SCIENCE CHINA
Information Sciences

• LETTER •

December 2018, Vol. 61 129207:1–129207:3
https://doi.org/10.1007/s11432-018-9632-x

Operation optimization for integrated energy system with energy storage

Fan LI, Bo SUN & Chenghui ZHANG*

School of Control Science and Engineering, Shandong University, Jinan 250061*, China*

Received 4 June 2018/Revised 19 August 2018/Accepted 19 October 2018/Published online 22 November 2018

Citation Li F, Sun B, Zhang C H. Operation optimization for integrated energy system with energy storage. Sci China Inf Sci, 2018, 61(12): 129207, https://doi.org/10.1007/s11432-018-9632-x

Dear editor,

The integrated energy system has attracted widespread attention owning to its high energy efficiency, low emission, and reliability [1]. It is a typical cyber-physical integrated energy system (CPIES) that combines information and energy technologies, in which the cyber information platform collects information from the energy plant and controls most of the energy devices [2]. Many optimized operation strategies have been presented for the information platform to guarantee that the energy plant works stably and efficiently. Generally, the operational optimization of energy systems needs to solve a combinatorial optimization problem. Several methods have been employed to calculate the optimal set-point of each energy device, including the genetic algorithm (GA), particle swarm optimization (PSO), non-linear programming (NLP), and mixed-integer non-linear programming (MINLP). However, the integrated energy system usually uses an energy storage unit to address fluctuations in load demands [3]. For this complex energy system, the above methods need to transform the optimization of the dynamic storage process into a high-dimensional non-linear optimization problem. However, it is hard to solve this optimization problem with multiple constraints. Some studies combined fixation strategies with optimization methods to achieve a satisfying solution [4–6]. Deng et al. [4] developed a fixation storage strategy that stores thermal energy at night and supplies energy in the daytime, and employed MINLP to determine the optimal set-points of other devices. Bao et al. [5] defined that the energy storage unit continuously runs at valley time and presented an improved PSO method that can be used to correct the particle's position to satisfy the non-linear constraints. Zheng et al. [6] determined the set-points of the storage unit and generator by calculating the shortest distance between the load points and the output curves of the energy equipment. Nevertheless, these methods cannot guarantee that the obtained operational strategy is optimal for an integrated energy system with energy storage.

In this study, a hybrid method based on dynamic programming (DP) and GA is proposed in order to find the optimal operational strategy for an integrated energy system. Compared with the existing methods, the proposed method does not require the conversion of the optimization of the energy storage to a high-dimensional static optimization problem. Instead, it uses DP as the main optimization framework to calculate the optimal energy storage state for the entire optimization period. The GA is then embedded into the DP to optimize the corresponding set-points of the device in each energy storage state for every period. DP can be used to find the global optimal solution to the energy storage problem. The determination of optimal device set-points is guaranteed by the GA because there are only one or two optimiza-

* Corresponding author (email: zchui@sdu.edu.cn)

tion variables in every period [7]. Therefore, the proposed method can be used to obtain the optimal operational strategy for the integrated energy system with energy storage so that its overall performance can be improved. Some numerical simulations were conducted to verify the validity of the proposed method.

Optimization model and methodology. The integrated energy system is evaluated based on its performance with regard to the energy, economy, and environment. In order to quantify these performance aspects on the same scale without considering the details of the system structure, the primary energy saving ratio (PESR), cost saving ratio (CSR), and carbon emission reduction ratio (CERR) of the integrated system to a typical separation production (SP) system [8] are chosen as optimization objects as follows:

$$\max \text{PESR} = \frac{\sum_{t=1}^{24} F_{\text{sp}}(t) - \sum_{t=1}^{24} F(t)}{\sum_{t=1}^{24} F_{\text{sp}}(t)}, \quad (1)$$

$$\max \text{CSR} = \frac{\sum_{t=1}^{24} C_{\text{sp}}(t) - \sum_{t=1}^{24} C(t)}{\sum_{t=1}^{24} C_{\text{sp}}(t)}, \quad (2)$$

$$\max \text{CERR} = \frac{\sum_{t=1}^{24} \text{CE}_{\text{sp}}(t) - \sum_{t=1}^{24} \text{CE}(t)}{\sum_{t=1}^{24} \text{CE}_{\text{sp}}(t)}, \quad (3)$$

