Steam Cycle Off-design Analysis of An Energy Storage System integrated Nuclear Power Plant

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1. Introduction

Most of global energy policies are based on increasing the share of renewable energy i to reduce impact of climate change. However, renewable energy source is intermittent in nature. Power from renewable energies is produced according to the intermittent supply of a source regardless of power demand. The intermittent problem of renewable energies must be resolved to ensure stability on the power grid. Other power supplies must change the output to match the total power demand. Research has been conducted on ESS (Energy Storage System) technology or flexible power generation to solve the problems resulting from the intermittency of renewable energy sources. In this paper, the authors propose an ESS integrated nuclear power plant (NPP) as a load-following power source [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. Meanwhile, the reactor thermal output kept at constant level. The branch flow transfers heat to ESS. After passing the ESS, the branch flow merges back into the steam cycle of the NPP. In this paper, the steam cycle of the ESS integrated NPP is designed and off-design analysis under a specific load is performed. Therefore, this study demonstrates the possibility and competitiveness of an ESS integrated NPP as a win-win plan for renewable and nuclear energies.

2. Steam Cycle Modeling

2.1 Steam cycle design of NPPs

A generic steam cycle design takes precedence for ESS integrated steam cycle design. The steam cycle is based on the secondary side of the pressurized water reactor (PWR) plant, the most widely used nuclear power plant. Fig. 1 shows the layout of the ESS connected to the designed steam cycle. The design conditions for the steam cycle are listed in Table 1.

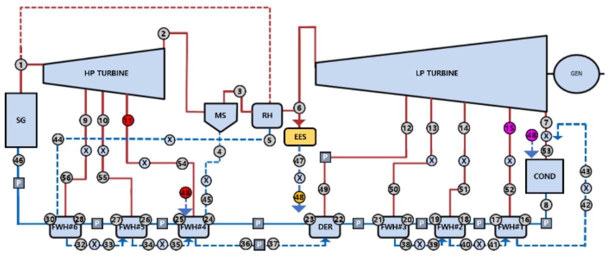

Fig. 1 Layout for the steam cycle of the energy storage system integrated nuclear power plant

Table 1 Steam cycle design conditions

Input variable	Value
Thermal output [MW]	3983
Electric output [MW]	1423
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
Condenser pressure [kPa]	5.08
Turbine exit quality	> 0.8
Feedwater heater exit quality	< 0

2.2 Connection with ESS

The location connecting the ESS and the steam cycle of the nuclear power plant is important. Because it determines how much energy is delivered to the ESS. In order to deliver enough energy to the ESS, the branch point must have a sufficient mass flow rate and be placed in front of the low-pressure (LP) turbine to vary the output. The inlet of the high-pressure (HP) turbine close to the reactor is excluded due to the reactor safety. Therefore, as shown in Fig.1, the branch point of the EES integrated NPP is determined by the inlet of the LP turbine (no.6 on Fig. 1). Depending on the type of ESS, ESS exit condition may be varied. This is because the form of transferred energy may be different, such as work or heat depending on the type of ESS. In addition, the condenser and the FWH #4 are respectively determined as the merging point to explain the cases where energy is transferred in the form of work and heat. In this paper, steam cycle optimization according to branch flow is performed for each merging point.

2.3 Off-design analysis

2.3.1 Turbine off-design modeling

An off-design analysis for the ESS integrated NPP is performed by branching mass flow to the ESS. The cone law (eq. 1) is applied to the turbine off-design analysis [2]. n is the polytropic index, κ is the isentropic index, ν is the specific volume for each physical state, r is the enthalpy of evaporation, and η is the turbine efficiency at design conditions. κ is regarded as 1.135 for wet steam. n is assumed to be 1 for steam and the ideal gas and *N* is turbine rpm. α is a positive constant determined empirically. In this study, the α value is assumed to have from 0, 0.1, 0.9, 2 to observe sensitivity of the cycle to the parameter. Turbine efficiency is calculated for each α. Fig. 2 shows the turbine efficiency map according to α.

