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Day-ahead optimal energy dispatch schedule for integrated energy system based on AC/DC interconnected infrastructure

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Abstract: This study proposes a day-ahead optimal energy dispatch model for integrated energy system based on AC/DC interconnected infrastructure. In the infrastructure, micro-turbines turn high-frequency AC power into industrial-frequency AC power and incorporate it into the energy system's power system. Within the process, waste heat is sent into the waste heat boiler and lithium bromide chillier to interconnect with the heating and cooling systems. DC battery and photovoltaic generations connected with the energy system's power grid through the inverter are used as the flexible energy storage and power generation unit to build an autonomous integrated energy system based on AC/DC interconnection. In the optimisation model, the goal is set as system's lowest daily operation cost and lowest energy consumption. The constraints include system operation constraints and equipment constraints. Simulation results show that by performing the schedule made by the dispatch model, the operating efficiency of various types of AC/DC equipment in the energy system has been improved, energy waste scene has been reduced significantly and energy consumption in the energy system is reduced by 16% compared with other energy supply structure without AC/DC interconnected infrastructure under traditional schedule strategies.

1 Introduction

Electricity, gas and thermal systems are coupling increasingly closely every day. In the future, an integrated energy system with the core part of power system will become the major form of a distributed energy system.

At present, the research works on the integrated energy system mostly focused on the equipment modelling and making a schedule plan [1, 2]. The capacity planning model of the energy supply equipment in the integrated energy system is given in [3], and a differential evolution particle swarm algorithm is used to solve the model. The residential-side combined cooling heating and power (CCHP) system is studied in [4], and an optimised schedule algorithm is proposed to reduce residents' operating costs. In terms of scheduling strategies, the two most common scheduling strategies in the integrated energy system are FEL (following the electric load) strategy and FTL (following the thermal load) strategies [5, 6]. The authors in [7] analyse the operating characteristics of different types of energy storage equipment in the integrated energy system and makes comparison between the performances of the energy storage equipment, which provides guidance for the selection of energy storage equipment in integrated energy systems. In [8], the working principle of the waste heat boiler is described in detail. Based on the law of energy conservation, a partial load dynamic mathematical model of the non-combustion waste heat boiler is built, and the model has good universality.

This paper focuses on the energy supply infrastructure of an integrated energy system. Then, a day-ahead optimal energy dispatch model for the integrated energy system is built on the basis of AC/DC interconnected infrastructure and solved to make dispatch schedule for improving the energy consumption efficiency of the system.

2 Energy supply infrastructure of the integrated energy system with AC/DC interconnection

2.1 Energy supply infrastructure

The energy supply infrastructure of the integrated energy system contains four energy parts: heat, cold, power and gas. Within the four parts, micro-turbines unit is the key equipment to connect the whole energy system.

Microturbines turn high-frequency AC power into industrial-frequency AC power and incorporate it into the energy system's power system. Within the process, waste heat is sent into the waste heat boiler and lithium bromide chillier to interconnect with the heating and cooling systems. DC battery and photovoltaic generations connected with the energy system's power grid through the inverter are used as the flexible energy storage and power generation unit, respectively, to build an autonomous integrated energy system based on AC/DC interconnection.

The heating(cooling) loads in the integrated energy system are satisfied by the energy storage equipment directly instead of the energy supply equipment, and the storage equipment are charged by a variety of energy supply devices. The energy supply infrastructure of integrated energy systems is shown in Fig. 1.

2.2 Energy supply and storage equipment of integrated energy system

In the integrated energy system, the equipment include micro-turbines, a hot water tank, lithium bromide refrigeration units, a chilled water tank, an electrical heater, an electrical heating storage tank, a battery, and a distributed solar system. In this paper, the models of the equipment are divided into three categories [9–11]: a micro-turbines model (comprising micro-turbines), an energy storage model (comprising a hot water tank, a chilled water tank, an electrical heating storage tank and a battery) and an auxiliary equipment model (comprising the rest).

