Comparative Analysis of Price-based Control Strategies for a High Temperature Thermal Energy Storage System

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The increasing penetration of renewable energy production necessitates the use of thermal energy storage systems (TES) to balance fluctuating renewable energy production with fluctuating energy demand. Implementation of advanced control strategies such as model predictive control (MPC) for TES has been widely investigated to facilitate energy-efficient/cost-effective operations (Tarragona et al. 2021). However, most of the studies focus on water-based TES and MPCs for high temperature thermal energy storage systems (HTTES) are still limited. This work contributes to bridging this research gap in the literature via implementing an MPC for HTTES and evaluating its control performance.

To that end, an emulator for a high temperature thermal storage system was first developed and verified. Figure 1 illustrates the system layout consisting of charging, discharging, and a Rankine cycle process. In the charging loop, the air is heated with electricity from the grid and blown into the energy storage consisting of a rock bed as the storage medium. When discharging, the air is extracted to heat the working fluid in the organic Rankine cycle. The produced electricity will be entirely sold to the grid. The Rankine cycle loop is connected to a district heating network supplying additional heat.

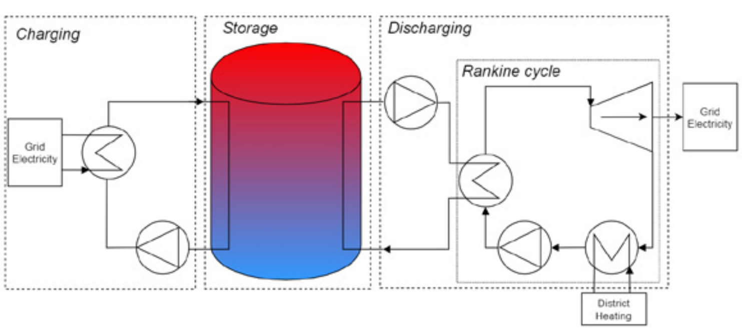

Figure 1. Schematic diagram of the HTTES

Next, a nonlinear MPC for the HTTES was formulated and implemented in Matlab MPC block and Simulink, allowing co-simulation using functional mock-up units (FMU). The objective of the MPC is to maximize the cumulated net revenue of the ssystem, which is calculated as the profits of selling electricity subtracted by the energy cost of electricity consumption in the charging process and the district heating consumption. The manipulated variable of the MPC is the air mass flow rate of the charging/discharging process. It is assumed that simultaneous charging and discharging cannot take place. The storage temperature has to satisfy the constraints of the lower and upper limits (100°C and 600°C). A parameter tuning procedure concerning sampling time, prediction horizon, and control horizon for the MPC was conducted to find the optimal setup.

In order to benchmark MPC control performance, a rule-based control (RBC) strategy was developed in Modelica and compared with MPC. Modelica has previously demonstrated good ability in implementing controls for thermal storage systems enabling dynamic simulation in many studies, which can be exemplified in (Rohde et al. 2021). The control logic of RBC is shown in Figure 2a, where Pricemin and Pricemax are the lower and upper thresholds for electricity price. They are chosen as 258 DKK and 358 DKK, respectively. Likewise, Tmin (100°C) and Tmax (600°C) are the lower and upper limits of the storage temperature (Ts). Based on the electricity price, storage temperature, and charging/discharging process of the previous time step, the RBC divides the system into five operation modes. The MPC and RBC were simulated for 7 days and the comparison of simulation results is shown in Figure 2b. From the top to bottom, the subplots are storage temperature, air mass flow rate, and electricity price respectively. The negative value of air mass flow rate represents discharging process while positive values mean the charging process. As shown in the figure, RBC only supplies maximum air mass flow rate when charging/discharging. However, the nonlinear MPC allows supplying varying air mass flow rates. Besides, a more frequent running of the charging/discharging process is observed in MPC than that in RBC due to MPC being capable of predicting electricity price and system dynamics and optimally choosing operation mode through optimization. The net cumulated revenue was calculated to quantitively evaluate the economic benefits of the two control strategies, resulting in 469.7 DKK for MPC and 170.7 DKK for RBC.

The preliminary results show that MPC outperforms RBC. However, the current RBC performance highly relies on the choice of electricity price threshold. The continuation of the work involves tuning the Modelica-based RBC settings based on price margin including customizing different RBCs under different price scenarios.