Control Strategy of a Laboratory-Scale Carnot Battery Experimental Rig

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***Abstract*—Carnot Batteries are promising short- mid-duration energy storage systems that convert electrical energy into thermal energy during charging and recover it through a power cycle during discharging. This paper presents the control architecture implemented in a laboratory-scale Carnot Battery test bench. The proposed control strategy aims to ensure stable operation, maintain desired thermal conditions, and maximize energy recovery during discharge. Different control loops are employed for temperature regulation, mass flow rate control, and power optimization throughout the charging and discharging processes.**

Keywords—Carnot Battery, Pumped Thermal Energy Storage, Process Control, Supervisory Control, Experimental Test Bench.

I. INTRODUCTION

The increasing penetration of variable renewable energy sources in power systems calls for robust, flexible, and cost-effective energy storage solutions [1]. Among the emerging technologies, Carnot Batteries (CBs), also known as Pumped Thermal Energy Storage systems, are gaining attention for their ability to store electricity in thermal energy and reconvert it when needed using thermodynamic cycles [2]. By leveraging well-established components such as heat pumps and Organic Rankine Cycles (ORC), Carnot Batteries offer the potential for large-scale deployment with geographical flexibility and long storage durations [3].The core concept of a Carnot Battery is based on the reversible conversion of electrical energy into heat during the charging phase (via a heat pump), followed by the conversion of stored heat back into electricity during the discharging phase (via a heat engine, typically an ORC) [4]. This approach provides a pathway to decarbonize energy storage, especially when integrated with low-grade or waste heat sources such as industrial residual heat, solar thermal energy, or geothermal reservoirs [5].

II. METHODOLOFY

A. *Carnot Battery system*

The experimental facility under development reproduces the operating principles of a Carnot Battery by combining a heat pump system, thermal energy storage, and an Organic Rankine Cycle (ORC). During the charging phase, thermal energy from a simulated waste heat source is upgraded by the heat pump and stored in the thermal storage system. During discharge, the stored thermal energy is supplied to the ORC for electricity generation. Figure 1 illustrates the overall configuration of the test bench and the interactions between the different subsystems. A dedicated control strategy is required to coordinate the operation of all subsystemsand guarantee safe and efficient operation, shown in Figure 2.

B. *Charging Mode Control Strategy*

The Heat Source Cycle emulates an industrial waste heat source using a 300 L water tank equipped with three electrical resistances. The control objective is to maintain a constant source temperature, typically around 70 °C. A simple on-off temperature control is implemented where the tank temperature is continuously monitored, the electrical resistances are switched on when the temperature falls below the setpoint and switched off when the temperature exceeds

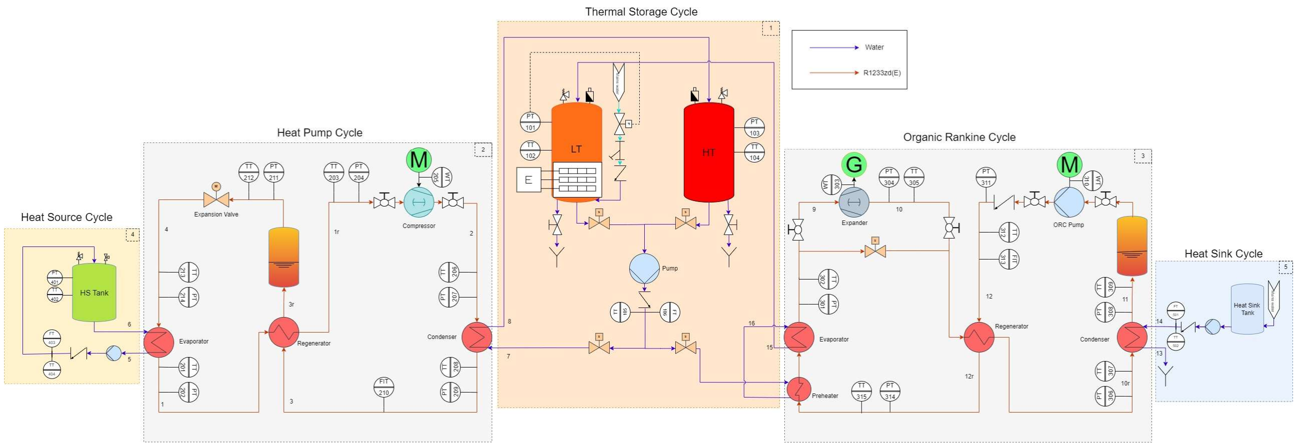

Fig. 1. Carnot Battery experimental test-bench – system architecture and instrumentation

