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Preliminary analysis for application of thermal energy storage system in nuclear power plant

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1. Introduction

The changing global electricity landscape, driven by the Paris Agreement's emission reduction objectives, escalating renewable energy integration, and shifting natural gas dynamics due to increased shale gas production, is causing a significant change in the energy industry. The main focus is on maintaining harmony with the environment, ensuring a reliable power supply, and ensuring economic viability. The growth in renewable energy generation is remarkable, but its intermittent nature poses challenges for steady supply and quality. To address these issues, the concept of nuclear renewable hybrid energy systems (NRHES), which combine different energy production methods and different storage systems to achieve synergy, as shown in Figure 1, has gained traction [1-2]. Among these, thermal energy storage (TES) can utilize the thermal energy of nuclear power plants to cover the intermittency of renewable energy. However, the use of TES requires transferring the heat of the high-temperature steam generated by nuclear power plants, which can have an impact on core temperature as well as secondary systems.

Therefore, this paper focuses on evaluating the impact of TES application on the thermal behavior of a nuclear power plant including primary and secondary systems using MARS-KS version 1.5 [3].

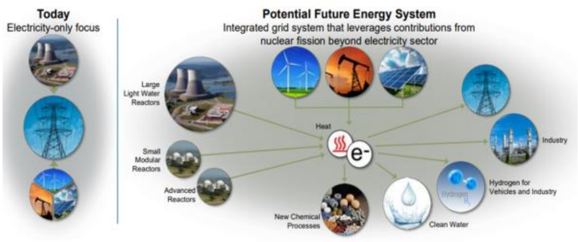

Figure 1. A comprehensive review for NRHES [1]

2. Modeling and analysis scenario

For the TES analysis, we utilized integrated dynamic model that includes both the primary and secondary system of SMART developed previously [4].

2.1 TES concepts

TES involves extracting a portion of steam from a secondary side in the NPP and storing it in thermal storage tanks as thermal energy for applications like hydrogen production, desalination, district heating, etc. The fluid that has lost its thermal energy is then returned to the specific components (e.g., condenser, deaerator, etc.) of secondary system. Thus, TES operation could result in a decrease in the feedwater and the core inlet temperatures, as some of the thermal energy intended for the secondary system is diverted to TES.

At that point, variations in coolant temperature flowing into the core could directly affect core power and nuclear operations. Thus, for TES operation, steam must be extracted within the temperature margin. To ensure core safety, we assumed core inlet temperature deviation within ±3 K under full power in SMART.

2.2 Analysis method and scenario

The objective of the analysis is to analyze the impact of steam extraction from the secondary system on the overall behavior of the plant's thermal-hydraulic conditions, rather than on the TES efficiency or capacity. Therefore, the TES model was substituted with a boundary condition that represented TES's thermal properties and extraction flow rate using time-dependent volumes and junctions as shown Figure 2. The extraction point was assumed at the High-Pressure Turbine (HPT) inlet, with the return point at the condenser. The boundary condition for the returned fluid passing through the TES heat exchanger was set as saturated water at 0.09 bar. The extraction flow rate was sequentially increased to 5%, 10%, and 20% of full-power steam production. It is assumed that the TES operation occurs at 4,500 seconds and that it takes 300 seconds for the targeted extraction flow rate to build up. The TES operation scenarios are summarized in Table 1.

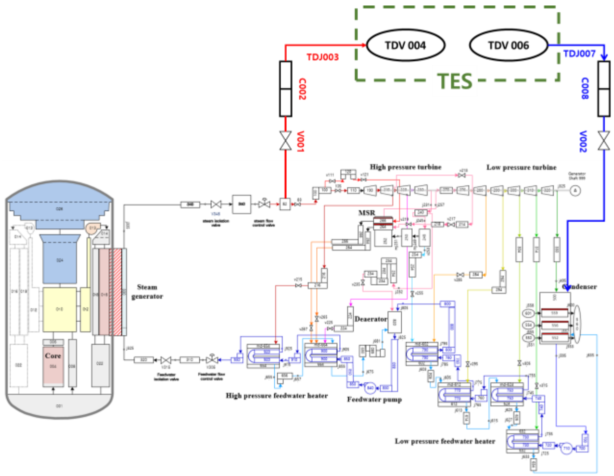

Figure 2. Nodalization of SMART integrated with TES

Table I. TES analysis scenario

TES operation scenario	Operator actions	Extraction flow rate [kg/s]
0 – 4,500 s (Steady stats condition)	-	0.0
4,500 s (- 4,800 s)	TES valve opening	0.0 to 9.52
7,100 s (– 7,400 s)	Additional opening	9.52 to 19.04
9,100 s (– 9,400 s)	Additional opening	19.04 to 38.0
14,400 s (- 15,000 s)	TES valve closing	38.0 to 0

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3. Analysis results and discussion