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

$$\text{n} = \frac{\kappa}{1+\frac{\kappa p(v_{vapor}-v_{liquid})}{r}(1-\eta_{turbine,on})} \approx 1 \quad (2)$$

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

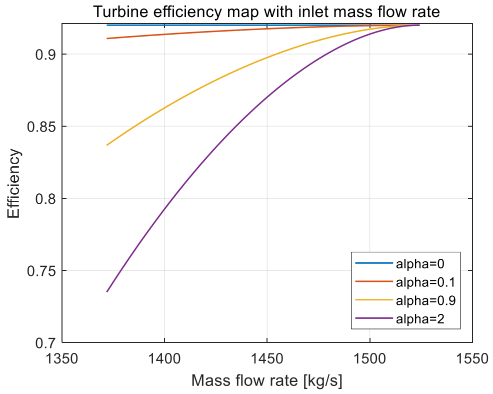

Fig. 2 Turbine efficiency map with inlet mass flow rate

2.3.2 Heat exchanger off-design modeling

All feedwater is assumed to be counter-current closed heat exchangers. Heat exchangers are modeled based on the Number of Transfer Units (NTU) method for off-design performance analysis (eqs. 4-7). The design parameters of the feedwater heaters (FWHs) are listed in Table 2 [3].

Table 2 Design parameters for feedwater heaters

Design 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

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

$$\frac{1}{UA} = \frac{1}{h_{cold}A_{cold}N_c} + \frac{log(D_O/D_i)}{2\pi kLN_c} + \frac{1}{h_{hot}A_{hot}N_c} \quad (5)$$

$$\text{NTU} = \frac{UA}{C_{min}} \quad (6)$$

$$\varepsilon_{off} = \frac{1-exp[1-NTU(1-C_r)]}{1-C_r exp[1-NTU(1-C_r)]} \quad (7)$$

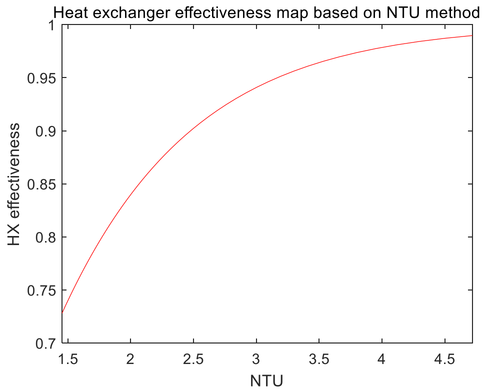

Fig. 3 Heat exchanger effectiveness map based on NTU method

2.4 Cycle optimization

Since the ESS integrated NPP operates on load-following without changing reactor output, it should not affect the primary side even if some of mass flow branches to the ESS. However, as the branch flow increases, the feedwater temperature at the SG inlet changes as shown in Fig. 4. The optimization is performed to maintain the feedwater temperature at the SG inlet while increasing the branch flow. The tolerance for feedwater temperature variation is determined as 0.1% from its design point. Optimization parameters are determined in each case. In case of merging into FWH #4, the last extraction for the HP turbine (no.11) is an optimization parameter. In case of merging into the condenser, the last extraction of the LP turbine (no.15) is the optimization parameter. This is to ensure that other components do not deviate significantly from design conditions. The ESS exit condition is the same as the design condition of no.11 when the merging point is FWH #4, and the design condition of no.7 when the merging point is the condenser.

