Sensitivity Analysis of Steam Branching Location for Thermal Energy Storage Integrated Nuclear Power Plants

Ju Yeon Lee, Jeong Ik Lee
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of KOREA
moveyeon@ kaist.ac.kr; jeongiklee@kaist.ac.kr

1. Introduction

Due to global concerns of greenhouse gas emission, emphasis on renewable energy becomes greater in the world electricity market. The Korean government announced the renewable energy 2030 plan in which the share of renewable energy will reach to 20% by 2030 [1]. However, there are some concerns about the quality and stability of the electricity supply in the future. It is due to the intermittency of renewable energy sources. The intermittent power supply of renewable energy can require load-following options of other power sources. As one of resolutions to this problem, a thermal energy system (TES) integrated nuclear power plant (NPP) is proposed as a new nuclear load-following operating mode [2]. In order to evaluate the load-following operation capability of the TES integrated NPP, it is needed to study where the steam flow is diverted to the TES and returned to the secondary system of the nuclear power plant. Since this determines how much energy will be stored in TES and how much the power of nuclear power plant will decrease, it is an essential step for developing the concept. In this paper, the authors performed thermodynamic cycle analysis for different TES branching positions in the secondary system of a pressurized water reactor (PWR) type nuclear power plant (NPP).

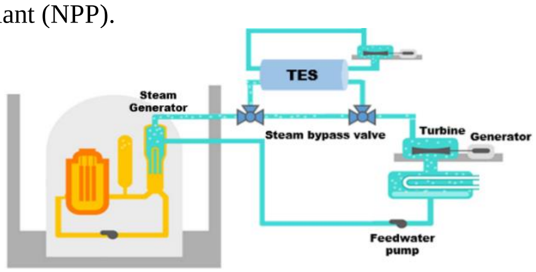


Fig. 1 The conceptual diagram of TES integrated PWR type NPP

2. TES integrated NPP

2.1 TES integrated PWR type NP

The TES integrated PWR nuclear power plant is a system for storing heat by branching the steam mass flow of the secondary system when the power is needed to reduce. The stored heat is used for additional electricity generation when the power is needed to increase. Where the steam branch to TES is located in the secondary system of a nuclear power plant is important to evaluate the capability of this system. In this study, two cycle layouts based on different steam branching location of TES are presented, and thermodynamic analysis for each cycle is performed with KAIST-CCD. KAIST-CCD is a MATLAB-based closed cycle design code that performs cycle analysis and design optimization with real gas properties. The cycle simulation is performed for the steady-state conditions.

2.2 Cycle condition

In this study, a pressurized light water reactor (PWR) type was selected for the TES integrated NPP cycle simulation. Two layouts are proposed with different positions for steam branching. Figs, 2 and 3 show generic saturated steam cycle layouts with multiple regenerations that combines TES. On these layouts, a certain amount of the total steam mass flow diverts to the TES. In Fig. 2, some of mass flow rate is branched to TES before high-pressure turbine inlet. The branch flow to TES is merged back with the main feed water at the last preheater stage. In this layout, as the branch flow to TES increases, the mass flow rate to both high- and low-pressure turbines decreases. It is assumed that the outlet temperature of TES is equal to the reheater outlet temperature (No. 44 in Fig. 2).

In Fig. 3, some of mass flow rate is branched to TES before low-pressure turbine inlet. The branch flow to TES is merged back with main feed water on one of the preheater stages. In this case, the mass flow rate to high-pressure turbine is kept constant, but the mass flowrate to low-pressure turbine decreases. It is assumed that the outlet temperature of TES is equal to the outlet temperature of moisture separator waterline. (No. 4 in Fig. 3).

The steam cycle operating conditions are given in Table 1. Based on these conditions, the authors will analyze the amount of energy stored in the TES for different branch steam flow rate, the output of the HP turbine and the LP turbine, and the temperature of the feedwater on the steam generator inlet.

