Control Logic Optimization of Hybrid Micro Modular Reactor Power Cycle

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1. Introduction

Hybrid Micro Modular Reactor (H-MMR) is a 24 MW_{th} solar-nuclear hybrid system with S-CO_2 reheat-recompression power cycle. Previously, the power cycle of H-MMR system was designed, and the steady-state input was prepared using GAMMA+ code [1]. Since the deviation between steady-state results and the design values are negligible, the full transient of the H-MMR system can be performed. During the transient analysis, the cycle operates at off-design condition, and different control logics, specifically turbine bypass control and inventory control, can be applied. In this paper, the control logic of H-MMR system is optimized during the part-load operation.

2. Methods and Results

2.1 Target Scenario Selection

To optimize the control logic for the H-MMR system, the operating range of the system has to be selected. The 2020 annual electricity demand at 5-minutes interval in South Korea was selected and scaled to the power of H-MMR system [2]. Figure 1 and 2 show the maximum and minimum electricity demand and maximum electricity demand ramp rate, respectively. Based on the given data, the electricity demand ranges from 100% to 44 % of the power with the maximum ramp rate of 8.207 $\left[\frac{\%\ Power}{min}\right]$. The target scenario for the H-MMR part-load operation was selected as reducing the power from 100% to 40 % with ramp rate of 10 $\left[\frac{\%\ Power}{min}\right]$, conservatively.

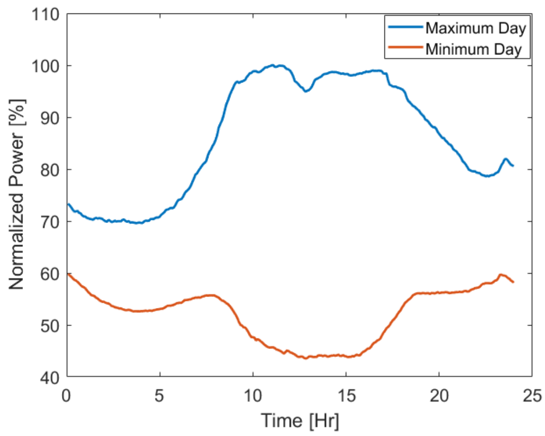

Figure 1. Maximum and minimum demand curve in 2020

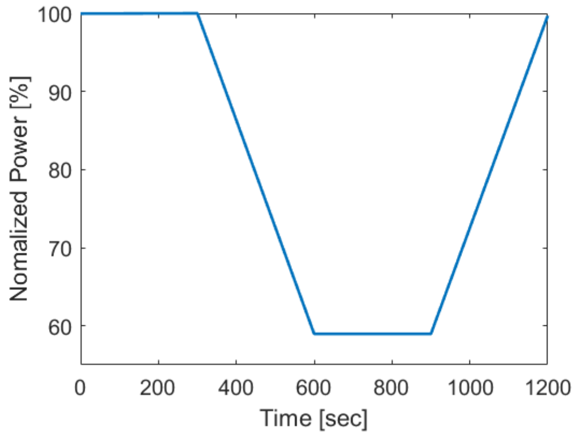

Figure 2. 2020 South Korea Electricity Demand maximum ramp rate

2.2 Turbine Bypass Control

During the part-load operation, the parameter to be maximized for the H-MMR system is the cycle thermal efficiency. Hence, the cycle thermal efficiency between turbine bypass control and inventory control were compared during the load reduction.

During the turbine bypass control, the S-CO_2 mass flow rate going to the turbine is bypassed to reduce the power and maintain the rotational speed of the turbomachineries. The flow bypass location is from the High Temperature Recuperator (HTR) cold side inlet to the hot side outlet, as shown in figure 3, because at that point, the temperature difference is minimum.

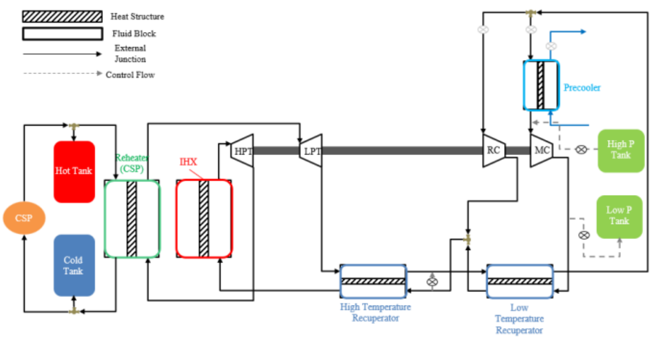

Figure 3. H-MMR system nodal with turbine bypass and inventory control

For each control logic, a control valve with PID controller is implemented. The valve opening area is calculated with the following equations:

$$f_{TBP} = K_P \left[E_{TBP} + \frac{1}{K_I} \int E_{TBP}(t)dt + K_D \frac{dE_{TBP}}{dt} \right]$$

$$E_{TBP} = \frac{\omega(t) - \omega_{design}}{\omega_{design}} \quad \omega = Rotational\ Speed$$

