A MOVING BOUNDARY U-TUBE STEAM GENERATOR – UTSG Dynamic Simulation Model

Lamartine Nogueira Frutuoso Guimarães¹,², Nilton da Silva Oliveira Jr.² and Eduardo Madeira Borges³

¹ Instituto de Estudos Avançados (IEAv)
Centro Técnico Aeroespacial (CTA)
Rodovia dos Tamoios, km 5,5
Torrão de Ouro
12228-840 São José dos Campos, SP
guimarae@ieav.cta.br

² Universidade Braz Cubas (UBC)
Mogi das Cruzes, SP
nnjunior@ig.com.br

³ Instituto de Estudos Avançados (IEAv)
Centro Técnico Aeroespacial (CTA)
eduardo@ieav.cta.br

ABSTRACT

This work is a continuation of the presentation of some dynamic simulation models part of a library called SIMODIS - SImulation MODeling Integrated System ("SIstema MODular Integrado de Simulação"). Some of these models have been presented elsewhere. Previously, it was presented a 9 node U-Tube Steam Generator – UTSG model. In the new version briefly presented here a moving boundary that exists between the subcooled and boiling regions is taken into account. This increases the number of nodes to 16, and also increases the number of equations. This model was developed as test bed to build a complete power plant simulator and to test advanced control strategies. A proportional-integral three element controller was coupled with the UTSG model. Some transient analysis results are presented. The simulation program was developed in MATLAB.

1. INTRODUCTION

This paper presents a brief description of a 16 node model of a U-Tube Steam Generator – UTSG that is part of the SIMODIS - SImulation MODeling Integrated System ("SIstema MODular Integrado de Simulação") library of reactor components models [1]. The detailed derivation and the MATLAB program of the 16 node model can be found in reference [2]. Some of the SIMODIS models have been presented elsewhere [3, 4]. The purposes of the SIMODIS are to allow a fast prototyping of a nuclear power plant (PWR and LMR), to design new and advanced control methodologies [5] and educational [6].

2. THE UTSG

Steam generators, in a nuclear power plant, have basically three functions: generate steam for the turbine to produce power, be a separating boundary between the primary and secondary water coolant and remove the residual core heat with the reactor shut down. 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.

Fig. 1 shows a schematic diagram of a UTSG. Several variations on the design may be found depending on the manufacturer. Fig. 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 used in PWRs. A brief description is provided here. More details may be found at [7, 8, 9].

A 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. A 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 exits 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 in 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).

Fig. 2 presents the nodalization schematic for the 16 node UTSG model. Note that the schematic shown in Fig. 2 matches nicely the schematic of the UTSG presented in Fig. 1. This ensures the accuracy of the developed modeling dynamics. The 16 node UTSG modeling includes the following phenomena: heat transfer between the primary working fluid (water) and the U shaped metal tubes; heat transfer between the U shaped metal tubes and the secondary working fluid (water/steam mixture); chimney effect, with saturated vapor and liquid separation, where vapor is conducted to the access tube that leads to the turbine and the liquid is re-circulated in side the steam generator; mixture effect of the re-circulated saturated liquid with the feedwater entering the steam generator; accurate representation of the U tube geometry; representations of the moving water (mixture between re-circulated water and feedwater) level with the dilatation and contraction effects (shrink and swell); and, finally, moving boundary effect that occurs between the saturation water and the boiling water that flows in between the metal U-tubes.
The 16 node UTSG model uses the finite volume method to deal with the spatial dependency as can be seen from the Fig. 2. The vertical arrows in Fig. 2 show the fluid flow direction, whereas the horizontal arrows show the heat flow direction. The boxes marked with $T_{p1}, T_{p2}, T_{p3}, T_{p4}, T_{po}$ represent respectively the inlet, inferior and superior upwards, superior and inferior downwards, and outlet primary water temperatures. The boxes marked with $T_{m1}, T_{m2}, T_{m3}, T_{m4}$ represent respectively the inferior and superior upwards, and the superior and inferior downwards metal tube temperatures. The secondary fluid side has the following boxes marked as SFSL, SFBL, SFDRL and SFDCL, which represent respectively the subcooled secondary water, the boiling water, the water/steam separation drum and the annular water recirculation downcomer regions. From these regions the following state variables are produced $T_s, x, P_{sat}, L_0, L_{dw}, T_d$ which are respectively the subcooled secondary water temperature, the boiling water quality, the water/steam saturation temperature, the water boiling height, the water level in the drum region and the water temperature in the downcomer region. All the 16 variables described above are the model state variables.

A PI three-element controller was coupled with the 16 node UTSG model in order to provide stability and control for the model. This PI three-element controller was first presented in [10]. The target of the controller is to keep $L_{dw}$ at a preset value. This is accomplished by the mismatch between $L_{dw}$ and its preset value, and between the steam outlet flow and the feedwater flow.