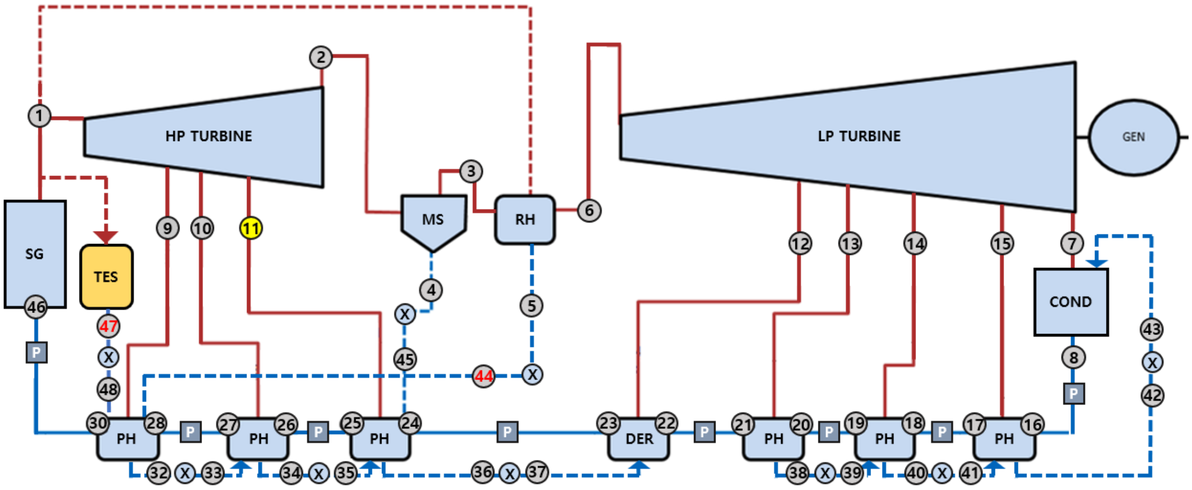


Fig. 2 Steam cycle layout of TES integrated NPP (Before HP turbine)

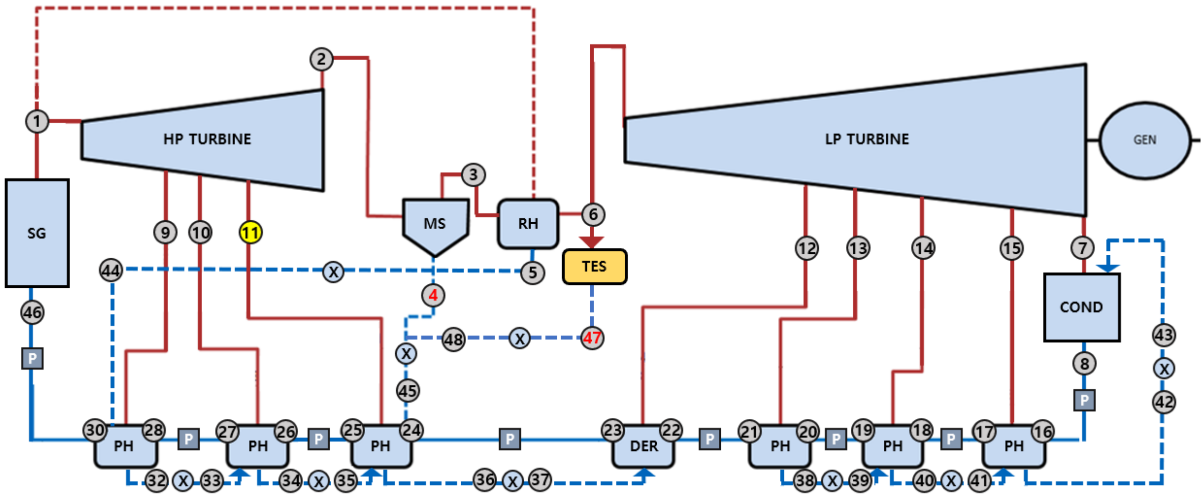


Fig. 3 Steam cycle layout of TES integrated NPP (Before LP turbine)

Table 1. Cycle condition

Parameter	Value
Reactor thermal Output (normal)	3983 MWt
Electric Output (normal)	1412 MWe
Steam Generator Pressure	6.9 Mpa
Steam Generator Outlet Temperature	285°C
Condenser Pressure	5.08 kPa
Secondary cycle Mass flow rate	2230.33 kg/s
HP Turbine Efficiency	0.9
LP Turbine Efficiency	0.9
Pump Efficiency	0.85
Generator Efficiency	0.98

2.3 Thermodynamic Analysis

As a result of thermodynamic analysis, in the layout (Branch before HP Turbine) shown in Fig. 2, when the branch flow to TES exceeds 5% of the total mass flow, the temperature of feedwater passing through the deaerator exceeds the saturation temperature. In the case of the layout (Branch before LP Turbine) shown in Fig. 3, when the branch flow to TES exceeds 4% of the total mass flow, the phenomenon in which the temperature of the feedwater passing through the deaerator exceeds the saturation temperature also occurred. Therefore, from the point where the feedwater temperature of the deaerator exceeded the saturation temperature, the last extraction flow rate of the HP turbine was adjusted and optimized so that the deaerator conditions are below saturation conditions. The last extraction flow is indicated by the station number 11 on Figs. 2 and 3. For the layout of Fig.2, the authors will express it as Before HPT and for the layout of Fig.3 Before LPT. The following results show the branching of TES up to 25% of the total steam mass flow.

