Development and Analysis of Control Systems for Thermal Energy Storage System

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1. Introduction

The Thermal Energy Storage (TES) System is one of the Energy Storage System (ESS) that can be used as a buffer in the power grid in response to the increasing intermittent and volatility of renewable energy. The TES systems are considered a promising alternative among ESSs due to their strength such as relatively few installation restrictions, eco-friendly, long-term energy storage, long life, and economical efficiency. In particular, the TES systems can be used not only as a power generation source, but also as a heat supply source for industry or heating, and when using heat directly, the roundtrip efficiency of the system becomes very high by lowering the energy conversion loss.

The TES systems are commonly classified as sensible heat storage, latent heat phase-change materials, and thermochemical storage. Among them, the two tank TES system using alkali metal as a storage material is considered an economical storage technology that can be commercialized. In particular, the sodium as a working fluid has a wide operating temperature range, so it is highly usable. The energy storage density can be increased using the large temperature difference between the hot tank and cold tank. Also, the thermal conductivity of sodium is very high, more than 100 times that of molten salt, so the size of the heat exchange devices can be minimized.

As a storage material of the TES system, sodium could operate at temperature above 600°C due to its high temperature stability and could expect high power generation efficiency when combined with a supercritical CO_2 power cycle. The supercritical CO_2 brayton cycle offers a more efficient, significantly simpler and more compact alternative to the superheated steam cycle [1]. In a previous study, we compared the heat balance and efficiency of the cascade cycle and the partial heating cycle to find the suitable sCO_2 brayton cycle for the large temperature difference between the hot and cold tank of the TES system. Finally, a partial heating cycle with higher efficiency than the cascade cycle was selected [2].

In this study, a control system for TES and power generation system as a buffer for intermittent and volatility of the power grid was developed and the control performance was analyzed.

2. Methods and Results

2.1 Plant Control Strategy

The flexibility characteristics in change rate of power sources are about 46%/min for pumping-up power generation, about 3%/min for combined cycle power plant, and about 1%/min for steam power cycle. In addition, according to the operating standards for power change rate of generators newly entering the electricity market under the Electricity Industry Act of the Ministry of Trade, Industry and Energy requires at least 3%/min for coal-fired power plant, 4.5%/min for heavy oil power plant, and 5%/min for gas turbine power plant [3]. The performance requirements for TES and power generation systems to respond to power demand fluctuations are as follows.

- The ramp load change within 30% - 100% range: 5%/min (settling time 60 s)
- The step load change when power grid fluctuates in the range of ±10%: 10%/10sec (settling time 20 s)

The purpose of the control system on the TES is to form a thermal equilibrium between the TES and the power generation system according to the change of power demand. In addition, while making the best use of the stored thermal energy in the high-temperature tank, the temperature of sodium flowing into the low-temperature tank should maintained at 200 degrees to prevent sodium from solidifying. This can be achieved with sodium flow control, so the control is relatively simple compared to the power generation system.

In the case of a power generation system to which the sCO_2 brayton cycle is applied, inventory control is known to have the highest efficiency [4]. However, the inventory control is limited in the range of power change by the maximum amount that can be stored and removed. Also, as the CO_2 inventory changes, it can cause pressure fluctuations inside the system, so it can be used only for very slow power transients. Therefore, it is common to use a combination of inventory control, turbine bypass, and turbine throttling to respond to power demands [5-7]. In this study, with reference to this, the control logic of the power generation system was established.

Fig. 1 and 2 show schematic diagrams of control systems for TES and power generation system in power operating mode. In the power operating mode, the control system is composed of a sodium pump controller, a sodium valve controller, a turbine bypass

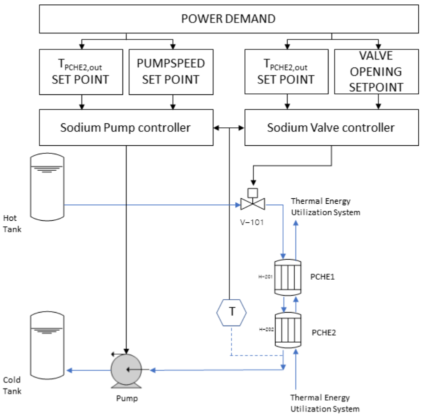

Fig. 1 Control system for TES system

controller, a turbine throttle valve controller, an inventory controller, and a cooling water flow controller. When the power demand is changed, each individual controller operates an actuator to control the controlled variables to the set value corresponding to the required load.