To tune the PID controller, Ziegler-Nichols tuning method was used [3]. The PID controller can be tuned by setting K_I, and K_D to zero and increase K_P from zero to critical gain, K_{Cr}, at which the output of the target system has stable and constant oscillation. Then, each coefficient can be calculated using Table 1. Figure 4 shows the Ziegler-Nichols PID tuning method for turbine bypass control valve, where the output of the function is the turbine rotational speed. At K_P = 100, the turbine rotational speed shows stable and constant oscillation. The PID coefficients were calculated based on Table 1 and part-load condition was simulated using turbine bypass control only.

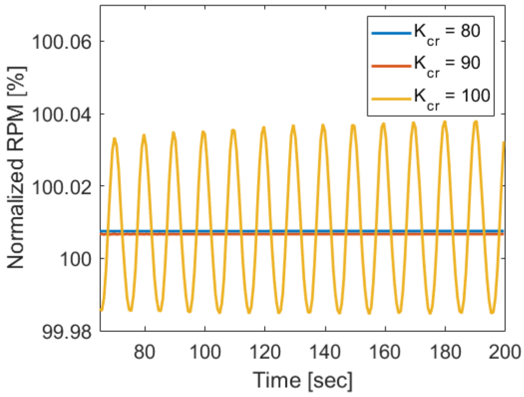

Figure 4. Ziegler-Nichols method for turbine bypass control valve

Table 1. Ziegler-Nichols PID tuning Method

	K_P	K_I	K_D
PID Controller	0.6 K_{Cr}	0.5 T_{Cr}	0.125 T_{Cr}

2.3 Inventory Control

For the inventory control, the generated power follows the grid demand by controlling total CO_2 inventory in the cycle. When the grid demand changes, CO_2 is charged or discharged from the cycle to the CO_2 tank as shown in Figure 3. The valves are located at the inlet and outlet of the main compressor, because the pressure of the S-CO_2 is the lowest and highest at those points.

Similar to the turbine bypass control, the discharging valve opening area is calculated with the following equations:

$$f_{discharge} = K_P \left[E_{INV} + \frac{1}{K_I} \int E_{INV}(t)\,dt + K_D \frac{dE_{INV}}{dt} \right]$$

$$f_{charge} = -f_{discharge}$$

$$E_{INV} = \frac{\omega(t) - \omega_{design}}{\omega_{design}}$$

As the grid demand increases, the turbomachinery rotational speed decreases, which allows the negative value for the discharging valve area. If the discharging valve area is less than zero, the charging valve is opened, allowing CO_2 to charge into the cycle. Figure 5 shows the Ziegler-Nichols PID tuning method for the inventory discharging valve. At K_P = 60, the turbine rotational speed shows stable and constant oscillation.

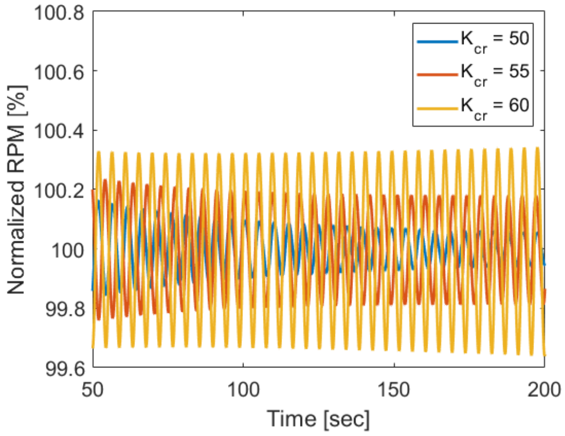

Figure 5. Ziegler-Nichols method for inventory control valve

2.4 Part-load Operation

With the tuned control valves, the inventory control and turbine bypass control during the part-load operation with ramp rate of 10 $\left[\frac{\%\ Power}{min}\right]$ were compared. According to Oh, the turbine bypass control has fast response time, but relatively low cycle thermal efficiency [4]. On the other hand, the inventory control has relatively high thermal efficiency, but slow response time.