Fig. 4 shows the change of electricity generation according to branch flow to TES. Until the temperature of the feedwater passing through the deaerator exceeds the saturation temperature, the output decreases with a nearly similar slope with respect to branch flow. Beyond this point, the output of Before HPT decreases more rapidly than that of Before LPT. When the branch flow is 25% of the total steam mass flow, the output decreases by 23.46% compared to full power in the case of Before HPT and 20.71% in the case of Before LPT. Fig. 5 shows the cycle efficiency according to branch flow to TES.

The reason for the change in the slope is because HP turbine last extraction (No. 11) flow rate was changed to avoid deaerator conditions becoming saturation conditions. As a result of the optimization, the change of HP turbine final extraction (No. 11) flow rate is also shown in Fig. 6.

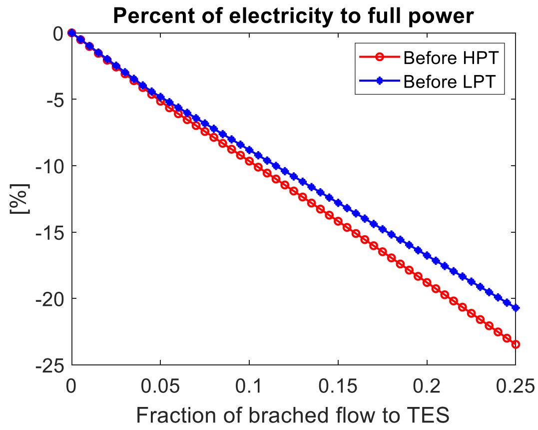


Fig. 4 The output change with branched flow into TES

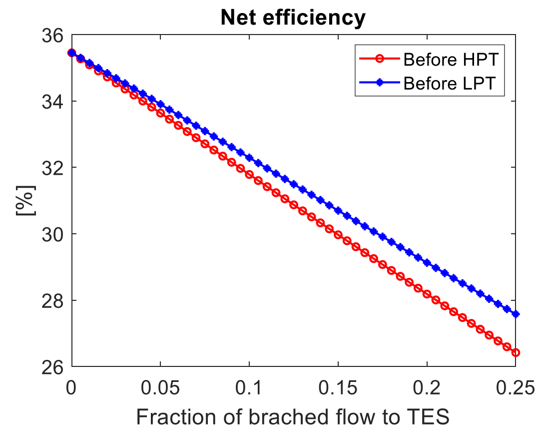


Fig. 5 The cycle efficiency with branched flow into TES

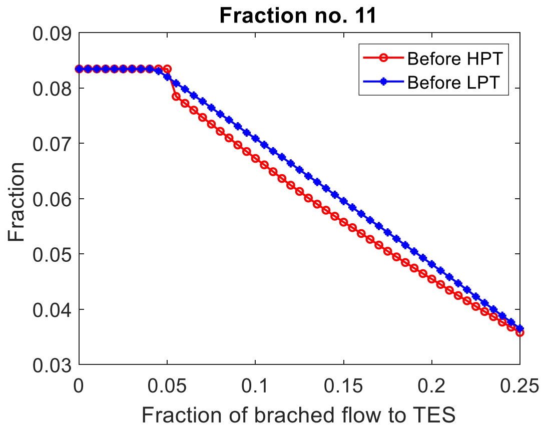


Fig. 6 The change of mass flow rate on HP turbine final extraction (no.11 on Fig. 2 and 3) with branched flow into TES

In normal operation, the temperature of the main feedwater into the steam generator inlet is 232.2 ºC. In the case of Before HPT, it is increased slightly to 232.3 ºC when the branched flow rate was 5% and then decreased to 221.9 ºC when the branched flow rate reached 25%. In the case of Before LPT, it is increased to 234.2 ºC when the branch flow rate was 4% and then it is decreased to 224.9 ºC when the branch flow rate reached 25%. The reason why the steam generator inlet temperature increases and then decreases is again due to a change in HP turbine extraction mass flow rate (no. 11). The temperature at the steam generator inlet increases when only the branch flow to TES is increased without changing the HP turbine extraction mass flow rate. When the HP turbine extraction rate is increased to prevent saturation of the main feedwater, the temperature at the steam generator inlet decreases even when the branch flow to TES is increased.

