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Special Focus on Optimization for Cyber-Physical Energy Systems

# Synergistic optimal operation for a combined cooling, heating and power system with hybrid energy storage

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Dear editor,
Improved penetration of renewable energy sources (RES) and strong coupling of multi-energy flows are crucial factors hindering the efficient utilization of energy in combined cooling, heating, and power (CCHP) systems [1]. To tackle this problem, energy storage, especially the adiabatic compressed air energy storage (A-CAES)-based hybrid energy storage system (HESS) [2, 3], is considered an important solution [4, 5]. This system combines multi-interface cooling, heating, and power, and offers unique advantages of peak shaving, fluctuation smoothing, and multi-time scale dispatching [6]. Given these advantages, it is essential to plan an operation strategy that can coordinate multi-energy flows.

Most current studies have designed power generation units (PGUs) as controlled plants in the CCHP system, with energy storage passively following the difference power between generators and loads [7]. The multi-energy interface of the A-CAES enriches the controllable variables, and the passive energy storage operation strategy may hinder its function. Hence, Yan et al. [8] proposed an active energy storage operation strategy, which optimized the dispatch of the A-CAES while the dispatch of the PGU ensured that operations continue as per the designed conditions. Although this operation strategy improved the PGU efficiency, it crippled its multi-condition operation ability. Thus, in such cases, the economy and efficiency might decrease. To coordinate the power allocation between energy storage in the HESS, spectrum analysis and a band-pass filter were adopted in most recent studies [3]. However, these methods mainly focused on traditional microgrids and give scant consideration to the interaction of multi-energy flows as well as the state of energy (SOE) of the energy storage.

Based on the above analysis, an HESS consisting of the A-CAES and Li-ion battery is adopted to solve the intermittence and fluctuation of the RES as well as the coupling problem of multi-energy flows in a CCHP system. Thus, a synergistic operation strategy is proposed by considering the active dispatching ability of the A-CAES to improve energy saving, economy, and environmental effects. Moreover, a coordinated control strategy for the HESS is proposed under the hierarchical control framework, which considers the time-scale discrepancy among multi-energy flows and the SOE balance of the energy storage. This strategy can solve the problem associated with the time-scale discrepancy among various energy flows as well as the large time scale range of RES. Thus, this study proposes a novel synergistic operation strategy to fundamentally improve energy utilization and simultaneously accommodate RES.

*Structure and energy flow analysis.* The HESS-based CCHP system structure is similar to that in [8], with one exception. The solar collector is included to enrich the heat source, and the Li-ion

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battery is added to coordinate with the A-CAES to form the HESS, which smoothes the fluctuation and enriches both cooling and heating modes. The internal combustion engine (ICE) is selected as the core generating unit, and a wind turbine (WT) and photovoltaic (PV) units are integrated. The waste heat recovered from the ICE and produced by the compression process of the A-CAES are the main heating sources, which are supplemented by a gas boiler. The cooling load is supplemented by the absorption chiller, electric chiller, and expansion process of the A-CAES.

*Synergistic optimization operation strategy.* A two-level synergistic operation strategy for the CCHP is proposed under the hierarchical control framework. The dispatching level determines the hourly power schedules of each component based on the forecasting data of the RES and demands of the next day. To smooth the fluctuations of the RES, the HESS coordinate control level creates a minute time scale control strategy for each energy storage unit, which are fed back to the dispatching level to adjust the hourly schedules of the thermal storage (TS) and power grid (PG). Thus, a rolling optimization is achieved.

• Dispatching level. A two-layer iterative method is adopted for this level to achieve synergistic optimal operation. The WT and PV function on the maximum power point tracking (MPPT) control strategy. The objectives as well as constraints are the same in both layers with one difference; the optimization variables are the hourly schedules of the A-CAES and PGU. Moreover, the results of each layer, which are considered as constraints, are transferred to the other to achieve iterative optimization. For the dispatching level, the primary energy saving ratio (PESR) and emission reduction ratio (ERR) for a separate production (SP) system, and operation cost are assumed to be the optimization objectives. In the SP system, electricity demand is supplied by the PG, the gas boiler meets the heating demand, and the cooling demand is met by the electric chiller. The objectives can be represented as

$$\begin{cases} \max \mathrm{PESR} \\ = 1 - \dfrac{\sum_{t=1}^{T} G_{\mathrm{CCHP}}(t)}{\sum_{t=1}^{T}\left(\frac{L_{\mathrm{ec}}(t)-P_{\mathrm{CAES}}(t)}{\eta_e^{\mathrm{sp}}\eta_{\mathrm{grid}}} + \frac{Q_l(t)-Q_s(t)}{\eta_b^{\mathrm{sp}}\eta_h}\right)}, \\ \max \mathrm{ERR} = \dfrac{\sum_{t=1}^{T} e_{\mathrm{sp}}(t) - \sum_{t=1}^{T} e_{\mathrm{CCHP}}(t)}{\sum_{t=1}^{T} e_{\mathrm{sp}}(t)}, \\ \min C_{\mathrm{op}} \\ = \displaystyle\sum_{t=1}^{T}\left(\begin{array}{c} E_{\mathrm{grid}}(t)\mathrm{Ep}_{\mathrm{grid}}(t)+G_{\mathrm{gas}}(t)\mathrm{Ep}_{\mathrm{gas}}(t) \\ -E_{\mathrm{ex}}(t)\mathrm{Ep}_{\mathrm{ex}}(t)\end{array}\right), \end{cases} \quad (1)$$