where $F_{\text{sp}}(\text{t})$, $C_{\text{sp}}(\text{t})$, and $\text{CE}_{\text{sp}}(\text{t})$ are the total energy consumption, operation cost, and carbon emission of the SP system in period t, respectively, and they can be obtained using the formulas in [8]; $F(t)$, $C(t)$, and $\text{CE}(t)$ represent the total energy consumption, operation cost, and carbon emission of the integrated energy system in period t, respectively. A comprehensive optimization objective can be defined as

$$\max \text{obj} = \alpha_1 \cdot \text{PESR} + \alpha_2 \cdot \text{CSR} + \alpha_3 \cdot \text{CEER}, \quad (4)$$

where α_1, α_2, and α_3 represent the weightings of the energy, economic, and environmental objectives, respectively. In addition, the integrated energy system can meet the diversified energy demands of the load, and hence the operational optimization should meet the following constraints of the energy balances:

$$E_{\text{pgu}}(t) + E_{\text{grid}}(t) - E_{\text{hp}}(t) = E_{\text{load}}(t), \quad (5)$$

in cooling mode:

$$Q_{\text{hp}}(t) + Q_{\text{ab}}(t) + Q_{\text{s}}(t) = Q_{\text{load,c}}(t), \quad (6)$$

in heating mode:

$$Q_{\text{hr}}(t) + Q_{\text{b}}(t) + Q_{\text{s}}(t) = Q_{\text{load,h}}(t), \quad (7)$$

where $E_{\text{pgu}}(t)$, $E_{\text{grid}}(t)$, $E_{\text{hp}}(t)$, and $E_{\text{load}}(t)$ represent the electricity generated by the power generator unit (PGU), electricity purchased from the power grid, electricity consumed by the heat pump (HP), and electricity load of buildings in period t, respectively; $Q_{\text{hp}}(t)$, $Q_{\text{ab}}(t)$, and $Q_{\text{load,c}}(t)$ are the cooling supplied by the HP, cooling supplied by the absorption chiller, and cooling load of the buildings in period t, respectively; $Q_{\text{hr}}(t)$, $Q_{\text{b}}(t)$, and $Q_{\text{load,h}}(t)$ represent the heat recovered from the PGU, heat produced by the gas boiler, and heat load of the buildings in period t, respectively; $Q_{\text{s}}(t)$ is the input or output of the storage unit in period t. The state of the energy storage unit also needs to meet the following dynamic constraints:

$$S(t) = S(t-1) \cdot \eta_{\text{s}} + Q_{\text{s}}(t), \quad (8)$$

where $S(t)$ represents the energy storage state in period t and η_{s} is the energy storage efficiency. In addition, the optimization model should include some inequality constraints that are related to the internal devices in the energy system.

Operational optimization is a hybrid problem with multiple constraints, which includes a dynamic optimization of the energy storage unit and set-point optimization of the energy devices. In this study, a hybrid optimization method based on DP and GA is presented to determine the global optimal operation strategy for integrated energy systems with energy storage. The details of the optimization are presented in Algorithm 1. The main framework is the DP algorithm, which contains three nested loops. In the inner loop, the GA is employed to optimize the set-point of each device from any $S(t-1)$ to $S(t)$ in sequence. Because there are generally only one or two optimization variables in the GA optimization procedure, the optimal solution is easy to obtain. In the middle loop, for any $S(t)$ from 0 to the rated storage state $S_{\max}$, the optimization object and corresponding $u^*(t)$ are calculated and recorded in sequence. In the outer loop, the optimization object and corresponding $u^*(t)$ for all the energy storage state are calculated and recorded from 1 to T. Finally, the maximum $J(T)$ and corresponding $u^*(t)$ and $Q^*(t)$ $(1 \leqslant t \leqslant T)$ are obtained. According to Bellman principle of optimality, the global optimal solution of the energy storage process can be obtained. The proposed method can be used to obtain the optimal operational strategy for an integrated energy system with energy storage.

Results and discussion. Some numerical simulations were conducted to verify the effectiveness of the proposed method in relation to the traditional GA method. A small-scale integrated energy system was used as a simulation model, which provides power, cooling, and heating energy for buildings. The time-of-use electricity price of the power

Algorithm 1 The hybrid optimization based on DP and GA

Input: Load forecasting data, device parameters, and GA parameters.
Output: Maximum $J(T)$, corresponding $u^*(t)$ and $Q_s^*(t)$.