![Figure 1. Simplified diagram for a U-tube steam generator.](image-url)
The model equations are based on mass, energy and momentum balance applied to the nodes. These equations are worked up to the point where they can be assembled in a matrix form presented below

$$\frac{dX}{dt} = AX + b.$$  \hspace{1cm} (1)

The vector $X$ is composed of 16 state variables, as specified previously by Fig. 2. As the PI three-element controller is added, the vector $X$ becomes a 22 state variables vector. The same happens with the state matrix $A$. For UTSG alone it is a $16 \times 16$ matrix. With the PI it becomes $22 \times 22$ matrix. Obviously, the vector $b$ dimension follows respectively. It is important to emphasize that the 16 node UTSG model preserves all non-linearities from its derivation.

3. RESULTS

Tables 1 and 2 present the state variable values before and after a specified transient. As may be seen from the tables, the state variable values are in the vertical columns. 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 $1.1*C_{\mu}$ 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, and, after that, the system is let run for another 500 s in the new conditions.

All the above transients agree in behavior with the responses previously shown by Ali and Naghedolfeizi [7,11]. Where in Ali’s case some experimental data is presented. The new model does not use linearization, and because of that it does not include the limitations presented at the one developed by Ali. Naghedolfeizi derivation tried to avoid linearization, but his derivation uses linear interpolation for the water/steam properties, which was also avoided here. The model presented here may be run in any conditions and it is not limited to an interval around its equilibrium point.

Table 1. Steady state and transient final responses for $T_{pi}$, $T_{p1}$, $T_{p2}$, $T_{p3}$, $T_{p4}$ and $T_{po}$.

<table>
<thead>
<tr>
<th></th>
<th>$T_{pi}$ (°C)</th>
<th>$T_{p1}$ (°C)</th>
<th>$T_{p2}$ (°C)</th>
<th>$T_{p3}$ (°C)</th>
<th>$T_{p4}$ (°C)</th>
<th>$T_{po}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>311.4</td>
<td>308.5</td>
<td>292.1</td>
<td>283.2</td>
<td>282.1</td>
<td>282.1</td>
</tr>
<tr>
<td>1,1*C_so</td>
<td>311.4</td>
<td>308.4</td>
<td>290.9</td>
<td>281.4</td>
<td>280.4</td>
<td>280.4</td>
</tr>
<tr>
<td>0.9*C_so</td>
<td>311.4</td>
<td>308.5</td>
<td>293.3</td>
<td>285.0</td>
<td>284.0</td>
<td>284.0</td>
</tr>
<tr>
<td>1.05*T_hl</td>
<td>327.0</td>
<td>323.2</td>
<td>307.1</td>
<td>297.7</td>
<td>296.2</td>
<td>296.2</td>
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<tr>
<td>0.95*T_hl</td>
<td>295.8</td>
<td>293.8</td>
<td>278.0</td>
<td>269.9</td>
<td>269.2</td>
<td>269.2</td>
</tr>
<tr>
<td>0.9*T_fi</td>
<td>311.4</td>
<td>307.4</td>
<td>291.3</td>
<td>282.4</td>
<td>280.9</td>
<td>280.9</td>
</tr>
<tr>
<td>0.9*W_pi</td>
<td>311.4</td>
<td>308.3</td>
<td>290.1</td>
<td>280.8</td>
<td>279.8</td>
<td>279.8</td>
</tr>
</tbody>
</table>

Table 2. Steady state and transient final responses for $L_{sb}$, $P_{sat}$, $x_e$, $T_{dw}$, $L_{dw}$ and $T_d$.

<table>
<thead>
<tr>
<th></th>
<th>$L_{sb}$ (m)</th>
<th>$P_{sat}$ (MPa)</th>
<th>$x_e$ (adim)</th>
<th>$T_{dw}$ (°C)</th>
<th>$L_{dw}$ (m)</th>
<th>$T_d$ (°C)</th>
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<tr>
<td>SS</td>
<td>1.10</td>
<td>5.730</td>
<td>0.196</td>
<td>262.0</td>
<td>2.94</td>
<td>263.0</td>
</tr>
<tr>
<td>1.1*C_so</td>
<td>1.04</td>
<td>5.519</td>
<td>0.205</td>
<td>260.6</td>
<td>2.94</td>
<td>260.6</td>
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<tr>
<td>0.9*C_so</td>
<td>1.16</td>
<td>5.960</td>
<td>0.186</td>
<td>265.6</td>
<td>2.93</td>
<td>265.6</td>
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<tr>
<td>1.05*T_hl</td>
<td>1.43</td>
<td>6.880</td>
<td>0.237</td>
<td>270.2</td>
<td>2.93</td>
<td>270.2</td>
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<tr>
<td>0.95*T_hl</td>
<td>0.81</td>
<td>4.786</td>
<td>0.162</td>
<td>255.2</td>
<td>2.94</td>
<td>255.2</td>
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<tr>
<td>0.9*T_fi</td>
<td>1.43</td>
<td>5.632</td>
<td>0.190</td>
<td>258.1</td>
<td>2.93</td>
<td>258.1</td>
</tr>
<tr>
<td>0.9*W_pi</td>
<td>1.02</td>
<td>5.574</td>
<td>0.190</td>
<td>261.9</td>
<td>2.94</td>
<td>261.9</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The UTSG model presented briefly here, is part of the SIMODIS set, which includes a series of power plant models, not only steam generators. 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.

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. 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.

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.

A MATLAB program was developed for this model. Copies of the program may be obtained, upon request, with the first author.

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REFERENCES