The sodium pump controller and sodium valve controller change the sodium flow rate on the TES in response to the heat transfer to the power generation system when the power demand changes, and form a thermal equilibrium between the TES and the power generation system. The sodium valve controller assists the sodium pump to control the flow rate when the control of the sodium pump alone is not possible in the low flow rate region. The inventory controller on the power generation system controls the pressure of the CO_2 storage tank to the set pressure programmed according to the power demand. When the pressure of the CO_2 storage tank is higher than the set pressure, the injection valve is opened to lower the pressure of the storage tank and at the same time inject CO_2 to the power generation system. In the opposite case, the discharge valve is opened. This increases the pressure in the storage tank and recovers CO_2 from the power generation system. Through the control of injecting or recovering the CO_2 inventory on the power generation system, the flow rate can be changed according to the power demand. In the turbine bypass controller, by controlling the turbine bypass flow at the front end of the turbine, the flow rate flowing into the turbine is controlled and the turbine work is formed by the load required for the power demand. When the turbine throttle valve controller is operated at the low power region, it assists the turbine bypass control to control the turbine and generator power. The turbine throttle valve controller receives the turbine power and controls the valve opening to control it to a set value. The cooler flow controller controls the flow rate of coolant flowing into the cooler to maintain the outlet temperature of the high-temperature side CO_2 flowing into the compressor at a constant temperature of 32°C above the critical point to maintain high compressor efficiency and prevent damage to the compressor.

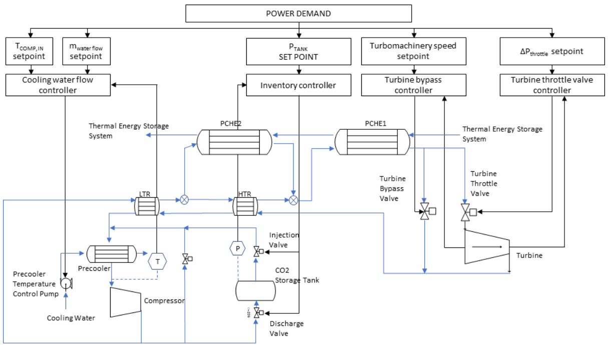

Fig. 2 Control system for power generation system

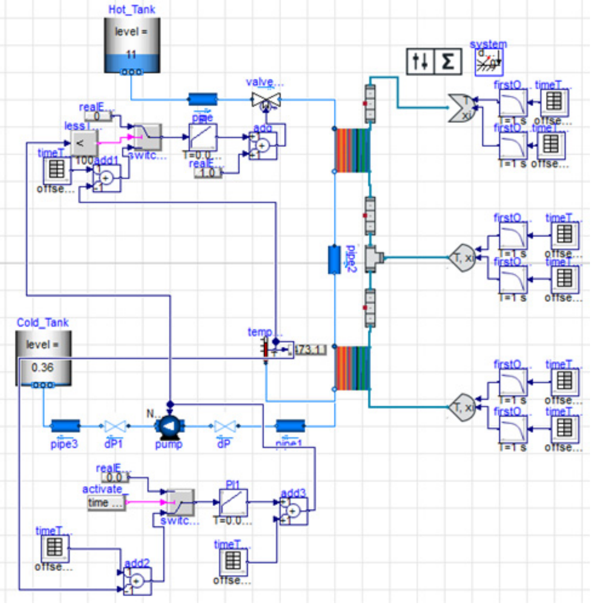

Fig. 3 Controller modeling using Modelica for TES

2.2 TES flow control performance evaluation

Fig. 3 shows the sodium pump controller and sodium valve controller models using Modelica for evaluating the control performance of the flow controller in the TES. The control performance of the sodium pump controller and the sodium valve controller of the TES was evaluated with respect to the power change rate of 5%/min within the range from 100% to 30% suggested as a performance requirement.

