Off-design modeling for Integrating Energy Storage System to Nuclear Power Plant

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1. Introduction

Most international energy policies are designed to increase share of renewable energy. Renewable energy is defined as energy obtained from renewable sources. However, many renewable energy sources such as solar and wind are intermittent in nature. As the share of renewable energy increases, the problem of renewable energy intermittency will become more severe and has to be resolved. For example, solar power cannot be used after sunset, and if wind does not blow wind energy supply will be disrupted.

The Energy Storage System (ESS) integrated nuclear power plant can be an alternative to intermittent renewable energy supply [1]. An ESS integrated NPP changes the electric output as a fraction of steam flow in the secondary steam cycle in nuclear power plants is diverted to ESS depending on the supply and demand fluctuation. The advantage of the concept is that the reactor thermal output can be kept at constant level and thus the service lifetime and economy associated with the primary side can be preserved. The branch flow from the steam turbine transfers heat to ESS when less electricity production is needed. After passing the heat to ESS, the branch flow merges back into the steam cycle of the NPP to maintain constant feed flow conditions. In this paper, an ESS integrated NPP is designed and off-design modeling for steam turbine and feed water heater is presented.

2. Methods

2.1 Steam cycle

The steam cycle utilized in this study is the secondary side of a large pressurized water reactor (PWR) plant, APR1400. Steam cycle design is shown in Figure 1 and design conditions for the steam cycle are listed in Table 1.

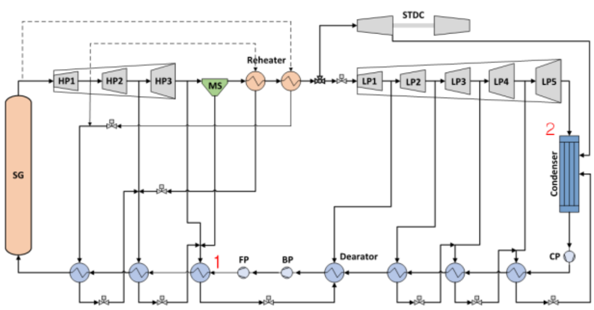

Fig. 1. Layout of the steam cycle

Table 1: Steam cycle conditions

Parameters	Value
Thermal output [MW]	3983
Electric output [MW]	270
SG outlet pressure [MPa]	6.9
SG inlet temperature [K]	505.15
SG outlet temperature [K]	558.15
Turbine efficiency [%]	92
Pump efficiency [%]	80
Total mass flow rate [kg/s]	2245
Turbine exit quality	> 0.8
Feed water heater exit quality	< 0

2.2 Turbine off-design modeling

In the case of turbines, the pressure ratio and efficiency change according to the change in the mass flow rate of the inlet. Therefore, turbine off-design performance analysis is required. The Cone law is applied for the off-design analysis of a turbine. The Cone law is the relationship between inlet and outlet pressures of a turbine and the mass flow through the turbine for given design parameters [2].

$$\frac{\dot{m}_{off}}{\dot{m}_{on}} = \frac{P_{off,in}}{P_{on,in}}\frac{\sqrt{T_{on,in}}}{\sqrt{T_{off,in}}}\sqrt{\frac{1-(P_{off,out}/P_{off,in})^{\frac{n+1}{n}}}{1-(P_{on,out}/P_{on,out})^{\frac{n+1}{n}}}} \quad (1)$$

$$n = \frac{\kappa}{1+\frac{\kappa p(v_v - v_l)}{r}(1-\eta_{tur})} \approx 1 \quad (2)$$

where n is the polytrophic exponent, p is the pressure and v the specific volume, κ is the isentropic exponent, v is the specific volume, r the evaporation enthalpy and η_{tur} the overall efficiency of the turbine. In the case of n, it is assumed to be unity for steam [3].