3 Optimal energy dispatch model for integrated energy system

3.1 Optimisation objective

The optimisation objective is to obtain the minimum of daily operation cost of the integrated energy system combined with the daily energy consumption, as shown in the following equation:

$$\min K = \min\,(\lambda_1 \times \text{price} + \lambda_2 \times \text{energy}) \tag{1}$$

where K is the optimisation objective of the model, price is the daily operation cost, energy is the daily energy consumption of the system, and λ_1 and λ_2 are the weight coefficients of the two sub-objectives.

The operation cost contains fuel cost, power exchange cost and equipment maintenance cost:

$$\text{price} = \text{pri}_{\text{fuel}} + \text{pri}_{\text{grid}} + \text{pri}_{\text{maintain}} \tag{2}$$

3.1.1 Fuel cost: The fuel cost of micro-turbine systems is shown as

$$\text{pri}_{\text{fuel}} = \sum_{t=1}^{24}\sum_{i=1}^{n_{\text{CHP}}} c^t_{\text{Gas}} \times f_{\text{CHP}i}(P^t_i) \times \Delta t \tag{3}$$

where *f*CHP*i* is the consumption characteristic function of the *i*th micro-turbine, *P t i* is the power output of the *i*th micro-turbine at moment *t* (kW), *c t* Gas is the gas price at moment *t* ($/kW h).

3.1.2 Power purchase cost: The power purchase cost of the integrated energy system with the grid is shown as

$$\text{pri}_{\text{Grid}} = \sum_{t=1}^{24} c^t_{\text{Grid}} \times P^t_{\text{Grid}} \times \Delta t \tag{4}$$

where *c t* Grid is the electricity purchasing price at moment *t* ($/kW h) and *P t* Grid is the exchange power between the integrated energy system and the grid at moment *t* (kW).

3.1.3 Equipment maintenance cost: The equipment maintenance cost of integrated energy system is shown as

$$\begin{aligned}\text{pri}_{\text{maintain}} = & \sum_{t=1}^{24}\sum_{i=1}^{n_{\text{CHP}}} p_{\text{mCHP}i} \times P^t_i \times \Delta t + \sum_{t=1}^{24} p_{\text{mEH}} \times P^t_{\text{EH}} \times \Delta t \\ & + \sum_{t=1}^{24} p_{\text{mdistri}} \times P^t_{\text{distri}} \times \Delta t + \sum_{t=1}^{24}\sum_{i=1}^{n_{\text{stor}}} p^i_{\text{mstor}} \times H^{i,t}_{\text{in}} \times \Delta t \\ & + \sum_{t=1}^{24}\sum_{i=1}^{n_{\text{stor}}} p^i_{\text{mstor}} \times H^{i,t}_{\text{out}} \times \Delta t + \sum_{t=1}^{24} p_{\text{mLBR}} \times C^t_{\text{LBR}} \times \Delta t\end{aligned} \tag{5}$$

where *p*mCHP*i*, *p*mEH, *p*mdistri, *p i* mstor and *p*mLBR is the maintenance cost of the *i*th micro-turbine, electrical heater, distribution generation, *i*th storage device and lithium bromide refrigeration units, respectively ($/kW h), and *P t i*, *P t* EH, *P t* distri and *C t* LBR are the power output of the *i*th micro-turbine, electrical heater, distribution generation and lithium bromide refrigeration units, respectively (kW). *H i,t* in and *H i,t* out refer to the power input and power output of the four kinds of storage devices (kW), respectively.

3.1.4 Daily energy consumption: The daily energy consumption of the system contains gas energy consumption and power consumption, which is converted to natural gas amount, as follows:

$$\text{energy} = \sum_{t=1}^{24} L^t_{\text{gas}} \times \Delta t + \left(\sum_{t=1}^{24} P^t_{\text{power}} \times \Delta t\right) \times c_{\text{p2g}} \tag{6}$$

where energy is the daily energy consumption of the system, L^t_{gas} is the gas consumption at the moment *t*, P^t_{power} is the power consumption from the grid at the moment *t* and c_{p2g} is the coefficient that converts the power energy consumption to standard gas volume.