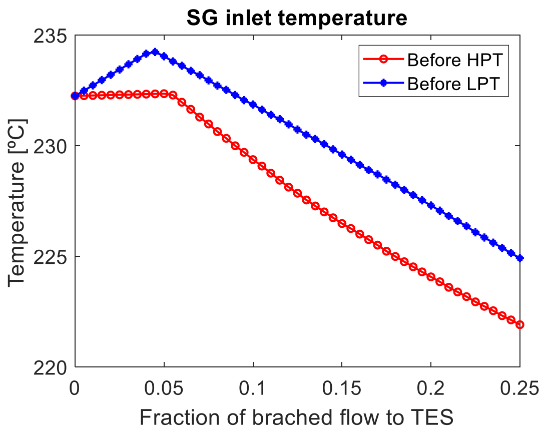


Fig. 7 The temperature change on steam generator inlet with branched flow into TES

As mentioned above, it is assumed that the TES outlet temperature is the same as the reheater outlet temperature in the case of Before HPT, and the outlet temperature of the moisture separator waterline in the case of Before LPT. When the branch flow into TES reaches 25% of total mass flow, 1005 MJ/s of heat is stored for Before HPT and 1150 MJ/s for Before LPT.

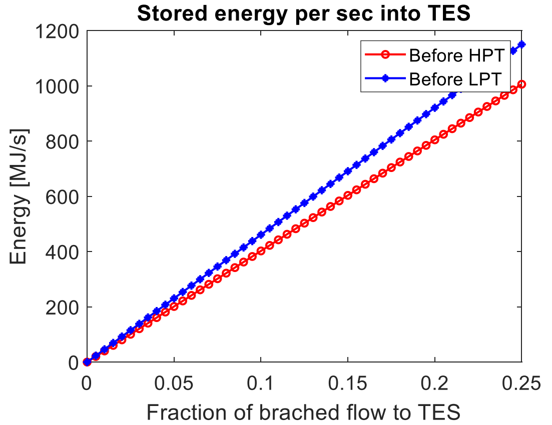
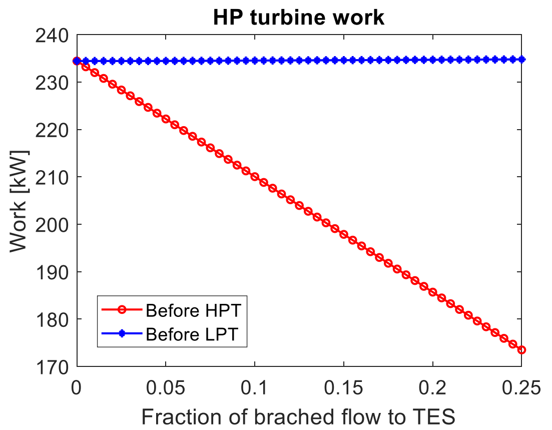


Fig. 8 The stored energy per second with branched flow into TES

Since it is assumed that the turbine efficiency is independent of the steam mass flow rate, the work of each turbine depends on steam mass flow rate to the turbine. The work of HP turbine increases by 0.17% for Before HPT and decreases 25.98% for Before LPT when the branch flow to TES reaches 25%. The work of LP turbine decreases by 21.74% for Before HPT and 30.87% for Before LPT when the branch flow to TES reaches 25%.



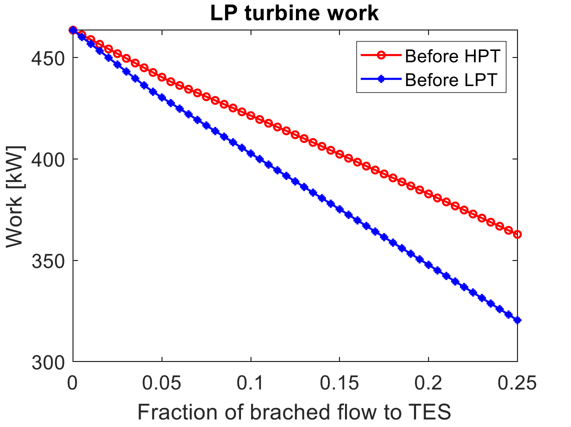


Fig. 9 The work of HP and LP turbine with branched flow into TES

3. Conclusions

The share of renewable energy may rapidly increase due to recent global energy market trend. However, it is technically challenging to cope with the increase of intermittent energy supply from renewable energy sources while grid stability is secured. As one of potential solutions to this problem, a TES integrated NPP is proposed to ensure the quality and stability of the grid. It is important to study where the steam mass flow is diverted in the secondary system of a PWR to TES and merges back to the secondary cycle to evaluate the load-following operational capability of the proposed concept. In this paper, the stored energy and power changes were analyzed by changing the position of the steam branch to TES in the steam cycle. An appropriate TES type for the steam branch conditions to TES will be designed, next. In the future, an optimal layout of TES integrated NPP will be selected and dynamic response of the whole system will be analyzed as well to evaluate its load-following performance in more detail.

ACKNOWLEDGMENT

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