Figure 3 show the flow rates at various points such as Steam Generator (SG) outlet, High Pressure Turbine (HPT) inlet, TES extraction, and feedwater according to TES operation. At TES operation, minor fluctuations were observed in feedwater flow due to Feedwater Pump (FWP) dynamics: when the TES started, a portion of the steam directed to the HPT was diverted to the TES, reducing the pressure in the steam line instantaneously. Conversely, downstream of the FWP, the deaerator was providing a buffer, resulting in a lower pressure drop. This caused momentary flow fluctuations due to the time lag between the upstream and downstream pressure drops, but overall system stability was restored as the secondary system reached steady-state conditions. Feedwater flow showed similar behavior to steam flow, with the main feedwater flow control valve (V305) operating in compliance with the control logic. Regulating this valve ensured that SG feedwater flow was equal to steam generation. Notably, although fluctuations occurred during TES operation, the system remained stable overall and returned to steady state after TES stop.

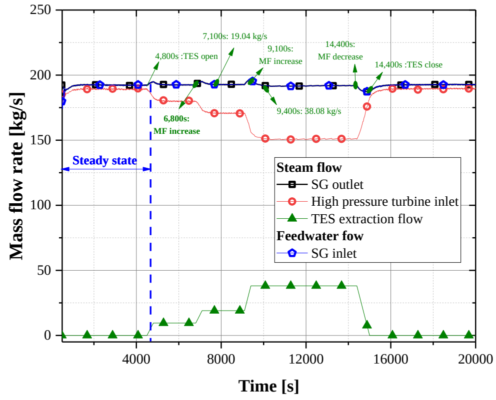

Figure 3. Mass flow rate behavior according to TES scenarios

Figure 4 shows how feedwater and core inlet temperatures varied in proportion to the TES extraction flow. The 5% extraction steam flow rate was very close to the core temperature limit (±3 K), indicating the need to limit the extraction flow rate to maintain core integrity.

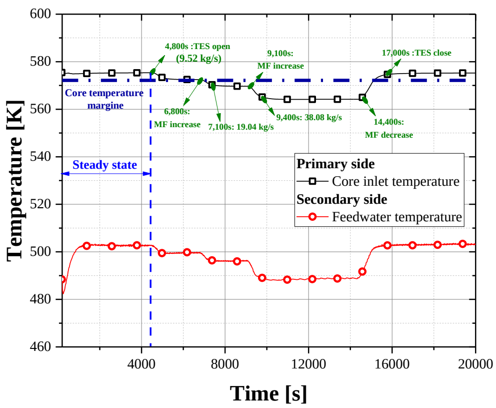

Figure 4. Temperature behavior according to TES scenarios

Figure 5 shows the turbine power, core thermal power according to the TES operation scenario. When the steam flow into the turbine decreased due to the extraction flow rate, the turbine output decreased. On the other hand, when the core inlet temperature dropped due to TES operation, the core output slightly increased by inducing positive reactivity through reactivity feedback.

It is noteworthy that the steady state is maintained and no rapid transients are induced as the TES operates. It can also be seen that when the thermal energy storage through the TES is terminated, the main thermal-hydraulic parameters of the nuclear power plant stably return to the normal full power condition.

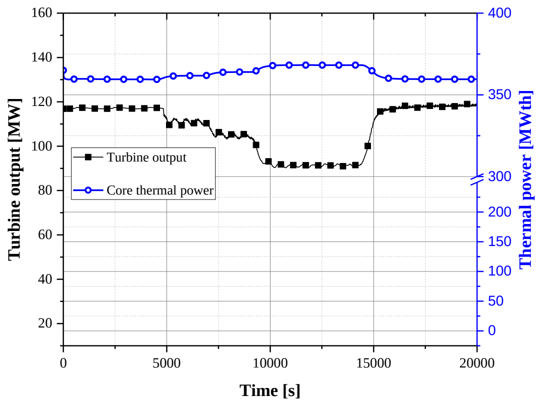

Figure 5. Turbine output and thermal power behavior according to TES scenarios

3. Conclusions

In this paper, a preliminary analysis of the impact of TES application on the major thermal-hydraulic variables of a nuclear power plant was performed based on the developed SMART integrated model. It was confirmed that the operation of the TES directly affects the feedwater and reactor core temperature, which may require a detailed thermal-hydraulic analysis for the actual application of the TES. Also, an operation strategy should be prepared to minimize the feedwater temperature change by properly utilizing the thermal energy recovered from the TES.

However, through the current analysis, it was confirmed that the operation of the TES does not cause major transients in the main parameters related to nuclear power plant safety and the steady state was well maintained. In addition, when the operation of the TES was terminated, the steady state is maintained at the existing full power condition.

Based on this preliminary study, we will conduct sensitivity analysis on various TES application locations and flow rates to suggest optimal locations and operating strategies to minimize the effects of feedwater temperature.

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