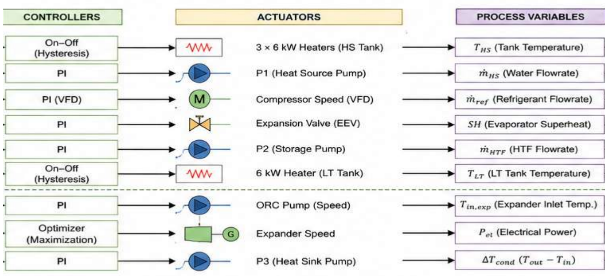

Fig. 2. Control strategy scheme

the upper hysteresis limit. The circulating pump P1 is controlled through a PID controller to maintain a constant water mass flow rate through the heat pump evaporator.

Two main control loops are implemented in the Heat Pump Cycle: (1) Compressor Speed Control adjusted through a variable-frequency drive to regulate the refrigerant mass flow rate and consequently the heating capacity delivered to the thermal storage; (2) Expansion Valve Control continuously adjusted to maintain an adequate evaporator superheat which guarantees stable operation while preventing liquid refrigerant from reaching the compressor suction line.

In the Thermal Storage Cycle, during charging, heat is transferred from the heat pump condenser to the thermal storage system. The circulating pump P2 is controlled through a PID controller to maintain a constant circulation rate through the storage loop. The auxiliary electrical heater is controlled in on-off mode to maintain the LT tank temperature at a predefined setpoint, typically around 80 °C. The charging process continues until the HT tank reaches its maximum admissible level and the system enters standby mode awaiting the discharge phase.

C. Discharging Mode Control Strategy

The thermal storage hydraulic circuit is reconfigured through four switching valves. During the transition, two valves are opened and two valves are closed. This configuration reverses the thermal storage flow path, allowing the heat transfer fluid to circulate from the HT tank towards the LT tank. Pump P2 is restarted and controlled to maintain a constant flow rate through the thermal storage loop.

Fig. 3. Control logic of the CB showing the operating mode selection

The Organic Rankine Cycle converts the stored thermal energy into electricity, and two main control loops are implemented: (1) ORC Pump Control - adjusted to desired temperature at the expander inlet, avoiding excessive superheating; (2) Expander Speed Control - actively controlled to maximize the electrical power output.

The Heat Sink Cycle removes the residual heat rejected by the ORC condenser. A circulating pump P3 regulates the cooling water flow rate. The control objective is to maintain a predefined temperature difference across the condenser

III. Supervisory Control Logic

The supervisory control layer is responsible for determining the operating mode of the Carnot Battery and coordinating the different subsystems according to the energy management objectives and storage conditions. As shown in Fig. 3, the system continuously monitors electricity market conditions, energy production and consumption levels, and the state of charge of the thermal storage system. Charging mode is enabled when surplus electricity is available or when the electricity price falls below a predefined threshold, provided that the LT tank is not empty. Discharging mode is activated when electricity demand exists or when the electricity price exceeds a predefined threshold, provided that sufficient thermal energy remains stored in the HT tank. During this mode, the thermal storage circuit is reconfigured by switching the directional valves. The HT and LT tank levels are continuously evaluated and automatically terminates the active operating mode when the corresponding storage limit is reached, returning the system to an idle state until new charging or discharging conditions are satisfied.

IV. Conclusions

This work presents the preliminary control architecture of a laboratory-scale Carnot Battery experimental facility. The proposed strategy combines temperature regulation, flow-rate control, refrigeration cycle control, and ORC power optimization. The implementation provides a flexible platform for future investigations into dynamic operation, energy management strategies, and advanced control techniques such as model predictive control and efficiency optimization.

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