The efficiency can be calculated for every turbine stage, once the pressure and the enthalpy at every point are known. The turbine pressure can be obtained from Eq.1 and Eq.2. Also the outlet enthalpy can be calculated by using inlet entropy and pressure. Based on this information the off-design efficiency can be calculated with Eq.3.

$$\eta_{off} = \eta_{on} - \alpha\left(\frac{N_{off}/\sqrt{\Delta h_{off}}}{N_{on}/\sqrt{\Delta h_{on}}} - 1\right)^2 \quad (3)$$

2.3 Feed water heater off-design modeling

For the heat exchanger, effectiveness is not fixed unless the inlet condition is held constant. The Number of Transfer Units (NTU) Method is used to calculate the rate of heat transfer in heat exchangers especially for counter current exchangers, when there is insufficient information to calculate the Log-Mean Temperature Difference (LMTD). In the heat exchanger analysis, if the fluid inlet and outlet temperatures are specified or can be determined with simple energy balance, the LMTD method can be used. However, when these temperatures are not available NTU method is used instead.

$$C_{min} = min(\dot{m}_{hot}c_{p,hot}, \dot{m}_{cold}c_{p,cold}) \quad (4)$$

$$\mathrm{NTU} \ = \frac{UA}{C_{min}} \quad (5)$$

The method proceeds by calculating the heat capacity rate C_{min}. The number of transfer units, NTU can be calculated. U is the overall heat transfer coefficient and A is the heat transfer area [4].

$$\varepsilon_{off} \ = \frac{1-exp[1-NTU(1-C_r)]}{1-C_r exp[1-NTU(1-C_r)]} \quad (6)$$

The effectiveness of a counter current flow heat exchanger is calculated with Eq. 6. Also, the design parameters for feed water heaters to calculate Eq. 5 are listed in Table 2.

Table 2: Design parameters

Parameters	Value
Outer diameter of tubes [mm]	19
Inner Diameter of tubes [mm]	17.755
Tube wall thickness [mm]	1.245
Effective length [m]	12
Tube wall thermal conductivity [W/m·K]	16.2
Pitch [mm]	23.8
Number of tubes	500
Inner Diameter of tubes [mm]	19

3. Results

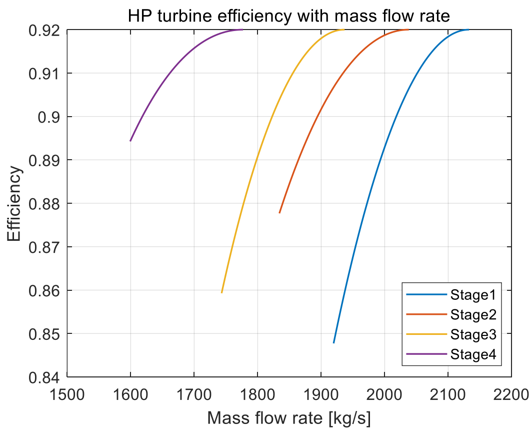

Fig. 2. Efficiency of high-pressure turbine

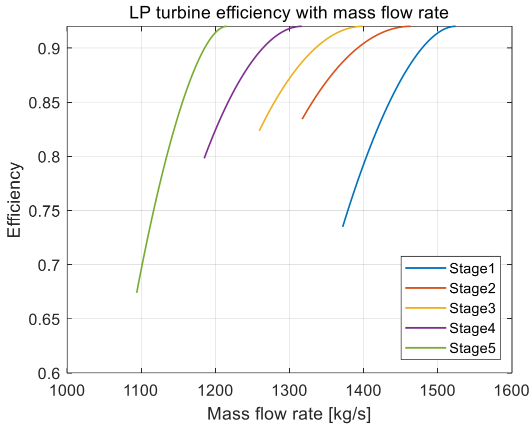

Fig. 3. Efficiency of low-pressure turbine

From Figure 1. The high-pressure turbine has 3 steam extractions and low-pressure turbine has 4 steam extractions. Therefore, a high-pressure turbine and a low-pressure turbine need at least 4 and 5 stages, respectively to represent the whole steam turbine. However, it is noted that the modeled stages do not exactly match with the real stages in a steam turbine. The stages referred in this study is closer to a group of stages in between steam extraction lines where the group of stages can be viewed as a stage. As shown in Figure 2 and Figure 3, turbine efficiency decreases as mass flow rate decreases from the value of 92%, which is the turbine efficiency for on-design conditions.