where $\eta_e^{\mathrm{sp}}$, $\eta_{\mathrm{grid}}$, $\eta_b^{\mathrm{sp}}$, and $\eta_h$ denote the generating and transport efficiencies of the PG, and the heat-generating and transfer efficiencies of the gas boiler, respectively. $\mathrm{Ep}_{\mathrm{grid}}(t)$, $\mathrm{Ep}_{\mathrm{gas}}(t)$, and $\mathrm{Ep}_{\mathrm{ex}}(t)$ denote the electricity price, gas price, and subsidized price of the redundant electricity sold back to the PG ($/kWh), respectively. $G_{\mathrm{gas}}(t)$ represents the gas consumption of the ICE and gas boiler. $E_{\mathrm{grid}}(t)$ and $E_{\mathrm{ex}}(t)$ denote the electricity purchased and sold back to the grid, respectively. $e_{\mathrm{sp}}(t)$ and $e_{\mathrm{CCHP}}(t)$ denote the carbon dioxide ($CO_2$) emission of the separation production system and the CCHP system, respectively.

Moreover, the optimization model includes constraints such as the offset of the SOE and power balance. A hybrid algorithm of the non-dominated sorting genetic algorithm-II and multi-objective particle swarm optimization (C-NSGA-II) is employed to solve the multi-objective optimization model [8]. Then, the Pareto optimal solutions are obtained, and this is followed by conducting the decision-making process to select the best desired solution. The proposed model is a typical multi-optimal model, and the weights of the three objectives are equal according to [9].

• HESS coordinate control level. At this level, the minute time scale power schedules of the A-CAES and battery during the next hour are optimized based on the short-term forecast RES data. Firstly, the hourly schedules of the A-CAES are superimposed by the minute time scale forecasting power of the WT and PV. The superimposed signal is decomposed into several intrinsic mode functions (IMFs) with the empirical mode decomposition (EMD) method. Then, the instantaneous frequency (IF) of each IMF is analyzed using the Hilbert–Huang transform (HHT). By designing the schedules of the A-CAES and its SOE as benchmarks, the optimization model is established with the objective of minimum offset from the benchmarks, to achieve the optimized dividing frequency $f_{\mathrm{HESS}}$. Thus, the sum of the IMFs at time $t$, whose IFs are higher than $f_{\mathrm{HESS}}$, is the dispatch of the battery at this minute. The sum of the remaining IMFs is the dispatch of the A-CAES. Furthermore, the SOE values of the A-CAES are considered because the SOE offset is used as a constraint for the dispatching level. During the optimization process, system stability, RES accommodation rate, and the SOE offset of the battery are added to the constraints.

*Case study.* A case study was conducted using typical data of a CCHP system. Figure 1 shows the comparison of optimization results (Pareto front) of the dispatching level for different operation strategies, namely, passive energy storage [7],

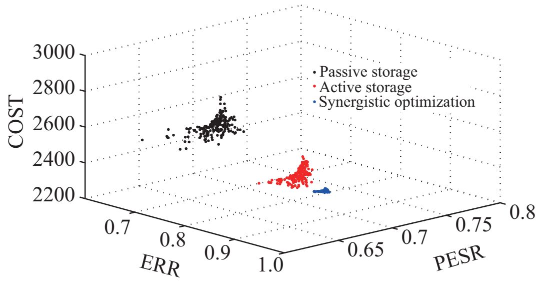


**Figure 1** (Color online) Optimization results of different operation strategy.

active energy storage [8], and synergistic optimization. It is obvious that the PESR and ERR are higher and the operation cost is lower when using the synergistic optimization strategy, which confirms the advantage of the proposed dispatch strategy in improving system performance and economy. Then, the best compromise schedules are extracted. By setting the hourly schedules of the A-CAES and its SOE as the benchmarks for the HESS coordinate control level, minute time scale schedules of the A-CAES and battery can be achieved for the next hour. These schedules are transferred to the dispatching level to adjust the TS and PG power schedules.

As the energy balance constraints are added to the optimization process at each level, the intermittence and fluctuation of the RES are smoothed, thus confirming the effectiveness of the operation strategy in accommodating RES and meeting load demand. The ERR, PESR, and operation cost are 82.89%, 72.46%, and $2159, respectively for the rolling optimization operation.

The contrastive control strategy, which is based on the low-pass filter and aims to track the hourly A-CAES schedules, shows similar results: 82.82%, 72.40%, and $2193, respectively. Compared with the EMD-based decomposition and reconstruction strategy, the contrastive strategy cannot constrain the SOE of both devices, which leads to an obvious deviation from the initial value. The deviation of the battery is 77.09%, while that under the EMD strategy is 5.28%.

*Conclusion.* Based on the hierarchical control framework and rolling optimization, this study proposes a novel synergistic optimization operation strategy for the HESS-based CCHP system. With this strategy, the multi-interface advantage of the A-CAES can be brought into full play to strengthen the association between various energy flows and the connection between different time scales. By stabilizing the fluctuation and intermittence of the RES, the new operation strategy solves the problem of the time-scale discrepancy among various energy flows and the large time scale range of the RES in a CCHP system.

An hourly synergistic optimal dispatch strategy is proposed, which combines the advantages of PGU optimization and active storage operation. The case study shows that, compared with current operation strategies, the synergistic optimal dispatch strategy substantially improves the environmental effects, economy, and energy saving.

An EMD-based decomposition-reconstruction strategy is proposed to coordinate the power of energy storage for the minute time scale. The strategy improves system performance by considering the SOE offset of energy storage as well as accommodating the RES.

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