Preliminary study of APR1400 steam cycle suited for ESS integration

Jin Young Heo, Jung Hwan Park, Seung Hwan Oh, Yong Jae Chae, Jeong Ik Lee

*Department of Nuclear and Quantum Engineering, KAIST, Daejeon, South Korea

jyh9090@gmail.com, junghwanpark@kaist.ac.kr, osh7202@kaist.ac.kr, yjchae33@kaist.ac.kr, jeongiklee@kaist.ac.kr

1. Introduction

The recent trends in the climate change dialogue have emphasized the roles of clean energy sources, including nuclear energy as well as renewables [1]. The integration of carbon-free energy sources introduces new grid challenges due to the duck curve phenomenon [2]. In other words, the more intermittent sources supply to the grid, the more instability they amplify with a supply-demand mismatch. The grid transition naturally motivates the existing baseload players to alter their load profiles. This situation leads to the negative pricing of generated electricity. For high-capital cost low-operation cost plants such as nuclear, this can harm their economics as they are forced to lower their load [3]. For the existing plants, such load-following operation cannot be implemented without significant modifications involving financial investment on the equipment.

Recently, research groups have paid attention to the potential of integrating energy storage systems (ESS) to existing large PWRs [4-6]. A variety of options have been suggested in the references, including thermal, electrical, and mechanical energy storage connections. To minimize the conversion losses from storing the available heat energy from nuclear plants, the solutions involving a steam bypass from the steam cycle have been explored. This research paper also covers the methods of ESS integration through a steam bypass retrofitting.

Using the steam available from the nuclear secondary side, energy can be directly stored in two ways: thermal and mechanical integration. One option is to transfer the thermal energy from steam to an energy storage and return the steam line back to a feedwater heater. Another option is to store the energy by running a turbine to transfer mechanically and return the line to the condenser.

One of the important aspects is investigating the effects of steam bypass on the performance of the nuclear secondary side. Targeting the APR1400 as the reference plant, the research paper investigates what happens to its steam cycle when the ESS-integrated system transitions from steady operation to charging/discharging mode. The paper introduces the methodology and results in conducting the preliminary study on the transient response of the APR1400.

2. Methodology

To model the APR1400 steam cycle, MATLAB-based Simulink software has been adopted. Compared to other modelling tools, it offers the simplicity and capabilities in controlling fluid systems with various functionalities. Because not all the design information of the steam cycle are available publicly, the selection of the design software had to balance between the modelling complexity and information availability.

In building the dynamic model of the APR1400 steam cycle, the steady-state design values have been obtained from the Design Control Document of the APR1400 in the US NRC database [8]. Based on the revealed information on the steam cycle, the simplified layout has been formulated, along with the state points. The design parameters used in the modelling are listed in Table 1.

![Fig. 1. Schematic of simplified APR1400 layout based on [8] and ESS integration options](image-url)

Table 1. Design parameters of APR1400 used in the modelling

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam generator maximum pressure</td>
<td>6.9</td>
<td>MPa</td>
</tr>
<tr>
<td>Steam cycle mass flow rate</td>
<td>2251</td>
<td>kg/s</td>
</tr>
<tr>
<td>Reactor core heat</td>
<td>3985</td>
<td>MW</td>
</tr>
<tr>
<td>Core coolant outlet temperature</td>
<td>323.9</td>
<td>°C</td>
</tr>
<tr>
<td>Coolant temperature</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Condenser pressure</td>
<td>5</td>
<td>kPa</td>
</tr>
<tr>
<td>High-pressure turbine stages</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Low-pressure turbine stages</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Pipe area</td>
<td>0.72</td>
<td>m²</td>
</tr>
<tr>
<td>Steam generator contact area</td>
<td>15205</td>
<td>m²</td>
</tr>
</tbody>
</table>

The steam cycle components are modelled using the built-in models from the Simscape Foundational Library and Simscape Fluids Library. The layout of the modelled APR1400 layout is displayed in Fig. 2.

The boundary conditions are given as temperature values in the model. These include the core coolant outlet temperature given in the steam generator as constant temperature boundary with convective heat transfer module. Also, the condenser coolant temperature is given similarly as constant temperature boundary attached on the condenser (saturated fluid chamber) module.
The steam turbine component is placed using the built-in model, which uses the Stodola’s equation for calculating the pressure ratio with respect to changing mass flow rate. The equations for the steam turbine model are written as the following:

\[ n_{\text{eff}} = \frac{\eta_{\text{poly}} + 1}{\eta_{\text{poly}}} \]  
(1)

\[ \phi = \frac{m}{\sqrt{\frac{P_{\text{in}}}{V_{\text{in}}}}} \]  
(2)

\[ \text{Sto} = \frac{\phi}{\sqrt{1 - PR^{n_{\text{eff}}}}} \]  
(3)

\[ \phi^2 = \text{Sto}^2 \cdot (1 - PR^{n_{\text{eff}}}) \]  
(4)

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The heat exchangers, including reheaters and feedwater heaters, are modelled by thermally connecting two-phase pipes together. The Simulink connections are shown as the following:

\[ n_{\text{eff}} = \frac{\eta_{\text{poly}} + 1}{\eta_{\text{poly}}} \]  
(1)

\[ \phi = \frac{m}{\sqrt{\frac{P_{\text{in}}}{V_{\text{in}}}}} \]  
(2)

\[ \text{Sto} = \frac{\phi}{\sqrt{1 - PR^{n_{\text{eff}}}}} \]  
(3)

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(2)

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(3)

\[ \phi^2 = \text{Sto}^2 \cdot (1 - PR^{n_{\text{eff}}}) \]  
(4)

For the case of mechanical integration with the steam cycle, the model can be constructed as the layout shown in Fig. 4. This section represents how the mechanical driven steam turbine is connected to the main system via steam bypass in front of the LP turbine.
\( \eta_{\text{poly}} \) polytropic efficiency
\( \Phi \) flow coefficient
\( \dot{m} \) mass flow rate
\( p_{\text{in}} \) inlet pressure
\( \nu_{\text{in}} \) inlet specific volume
\( St_{\text{o}} \) Stodola constant
\( PR \) pressure ratio

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**REFERENCES**