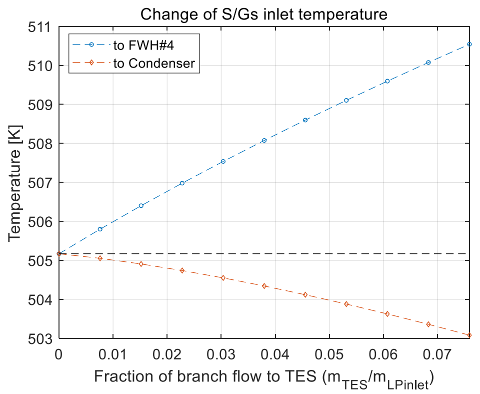

Fig. 4 Feedwater temperature change at S/G inlet

3. Optimization Results

In the ESS integrated NPP, the cases where the merging point is FWH #4 and condenser were analyzed. In both cases, cycle optimization was performed with different α values in eq. 3. When the results were analyzed comprehensively, the higher the α, the more the cycle power and efficiency decreased in both cases where the merging point was FWH #4 and condenser. This is because higher α leads to larger reduction in turbine efficiency.

To compare the results for different merging point, the case where the α value is 0.1 was analyzed in both cases. When the α value is 0.1 and 20% of the design mass flow is branched to the ESS, the cycle output and efficiency decreased by 36% for the merging point FWH #4 and 41% for the condenser.

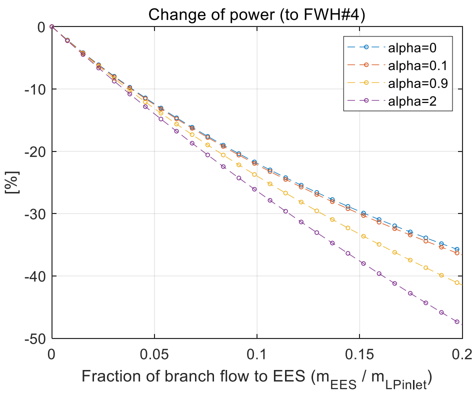

Fig. 5 Cycle power with branch flow for merging point FWH #4

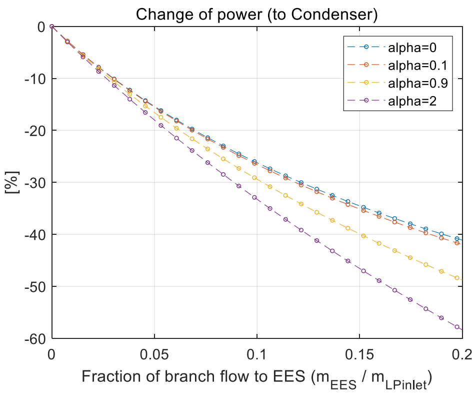

Fig. 6 Cycle power with branch flow for merging point condenser

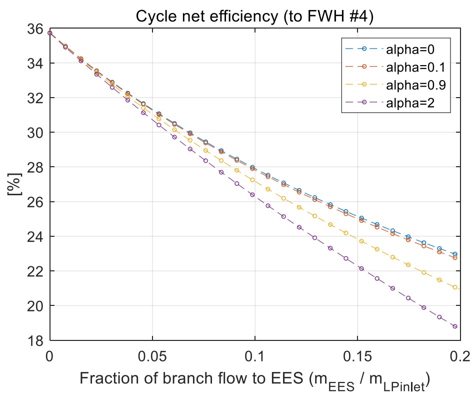

Fig. 7 Cycle net efficiency with branch flow for merging point FWH #4

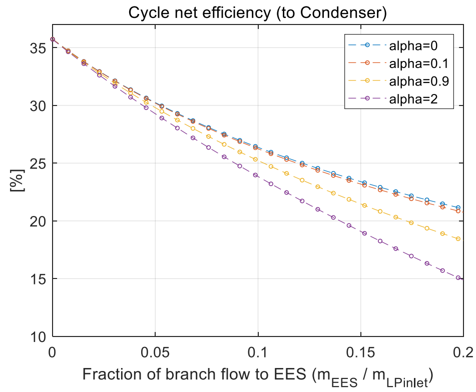

Fig. 8 Cycle net efficiency with branch flow for merging point condenser

Since the ESS inlet conditions are almost unchanged and the outlet conditions are fixed, the energy delivered to the ESS is constant even when the α value is changed. Therefore, as the branch flow rate increases, the amount of energy delivered to the ESS increases proportionally.

