Dynamic control evaluation of nitrogen Brayton cycle for decoupling strategy on thermal energy storage system and advanced reactor

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1. Introduction

As the global energy landscape evolves, nuclear energy is gaining renewed attention as a crucial energy source not only for high-density energy applications, such as artificial intelligence (AI), but also for renewable energy integration [1]. Even though renewable energy sources are clean and sustainable, their intermittency poses challenges for grid stability. To compensate for the intermittency of renewable energies, nuclear energy is required to provide a stable and scalable solution in the energy mix.

One promising approach to enhancing nuclear energy's flexibility is the integration of thermal energy storage (TES) systems. By storing excess thermal energy during periods of low demand and dispatching it when needed, TES systems enhance the adaptability of nuclear power, making it a viable complement to variable renewable energy sources. Recognizing the potential of this approach, several commercial nuclear companies are actively developing advanced reactor technologies integrated with TES systems [2]. Based on TES systems, it enables an operational approach known as the decoupling strategy, which allows independent operation of the advanced reactor and the power conversion system (PCS) [2]. From the perspective of advanced reactors, the most efficient and safe operation is to maintain 100% power. However, to accommodate fluctuations in grid demand, the net power output of the PCS must be adjusted, compensating for a mismatch between energy generation and consumption.

For the successful implementation of the decoupling strategy, it is essential to analyze the transient behavior of the system to ensure operational stability. Furthermore, although various control methods have been developed to maintain the stability of the system, it is crucial to identify effective control strategies that also satisfy safety requirements. Therefore, this study aims to investigate effective control combinations for decoupling strategy. A nitrogen (N_2) Brayton cycle is adopted due to its inherent stability and relatively simple operational strategies [3]. Different control combinations are evaluated to determine the effective controls. It is worth noting that the results provide insights into the safety and efficient control strategies for decoupling strategy.

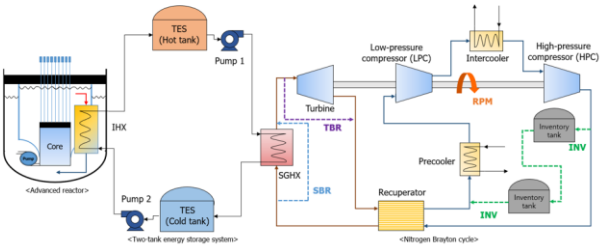

Fig. 1. N_2-PCS layout with advanced reactor and TES.

2. System layout with control methods

2.1. System layout with boundary conditions

As shown in Fig. 1, this study adopts an integrated system layout incorporating a TES system with two tanks. The TES system is positioned between advanced reactor (sodium-cooled fast reactor, SFR) and N_2-PCS. In this integrated system, maintaining stable temperature boundary conditions among the advanced reactor, TES system, and N_2-PCS is crucial to ensuring overall system stability and sustaining the decoupling strategy. This strategy allows the advanced reactor to operate continuously at 100% power while enabling flexible net power adjustments in the N_2-PCS. This is because it is essential to maintain stable inlet and outlet temperature conditions from the perspective of system stability. For the TES system, temperatures are assumed to remain constant in both the hot and cold tanks. This implies that the hot-side inlet and outlet temperatures of the sodium-to-gas heat exchanger (SGHX) must be controlled to provide consistent thermal conditions for the nuclear reactor, ensuring reliable and efficient system performance.

2.2. Control combinations for decoupling strategy

In this study, various control methods are applied to regulate the thermal boundary conditions and turbine inlet pressure (TIP), which is also critical for ensuring the N_2-PCS stability. The considered factors are turbine bypass ratio (TBR), SGHX bypass ratio (SBR), inventory tank (INV), and turbomachinery rotational speed (TRS), as illustrated in Fig. 1.

TRS control is primarily used to maintain a stable TIP by adjusting the rotational speed of all turbomachinery components. In contrast, INV control, which regulates the mass flow rate of the N_2-PCS, influences both TIP and the thermal boundary conditions. Additionally, bypass controls (TBR and SBR) are utilized to adjust the hot-side outlet temperature of SGHX under transient conditions. By employing different combinations of these control methods, both the thermal boundary conditions and TIP are effectively managed to enhance overall system performance and stability.

3. Transient N_2-PCS layout in system code

Since the advanced reactor operates in a steady-state condition at 100% full power, the transient behavior of the N_2-PCS in decoupling strategy can be analyzed with a simplified TES system in a commercial system code (Aspen Plus Dynamics), as shown in Fig. 2. The design methodology and off-design performance of main components were adopted from previous studies [3-5]. Moreover, the quasi-steady-state calculation result of the N_2-PCS was already evaluated in a previous study [5], and the design results of the main components meet the required duties of cycle components.

In this transient layout, transient analyses were conducted with respect to control combinations considering a 30% variation in SGHX heat duty. This means that the heat transfer rate of the SGHX decreases from 100% to 70% during the load-following operation. Using the developed N_2-PCS layout, the transient characteristics of the system were investigated to assess the necessity of control strategies for maintaining stability and efficiency in the decoupling strategy.