3.2 Model constraints

Constraints of the model include the balance constraints of power, heat and cold energy, capacity constraints and operation constraints of the energy supply and storage equipment [12].

3.3 Solution method for the model

Interior point method can take advantage of the sparsity of the modified matrix, which can solve large-scale non-linear optimisation problems more quickly than the traditional evolutionary algorithm such as ant colony optimisation algorithm

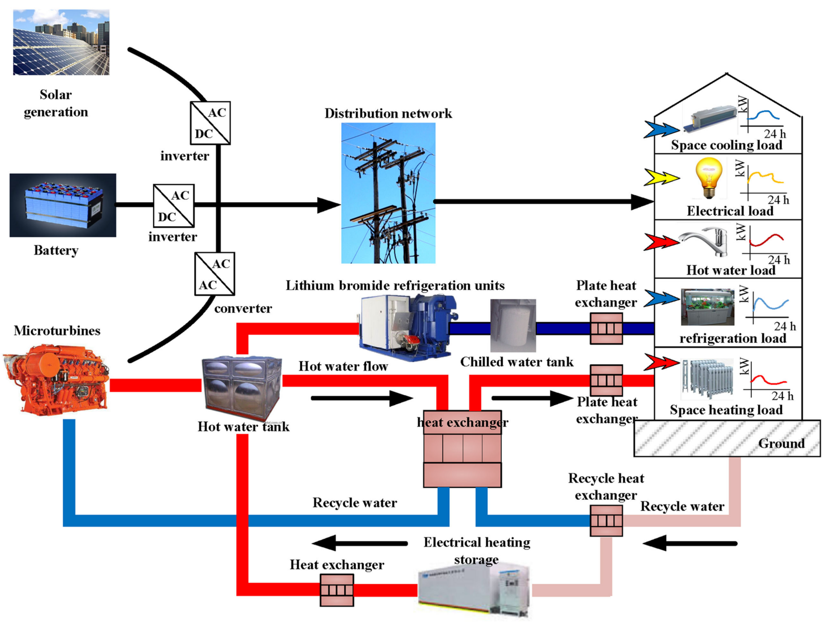

Fig. 1 *Energy supply infrastructure of the integrated energy system with AC/DC interconnection*

Table 1 Coefficients of energy supply equipment

Equipment	Parameter	Value
capstone C1000 micro-turbine systems	maximum power output, $P_{c1000,max}$	1000 kW
	nominal efficiency, η_{c1000}	0.33
lithium bromide refrigeration units	maximum power input, $P_{LBR,max}$	200 kW
	nominal efficiency, COP_{LBR}	1.2
electrical eater	maximum power input $P_{EH,max}$	200 kW
	nominal efficiency, COP_{EH}	2.0
external network	maximum power exchange, $P_{Bus,max}$	1800 kW
distributed solar system	maximum power generation, $P_{DG,max}$	187.8 kW

Table 2 Coefficients of energy storage equipment

Parameter	Equipment			
	Lead acid battery	Hot water tank	Chilled water tank	Electrical heating storage tank
charge efficiency	0.97	0.95	0.95	0.95
discharge efficiency	0.97	0.95	0.95	0.95
maximum charge rate	0.2	0.2	0.2	0.2
maximum discharge rate	0.3	0.2	0.2	0.3
self-discharge rate	0.02	0.03	0.03	0.03
maximum state of charge	0.9	0.9	0.9	0.9
minimum state of charge	0.2	0.1	0.1	0.1
capacity(kW·h)	200	10,000	2,000	2000

and simulated annealing algorithm [13, 14]. The standard solution form can be written as follows:

$$\begin{cases} \min f(x) \\ s.t. \, c(x) \le 0 \\ ceq(x) = 0 \\ Ax \le b \\ A_{eq}x = b_{eq} \\ lb \le x \le ub \end{cases} \tag{7}$$