1: $S(t) = 0$;
2: $S(t-1) = 0$;
3: Calculate $u^*(t)$ that maximize the object function $J(t) = J(t-1) + l(S(t), S(t-1), u(t), t)$ from $S(t-1)$ to $S(t)$ by using the GA, and record $u^*(t)$ and maximum $J_{S(t)}^{S(t-1)}(t)$;
4: Increment $S(t-1)$ by ΔQ_s;
5: Repeat Steps 3 and 4, until $S(t-1) = S_{\max}$;
6: Find maximum $J(t)$ from any $S(t-1)$ to $S(t)$, and record $J_{S(t)}^*(t)$ and corresponding $S^*(t-1)$ and $u^*(t)$;
7: Increment $S(t)$ by ΔQ_s;
8: Repeat Steps 2–7, until $S(t) = S_{\max}$;
9: Increment t by 1;
10: Repeat Steps 1–9, until $t = T$;
11: Find maximum $J(T)$ and corresponding $u^*(t)$ and $S^*(t)$ $(1 \leqslant t \leqslant T)$, and calculate $Q_s^*(t)$ using (10).

grid was considered for the simulation. The operational optimization selected a natural day as an optimized cycle and was on basis of hourly interval. $E_{\rm pgu}(t)$ and $S(t)$ were chosen as the optimized variables.

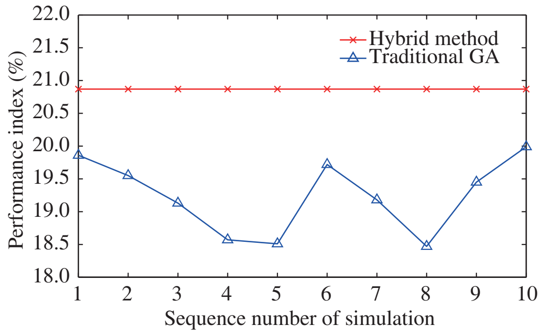

Figure 1 (Color online) Results of hybrid and traditional GA methods.

The simulation results are shown in Figure 1. The comprehensive performance indexes obtained using the proposed method are all equal to 20.87%. However, there are random fluctuations in the results obtained using the traditional GA method, in which the best result is 19.99% and the worst result is 18.47%. The proposed method has better energy, economic, and environmental performances compared to the traditional GA method. It is difficult to find an optimal global solution using the GA method, because 48 variables need to be optimized simultaneously. However, with the proposed method, the GA is sequentially called by the DP and only one variable is optimized at a time. Therefore, the proposed method can easily be used to find the global optimal solution.

Conclusion. This study proposed a hybrid method based on DP and GA to find the optimal operation strategy for the CPIES. The proposed method uses DP as the main optimization framework to determine the optimal energy storage state in every period, which works best for solving dynamic optimization problems. The GA is embedded into the DP to optimize the device set-points, considering that the GA is suitable for static optimization problems. Therefore, the proposed method guarantees the delivery of the global optimal solution. Numerical simulations demonstrated the superiority of the proposed method compared to the traditional method. However, owning to the time-of-use price of electricity, the tradeoff between the energy and cost objectives is unclear. This will be considered in our future work.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 61821004, 61733010, 61320106011, 61573224, 61573223), and the Young Scholars Program of Shandong University (Grant No. 2016WLJH29).

References

1 Fumo N, Mago P J, Chamra L M. Emission operational strategy for combined cooling, heating, and power systems. Appl Energy, 2009, 86: 2344–2350
2 Sridhar S, Hahn A, Govindarasu M. Cyber-physical system security for the electric power grid. Proc IEEE, 2012, 100: 210–224
3 Li J H, Wen J Y, Cheng S J, et al. Minimum energy storage for power system with high wind power penetration using p-efficient point theory. Sci China Inf Sci, 2014, 57: 128202
4 Deng N, Cai R, Gao Y, et al. A MINLP model of optimal scheduling for a district heating and cooling system: a case study of an energy station in Tianjin. Energy, 2017, 141: 1750–1763
5 Bao Z J, Zhou Q, Yang Z H, et al. A multi time-scale and multi energy-type coordinated microgrid scheduling solution-part II: optimization algorithm and case studies. IEEE Trans Power Syst, 2015, 30: 2267–2277
6 Zheng C Y, Wu J Y, Zhai X Q, et al. A novel thermal storage strategy for CCHP system based on energy demands and state of storage tank. Int J Electrical Power Energy Syst, 2017, 85: 117–129
7 Liu Y, Yang J N, Wang Y Z, et al. Multi-objective optimal preliminary planning of multi-debris active removal mission in LEO. Sci China Inf Sci, 2017, 60: 072202
8 Fang F, Wang Q H, Shi Y. A novel optimal operational strategy for the CCHP system based on two operating modes. IEEE Trans Power Syst, 2012, 27: 1032–1041