m^3}{kg \cdot MPa} \cdot$$

$$h_f; \text{hf}(Psat); \frac{kJ}{kg} \cdot h_g; \text{hg}(Psat); \frac{kJ}{kg} \cdot \rho_a; \text{dfsub}(Psat, Td); \frac{kg}{m^3} \cdot \rho_f; \text{df}(Psat); \frac{kg}{m^3} \cdot$$

$$\rho_g; \text{dg}(Psat); \frac{kg}{m^3} \cdot \rho_{w1}; \text{dfsub}(P0, Tp1); \frac{kg}{m^3} \cdot \rho_{w2}; \text{dfsub}(P0, Tp2); \frac{kg}{m^3} \cdot T_{sat}; \text{tsat}(Psat); ^\circ C.$$

$$v_f; \text{vf}(Psat); \frac{m^3}{kg} \cdot v_g; \text{vg}(Psat); \frac{m^3}{kg} \cdot$$

Numerical constants and geometric parameters. Symbol – meaning, value.

A_d – Water flow area inside the accumulation tank, 2.973 m². A_{dw} – Recirculated water flow area in the superior tank, 10.288 m². C_1 – Head loss between the annular tank and the metal tube entrance, $\frac{1}{\sqrt{9.733 * 10^{-6}}} \frac{\text{kg}}{\text{s}} * \left(\frac{\text{kg}}{\text{m}^2}\right)^{\frac{1}{2}}$. C_m – Metal tubes specific heat capacity, $460.5 \frac{\text{J}}{\text{kg} \cdot \text{°C}}$. C_{so} – Proportionality constant between steam flow and saturation steam pressure, $80.23 \frac{\text{kg}}{\text{s MPa}}$. D_{in} – U-tube internal diameter, 0.0197 m. D_{out} – U-tube external diameter, 0.0222 m. h_{oi} – Convective heat transfer coefficient between the primary water and the metal tubes, $2.555 * 10^4 \frac{\text{J}}{\text{s m}^2 \cdot \text{°C}}$. h_{ot} – Convective heat transfer coefficient between the metal tubes and the secondary water, $4.25 * 10^3 \frac{\text{J}}{\text{s m}^2 \cdot \text{°C}}$. K_{th} – Metal tube thermal conductivity, $55.0012 \frac{\text{J}}{\text{s m} \cdot \text{°C}}$. L – U-tube height, 10.83 m. L_d – Accumulation annular tank height, 10.83 m. L_{sb} – Subcooled water column height, 1.057 m. N – Total metallic U-tubes number, 3388. P_0 – Design primary water pressure, 15.51 MPa. ρ_m – Metal tube density, $8490 \frac{\text{kg}}{\text{m}^3}$. T_{fi} – Feedwater inlet temperature, 223.50 °C. T_{pi} – Primary water temperature, 311.39 °C. V_{dr} – UTSG drum total volume, 124.56 m³. V_r – Water/steam separator internal volume, 13.28 m³. V_s – Secondary water volume around the metal tubes, 94.36 m³. W_{pi} – Primary water flow, $4963.30 \frac{\text{kg}}{\text{s}}$. G_1 – Gain factor of the first PI controller, 65.2 (dimensionless). G_2 – Gain factor of the second PI controller, 1 (dimensionless). G_v – Gain factor of the feedwater valve system, 32.2 (dimensionless). τ_1 – Time constant of the first PI controller, 250 (s). τ_2 – Time constant of the second PI controller, 120 (s). τ – Filter time constant, 5 (s). z_{nv} – Damping factor of the feedwater valve system, 3.18 (dimensionless). w_{nv} – Natural frequency of the feedwater valve system, 0.63 (rad/s).

Constants, variables and parameters names. Symbol; meaning; dimension.

A_{ms} – Thermal contact area between metal tubes and secondary water, m². A_p – Primary water flow area inside the metal tubes, m². A_{pm} – Thermal contact area between the primary water and metal tubes, m². D_{avg} – Average metal tube diameter, m. $\frac{dh_{fg}}{dP} = \frac{dh_g}{dP} - \frac{dh_f}{dP}$, $\frac{\text{kJ}}{\text{kg MPa}}$. $\frac{dv_{fg}}{dP} = \frac{dv_g}{dP} - \frac{dv_f}{dP}$, $\frac{\text{m}^3}{\text{kg MPa}}$. $h_{fg} = h_g - h_f$, $\frac{\text{kJ}}{\text{kg}}$. $v_{fg} = v_g - v_f$, $\frac{\text{m}^3}{\text{kg}}$. L_b – Boiling column height, m. M_d – Annular tank water mass, kg. M_m – Half metallic tubes mass, kg. M_p – Half of the primary water mass, kg. U_{ms} – Global heat transfer coefficient between the metal tubes and the secondary water, $\frac{\text{J}}{\text{s m}^2 \cdot \text{°C}}$. U_{pm} – Global heat transfer coefficient between the primary water and metal tubes, $\frac{\text{J}}{\text{s m}^2 \cdot \text{°C}}$. W_{fi} – Feedwater flow, $\frac{\text{kg}}{\text{s}}$. W_{so} – Saturated steam flow, $\frac{\text{kg}}{\text{s}}$.