The solution process constructs the Lagrange auxiliary function, which meets the conditions of Karush–Kuhn–Tucker [15]:

$$\begin{aligned} L(x,\lambda) = f(x) + \sum \lambda_{c,i}c_i(x) + \sum \lambda_{A,i}(Ax - b) \\ + \sum \lambda_{\mathrm{ceq},i}\mathrm{ceq}_i(x) + \sum \lambda_{\mathrm{Aeq},i}(A_{\mathrm{eq}}x - b_{\mathrm{eq}}) \end{aligned} \tag{8}$$

The Hessian matrix in the second derivative of the modified function is shown as

$$\begin{aligned} \boldsymbol{H} = \nabla^2_{xx}L(x,\lambda) = \nabla^2 f(x) \\ + \sum \lambda_i \nabla^2 c_i(x) + \sum \lambda_i \nabla^2 \mathrm{ceq}_i(x) \end{aligned} \tag{9}$$

This paper applies the genetic algorithm combined with the interior point method with Hessian matrix iteration to solve the model; it first uses the genetic algorithm to search the relatively satisfactory solution point, and then uses the solution found as the initial values of the iteration of the interior point method.

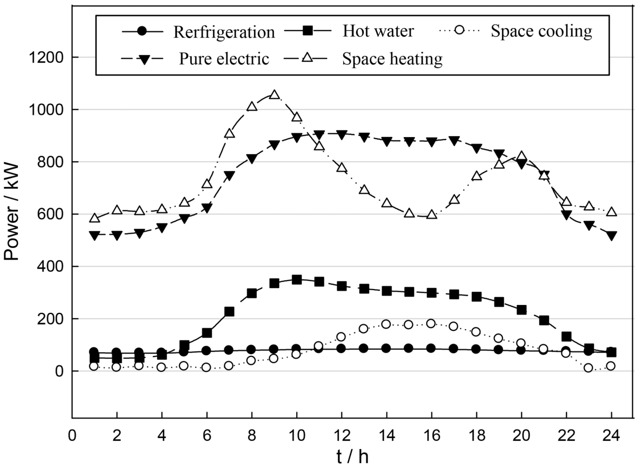

Fig. 2 *Day-ahead forecasting load curve of the building within the system*

Table 3 Time of use price

Time period	Detail time	Price, $/kW h
peak	9:00–11:00, 19:00–22:00	0.1353
valley	0:00–7:00, 22:00–24:00	0.0573
intermediate	7:00–9:00, 11:00–19:00	0.0952

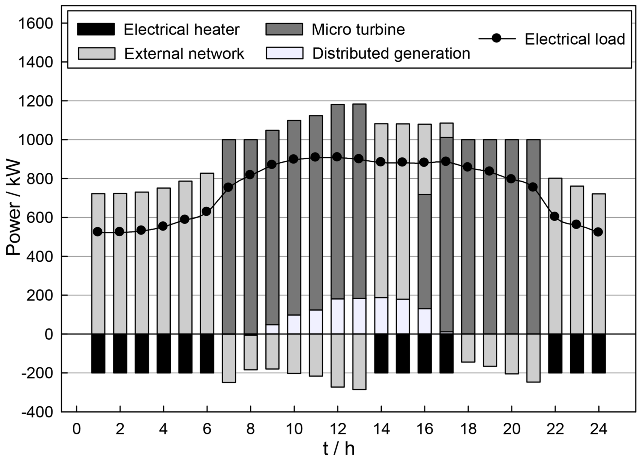

Fig. 3 *Electricity balance curve by the optimal energy dispatch schedule*

4 Case study

The case studied is an integrated energy system based on AC/DC interconnection located in the animation park of Sino-Singapore Tianjin Eco-City [16]. The optimal energy dispatch model is coded using MATLAB R2017a; the parameters of the energy supply and storage equipment in the case are presented in Tables 1 and 2.

