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
[a]*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.

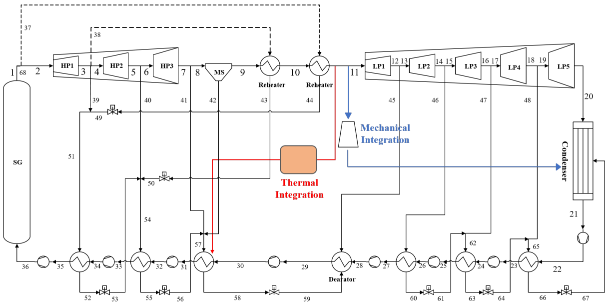

Fig. 1. Schematic of simplified APR1400 layout based on [8] and ESS integration options

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.

Table 1. Design parameters of APR1400 used in the modelling

Design parameters	Values	Units
Steam generator maximum pressure	6.9	MPa
Steam cycle mass flow rate	2251	kg/s
Reactor core heat	3985	MW_{th}
Core coolant outlet temperature	323.9	°C
Coolant temperature	15	°C
Condenser pressure	5	kPa
High-pressure turbine stages	3	-
Low-pressure turbine stages	5	-
Pipe area	0.72	m^2
Steam generator contact area	15205	m^2

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.

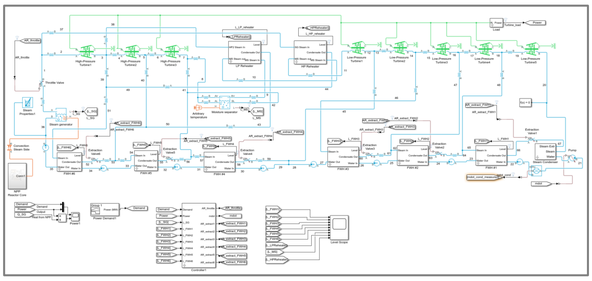

Fig. 2. Schematic of APR1400 layout model using Simulink

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:

$$n_{eff} = \frac{\eta_{poly} + 1}{\eta_{poly}} \qquad (1)$$

$$\phi = \frac{\dot{m}}{\sqrt{\frac{p_{in}}{v_{in}}}} \qquad (2)$$

$$Sto = \frac{\phi}{\sqrt{1 - PR^{n_{eff}}}} \qquad (3)$$

$$\phi^2 = Sto^2 \cdot (1 - PR^{n_{eff}}) \qquad (4)$$

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:

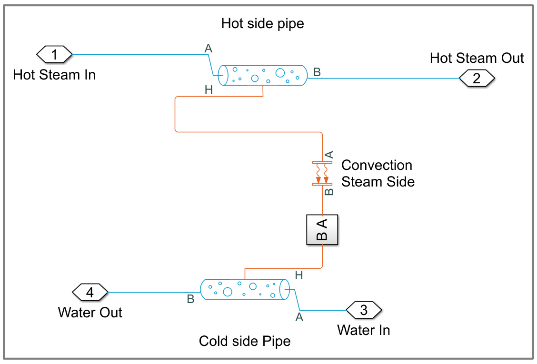

Fig. 3. Schematic of heat exchanger model used in APR1400 modelling

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.

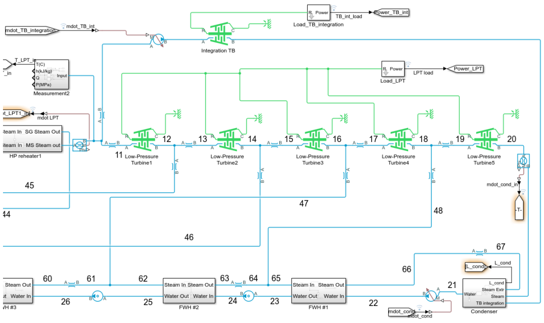

Fig. 4. Schematic of mechanical integration in Simulink modeling

3. Results

In the modelling procedure, it is required to obtain a steady-state result of the performance. Through the modelling, the overall high-pressure turbine and low-pressure turbine loads are calculated, as well as the steam generator inlet and outlet temperatures. The results are shown in Fig. 5, with the right figure representing the electric output of turbines.

Regarding the transient response of the system, the results will be displayed in the conference.

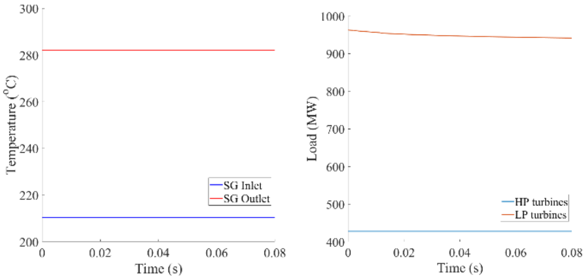

Fig. 5. Steady-state results for Simulink model of APR1400 (steam generator inlet and outlet temperatures, turbine loads)

4. Summary and future works

The research paper describes the preliminary study on the APR1400 steam cycle for ESS integration. Up to now, the model has been built under the Matlab/Simulink platform, so that the analysis can be done with publicly available information and technical simplicity. The system has been converged to steady-state conditions, showing that the model can predict the performance of the APR1400 steam cycle with the publicly available information.

In the future, the results of APR1400 transient modelling using Simulink will be obtained for the cases of steam bypass at the low-pressure turbine inlet point. Several options of how to return the bypass will be also evaluated with the model.

NOMENCLATURE

n_{eff} efficiency exponent

η_{poly}	polytropic efficiency
Φ	flow coefficient
$\dot{m}$	mass flow rate
p_{in}	inlet pressure
v_{in}	inlet specific volume
Sto	Stodola constant
PR	pressure ratio

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