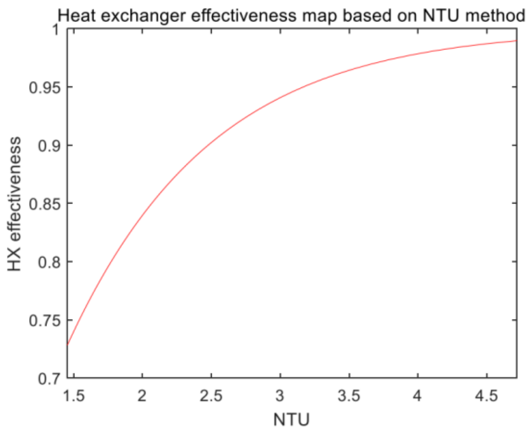

Fig. 4. Heat exchanger effectiveness

Figure 4 shows the heat exchanger effectiveness based on NTU method.

Two cases were selected for the sensitivity study. The first case is which the merging point of the branch flow from the high pressure turbine is the feed water heater inlet (point 1 in Figure 1). The second case is which the merging point of the branch flow is the condenser (point 2 in Figure 1) inlet. The outlet pressure and temperature of the ESS when branch flows are merged, are assumed to be the same as the inlet of the feed water heater for case 1 and inlet of the condenser for case 2, respectively.

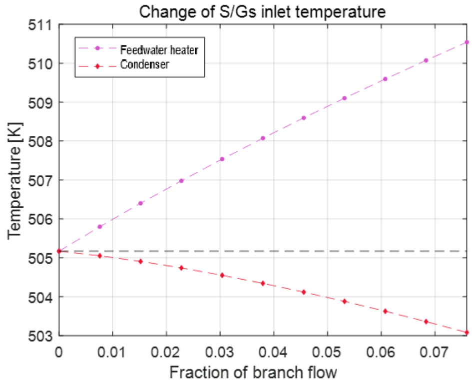

Fig. 5. S/G Feed water temperature change

The off-design results presented in Fig. 5. show that as the branch flow increases, the S/G feed water temperature changes but the trend can be opposite depending on the merging location. This shows that to maintain the feed water temperature at the inlet of the steam generator while branch flow portion is increasing, further optimization is required to maintain constant S/G conditions leading to the constant primary side power level even during the load following operation.

4. Conclusions and Future works

In this study, the authors proposed an ESS integrated NPP. The ESS integrated NPP performs load-following operation by adjusting mass flow to the steam turbine of the secondary side of a nuclear power plant, while the primary side operating conditions are held at constant. The ESS integrated NPP operates under varying load without altering the reactor power, so even if some mass flow branches to the ESS, it shall not affect the primary side. However, as the flow of the branch increases, the feed water temperature at the steam generator inlet changes. As the future study, an optimization of the branch flow is required to maintain the feed water temperature of the steam generator inlet. If so, it is expected that after optimization, the change in cycle efficiency according to the α, the branch of the design mass flow, and the merging point can be seen in the off-design model.

REFERENCES

[1] Baik, Seung Joon. Study on CO2 based mixture power cycle for flexible operation of nuclear power plant. KAIST. Republic of Korea. 2019
[2] Rafael Macián-Juan, et al. “Development and implementation of a Nuclear Power Plant steam turbine model in the system code ATHLET” Appl. Energy, 250 (2011), pp. 3-18.
[3] Traupel, W. Thermische Turbomaschinen, 4. Auflage. Berlin/Heidelberg/New York: Springer-Verlag. (2001)
[4] F. P. Incropera, D. P. DeWitt, T. L. Bergman & A. S. Lavine 2006 Fundamentals of Heat and Mass Transfer ,6th edition, pp 686–688. John Wiley & Sons US