The day-ahead forecasting load curve of the integrated energy system is shown in Fig. 2. The system adopts TOU pricing shown in Table 3.

The optimal dispatch schedule of the system can be made by solving the proposed day-ahead optimal energy dispatch model and the results are shown in the following.

Fig. 3 shows that micro-turbines generate power most of the time at peak price hours under the proposed optimal energy dispatch (OED) strategy and the operation periods of the electrical heater storage tank are concentrated in the valley price hours. Although the micro-turbine unit has some energy waste causing the energy recycle ratio of the system to not reach 100%, the micro-turbine unit operates at nearly maximum power output status because of profit compensation of the entire system. After making full use of the distributed photovoltaic power generation unit, the system bought power from the external grid to avoid energy waste, and the electricity purchasing period is also concentrated in the valley price hours.

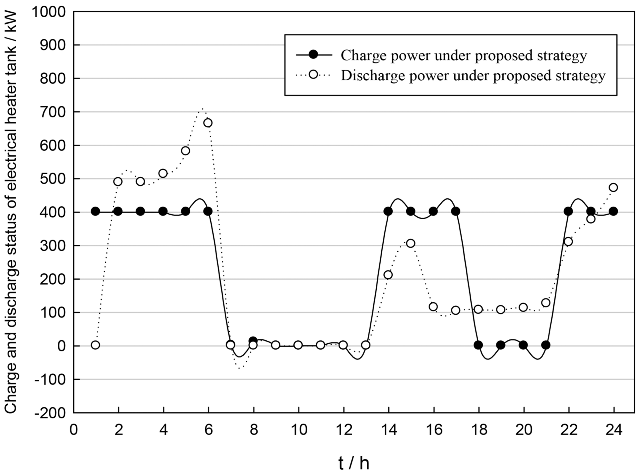

Fig. 4 *Charge and discharge status of the electrical heater storage tank under the proposed schedule strategy*

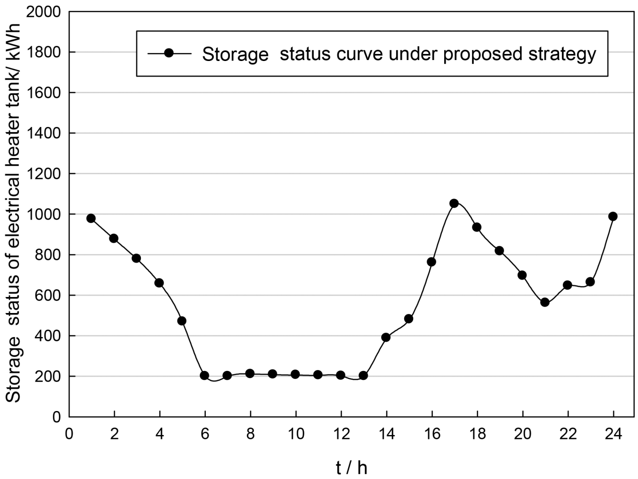

Fig. 5 *Storage status of the electrical heater storage tank under the proposed schedule strategy*