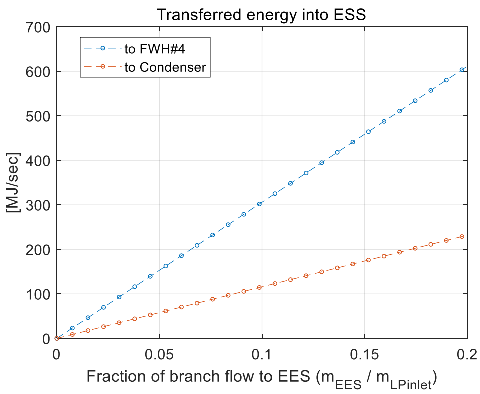

Fig. 9 Transferred energy into energy storage system with branch flow

As mentioned earlier, the feedwater temperature at the S/Gs inlet must be maintained within 0.1% tolerance at the design point. The optimization was performed by selecting optimization parameters according to merging points. Fig. 10 shows the change in the last extraction of the HP turbine (no.11), which is an optimization variable, when the merging point is FWH #4. Fig. 11 shows the change in the last extraction (no.15) of the LP turbine, an optimization variable when the merging point is a condenser.

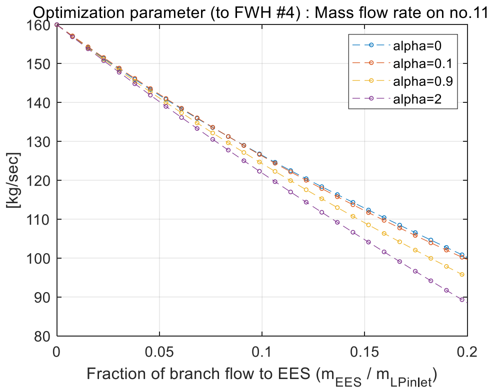

Fig 10. Mass flow rate on the last extraction of HP turbine with branch flow

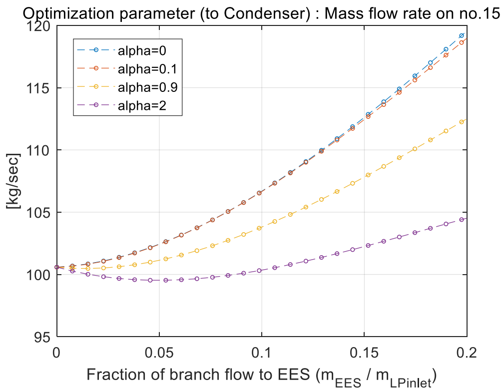

Fig 11. Mass flow rate on the last extraction of LP turbine with branch flow

4. Conclusions

As the share of renewable energy increases, concerns about the stability of power supply have occurred. This is due to the intermittent nature of renewable energy. To overcome this, energy storage technologies and flexible power sources are proposed. This paper claims an ESS integrated NPP can be a solution to this problem. An ESS integrated NPP is a system that diverts steam flow to the ESS from the steam cycle of a nuclear power plant and returns it after transferring energy to ESS. It has the advantage that the load-following operation of NPPs is possible without variation in reactor thermal output. Therefore, the optimization aims to maintain the feedwater temperature at the S/G inlet. In this paper, the steam cycle is designed and analyzed by varying the merging point, FWH #4 and condenser. Optimization is performed under specific cycle conditions while increasing branch flow by applying off-design model for components. As a result of the optimization, when α is 0.1 in the off-design model of the turbine and 20% of the design mass flow is branch to the ESS, the cycle power is reduced by 36% when the merging point is FWH # 4 and 41% when the merging point is the condenser. In order for ESS integrated NPP to be feasible in the future power market, more detailed dynamic responses need to be evaluated.

ACKNOWELGEMENT

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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] Ray, A. Dynamic modelling of power plant turbines for controller design. Applied Mathematical Modelling. Vol. 4, pp. 109-112. 1980
[3] Pressurized Water Reactor Plant, United Engineers & Constructors, Inc., p116-117, 1972