Fig. 4 - 7 show the CO_2 side boundary conditions of PCHE1 and PCHE2 when the power demand changes from 100% to 30%. By changing these boundary conditions, the ramp load change was simulated from 100% to 30%. It can be seen that the CO_2 flow rate of PCHE1 and 2 decreases for 840 seconds from 600 seconds to 1440 seconds. The CO_2 side inlet temperature of each heat exchanger was operated under the boundary condition corresponding to 100% power,

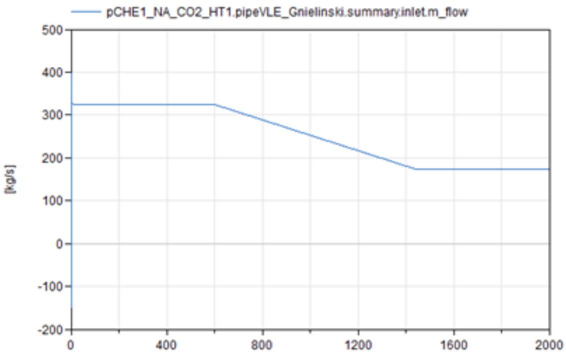

Fig. 4 Boundary condition of PCHE1 CO_2 flowrate

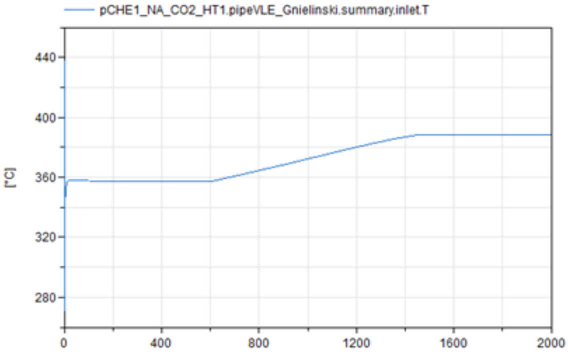

Fig. 5 Boundary condition of PCHE1 inlet CO_2 temperature

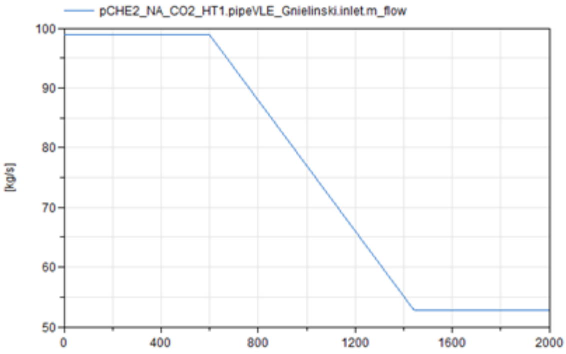

Fig. 6 Boundary condition of PCHE2 CO_2 flowrate

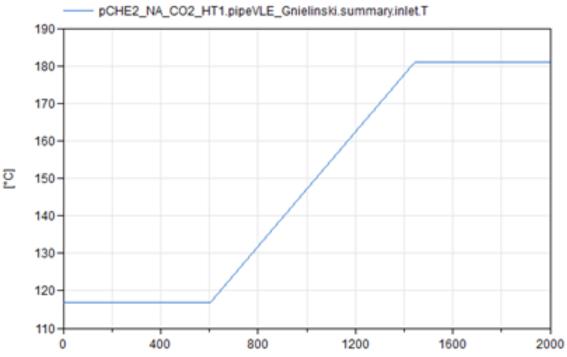

Fig. 7 Boundary condition of PCHE2 CO_2 inlet temperature

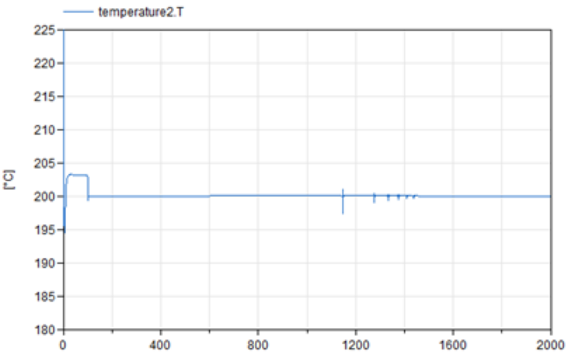

Fig. 8 PCHE2 sodium side outlet temperature

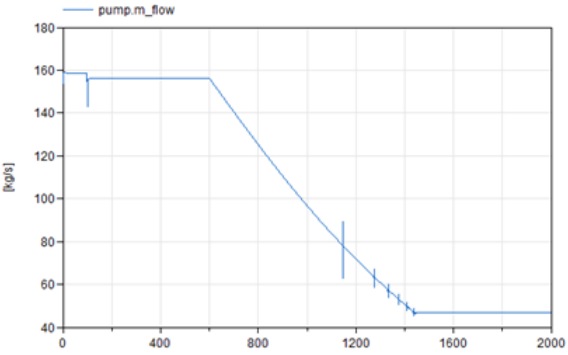

Fig. 9 Sodium pump flow rate

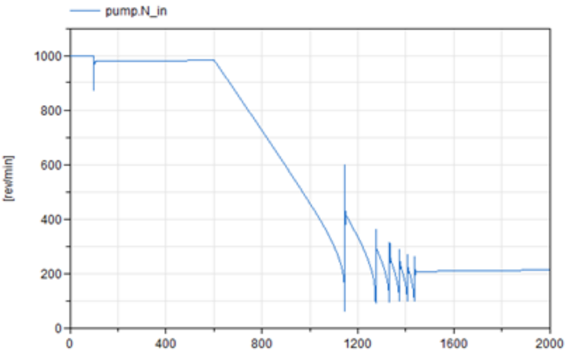

Fig. 10 Sodium pump rotating speed

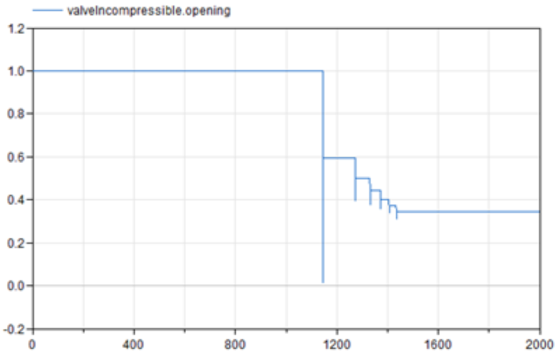

Fig. 11 Sodium valve opening

and then linearly increased to the boundary condition corresponding to 30%.

Fig. 8 - 11 show the process variable changes at each position of PCHE2, pump, and valve when the ramp load changes from 100% to 30%. It can be seen that although the heat transfer rate of PCHE1 and 2 is decreased due to the boundary conditions changed, the sodium outlet temperature of PCHE2 is well controlled at 200°C. The sodium pump flow rate is reduced in response to the reduced heat transfer rate. The rotation speed of the sodium pump also decreases in response to the reduced heat transfer rate. In the case of the sodium pump, it can be confirmed that it is controlled without going down below 100 RPM, which is the minimum pump speed, according to the previously set control logic. In the case of the sodium valve controller, it can be confirmed that the sodium valve is operated only when the rotation speed of the sodium pump is 100 RPM or less. Overall, all process variables are stabilized without fluctuation, and it can be confirmed that the control performance is satisfied by satisfying the control target, PCHE2 sodium outlet temperature of 200℃. The settling time for convergence to within 0.01°C of the set value was 2.4 seconds, showing quick response.

3. Conclusions

In this study, a control system for TES as a buffer for intermittent and volatility of the power grid was developed and performance analysis was performed. To evaluate the performance of the TES control system, a Modelica-based control system evaluation model was developed. The control performance evaluation was performed for the ramp load change, and it was confirmed that the change in the process variable satisfies all the control performance requirements.

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