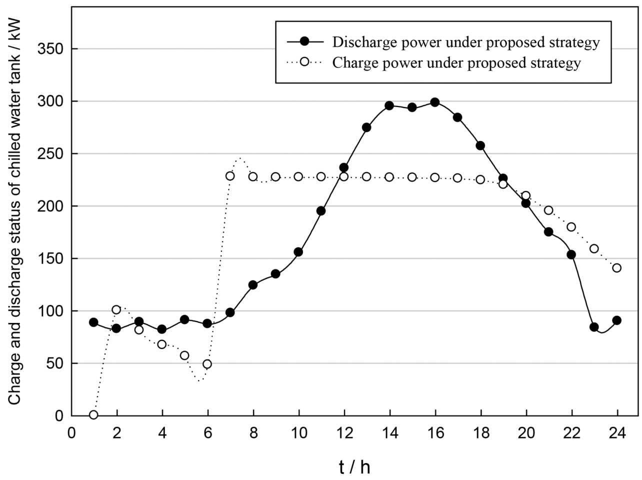

Fig. 6 *Charge and discharge status of the chilled water tank under the proposed schedule strategy*

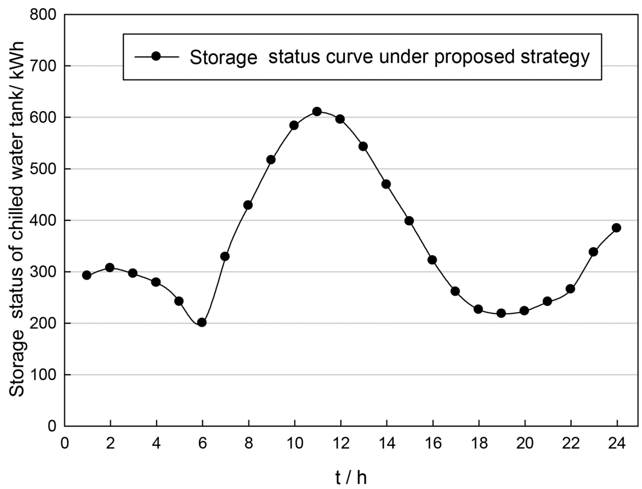

Fig. 7 *Storage status of the chilled water tank under the proposed schedule strategy*

Figs. 4 and 5 show that under the proposed OED strategy, the heating section of electrical heater storage tank develops the operation strategy based on time-of-use price. At valley price hours, the storage section of the electrical heater storage tank is charged. At midnight, the state of charge of the storage section reaches the highest point. During the daytime, the storage section releases heat energy to satisfy the heat load.

Figs. 6 and 7 show that the proposed OED schedule strategy could control the state of charge of the chilled water tank flexibly, yet the traditional control strategy could only charge and discharge for a long time, which could not make full use of the chilled water tank storage equipment.

Table 4 shows the daily operation cost and energy consumption of the integrated energy system under different schedule strategies. The daily operation cost under the proposed OED schedule strategy is \$2089.39. After adopting the proposed optimal energy dispatch strategy, the daily operation cost decreases 15% and 26% and the daily energy consumption decreases 16% and 29% compared to those of the other two traditional schedule strategies, respectively.

Table 4 Daily operation cost and energy consumption of the integrated energy system under different schedule strategies

Schedule strategy	Daily operation cost, \$	Daily energy consumption (convert to natural gas m^3)
proposed OED strategy	2089.39	3840.43
following the thermal load (FTL) strategy	2456.37	4576.61
following the electric load (FEL) strategy	2837.52	5389.48

5 Conclusion

This paper focuses on making optimal energy dispatch schedule for the integrated energy system based on AC/DC interconnected infrastructure and establishes a day-ahead optimal energy dispatch model. A case study shows that by performing the schedule made by the proposed OED model, the energy demand in the system could be fully satisfied and the situations of wasting of solar power, heat and cold energy do not occur. Through the comparison of charge and discharge status of the energy storage equipment, daily operation costs and energy consumption in the energy system under different schedule strategies, the proposed OED schedule strategy could adjust the charging and discharging powers of the various types of AC/DC energy supply equipment in the energy system more flexibly, thus controlling the storage status of the energy storage equipment more flexibly and reducing the daily operation price and energy consumption of the integrated energy system remarkably than other energy supply structures without AC/DC interconnected infrastructure under traditional schedule strategies, which verifies the effectiveness of the proposed OED schedule strategy.

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