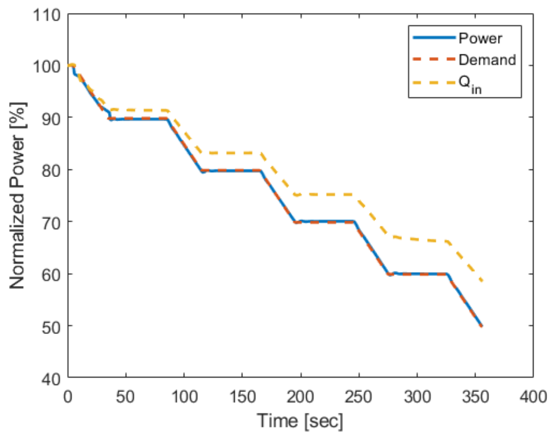

Figure 6. Normalized generated power and grid demand using inventory control

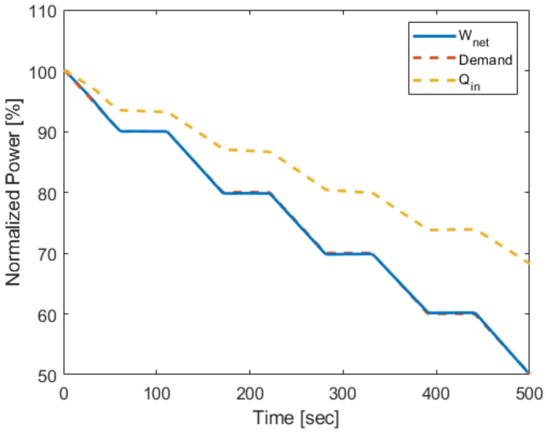

Figure 7. Normalized generated power and grid demand using turbine bypass control

Figure 6 and 7 shows the generated power and the grid demand for inventory control and turbine bypass control, respectively. Figure 8 shows the comparison of the cycle thermal efficiency using inventory and turbine bypass control. Based on the cycle thermal efficiency, the inventory control is preferred over the turbine bypass control, because the inventory control alone can satisfy the ramp rate of $10\left[\frac{\%Power}{min}\right]$ with higher efficiency. However, as shown in Figure 9, using the inventory control alone can cause the compressor surge, because too much of CO_2 is discharged from the system. Therefore, as the load demand decreases, the inventory control should be used primarily until the compressor surge margin reaches 10%. When the compressor surge margin is below 10%, discharging more CO_2 from the system could endanger the structural integrity of the system. Thus, the turbine bypass control should be used at such condition.

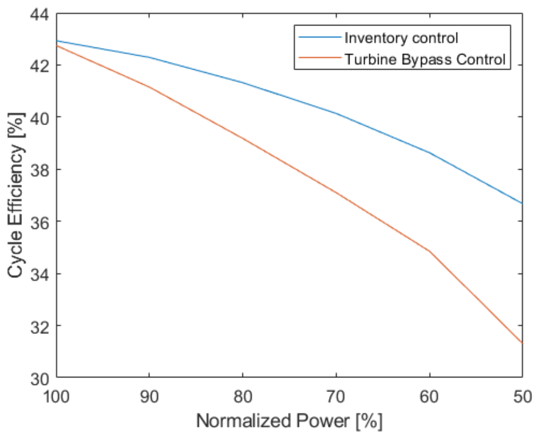

Figure 8. Cycle thermal efficiency comparison between inventory and turbine bypass control

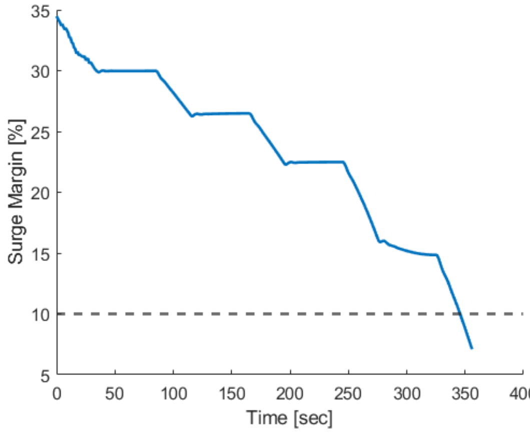

Figure 9. Recompressor surge margin during inventory control

3. Conclusions

For H-MMR system, two different control logics, inventory and turbine bypass control, were compared. Since the inventory control can satisfy the target ramp rate of $10\left[\frac{\%Power}{min}\right]$ with higher cycle efficiency than that of turbine bypass control, the inventory control should be preferred over the turbine bypass control. However, as the load demand decreases to the target demand, the compressor surge margin falls below 10% when only the inventory control is used. Thus, the inventory control is primarily used until the compressor surge margin drops to 10%. Then, as the surge margin is below 10%, the turbine bypass control should be used to secure the structural integrity of the system.

ACKOWLEDGEMENTS

This work was supported by the Korean government (MIST) [KAERI grant number 522310-22]

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