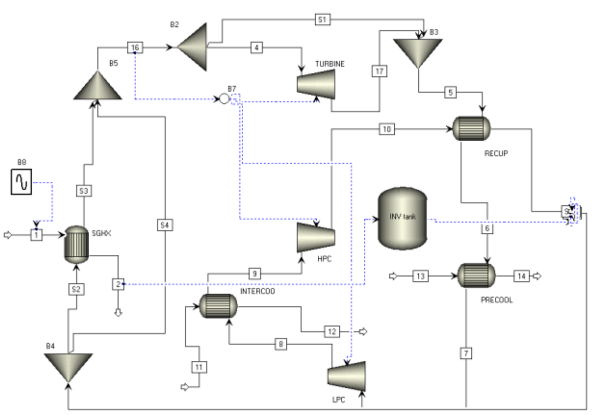

Fig. 2. Transient N_2-PCS layout in commercial system code.

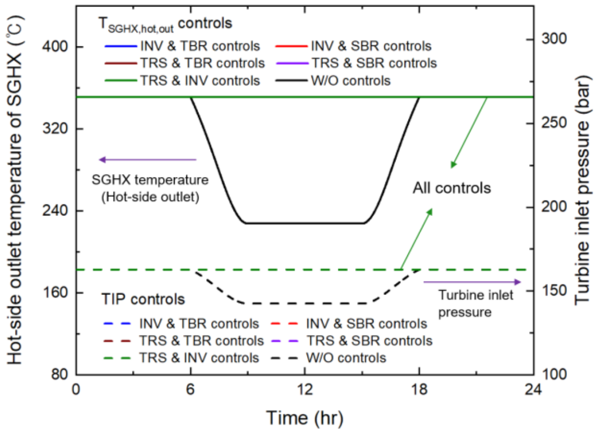

Fig. 3. Transient results with respect to control combinations.

4. Transient results with control evaluations

Based on the transient layout, the transient analyses were performed in terms of control combinations, as shown in Fig. 3. In the legend of Fig. 3, the first term represents the TIP control method, followed by the control method applied to maintain the SGHX thermal boundary condition. The results show that the integrated system can be unstable in the load-following condition of decoupling strategy without controls. This is because the thermal boundary condition and TIP can not be maintained in the transient condition. These results highlight the necessity of implementing control strategies to ensure overall system stability while sustaining the decoupling strategy.

As illustrated in Fig. 3, all considered control methods successfully satisfy the system requirements. Although all control combinations achieve system stability, the cycle thermal efficiencies vary significantly depending on the control strategies, as shown in Fig. 4. When TIP is regulated using INV control, system stability is maintained; however, the cycle efficiency is significantly reduced compared to the uncontrolled case.

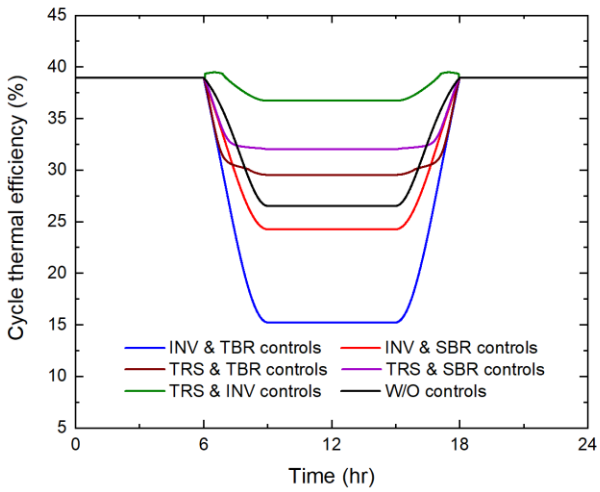

Fig. 4. Control combination evaluations of N_2-PCS.

In contrast, TIP regulation via TRS control improves cycle efficiency relative to the uncontrolled case, indicating that TRS control is a more effective approach for TIP management. While SBR control demonstrates better performance than TBR control in maintaining the thermal boundary condition, INV control exhibits the best performance for regulating the hot-side outlet temperature of the SGHX. For this reason, the combination of TRS and INV controls becomes the effective control method by considering both system stability and cycle thermal efficiency.

5. Conclusion

In this study, transient analyses were conducted for the decoupling strategy with a commercial system code, considering a 30% reduction in SGHX heat transfer duty. The results indicate that the system becomes unstable under load-following conditions without controls, emphasizing the necessity of active control strategies. Various control methods, including TBR, SBR, INV, and TRS, were applied to regulate TIP and thermal boundary conditions.

Among the evaluated methods, TRS control proved to be the most effective for maintaining TIP and improving cycle efficiency, while INV control performed best in stabilizing the hot-side outlet temperature of the SGHX. The combination of TRS and INV controls provided the best efficiency with the system stability.

This study confirms the feasibility of a decoupling strategy in nuclear systems with TES integration, providing insights into effective control strategies for flexible nuclear operation in future energy systems.

Acknowledgments

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