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Multi-time-scale scheduling strategy for regenerative electric heating system based on thermal demand response#

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ABSTRACT

With the development of renewable energy and the advancement of electric heating projects, the stable operation of grid has been affected. In this paper, LA is used as an auxiliary service provider to study the scheduling strategy for multiple time scales in thermal demand response. Then, a case verifies the effectiveness of the strategy. Through intraday or real-time scheduling, the load can be effectively reduced by 16.61% and 15.53%, and 406.5MWh and 405.9MWh of abandoned wind power were consumed respectively. All participants can benefit from both scheduling strategies. However, shortening the scheduling time interval cannot achieve better results in thermal demand response scheduling.

Keywords: thermal demand response; load aggregator; multiple time scales

NONMENCLATURE

Abbreviations	
LA	Load Aggregator
DR	Demand Response
TOU	Time-of-Use
Symbols	
i	Time
Δt	Time step
F_W^i	Consumption of wind power
E_W^i	Revenue of wind power plant
E_{LA}^i	Revenue of LA
E_U^i	Revenue of user
P_W^i	Preferential price of wind power
P_R^i	Subsidy price of peak cutting
P_B^i	Subsidy price given to user
P^i	TOU electricity price
L_{DC}^i	Heat release power
L_C^i	Heat storage power
L_m^i	Load of user
L_X^i	Reduction of user
$L_{X,m}^i$	Load that user actively reduces
L_A^i	Total amount of load reduction
N_m^i	Number of users participating in DR
θ	Load reduction ratio

1. INTRODUCTION

Promoting the transformation of energy structure and strengthening energy conservation have become the focus of all countries in the world. Electric heating has been popularized on a large scale as a zero-emission, pollution-free heating method [1]. With the rapid development of renewable energy, fluctuation of electric heating load and renewable energy affect the stable operation of the grid.

In response to above problem, researchers consider installing energy storage devices on the supply side to alleviate the impact on the grid [2,3]. Other researchers propose demand response (DR) scenarios to shift and reduce demand-side loads [4,5]. Regulation from the supply side or demand side alone is not enough to solve the problem [6]. By introducing load aggregator (LA) [7] to grasp the information on both sides of supply and demand, it can coordinate the interests of multiple parties and meet the peak regulation demand of the grid.

Load participate in optimized scheduling under the integration of LA. With the time scale changes, the wind power and load forecasting accuracy also change. Therefore, a day-ahead scheduling plan is difficult to adapt to the operation situation on a shorter time scale. At present, a large number of studies have been carried out to optimize the demand-side load response on multiple time scales by building a day ahead-intraday-real time scheduling model [8,9]. However, there are few researches on scheduling strategy for multiple time scales with heat load as the response object. For the regenerative electric heating system that integrates a high proportion of renewable energy and includes auxiliary service provider, this paper studies the optimal scheduling results for multiple time scales of LA in thermal demand response.

2. MODEL

2.1 Regenerative electric heating system

The regenerative electric heating system was constructed in this study, as shown in Fig.1. The sources of electricity on the supply side are the municipal grid and wind power plant. The demand side includes various types of small and medium users. LA controls the regenerative electric heating equipment and interacts with the grid, wind power plant and user.

Through the introduction of LA, system has formed a market transaction mode of wind power plant-grid-LA-user. All parties conduct transactions from purchase/sale of electricity and demand response under sufficient information exchange.

(1) grid-LA

In order to adjust the peak-valley difference, the grid usually uses time-of-use (TOU) electricity price to motivate user to cut peak. However, TOU has great randomness and cannot fully meet the demand of grid. LA uses the subsidy price of peak cutting to incentivize user to further reduce the load, and uses thermal storage device to assist in peak cutting.

(2) wind power plant-LA

Due to the "anti-peak cutting" feature of wind power generation, plant and LA will sign electricity sales contract to sell wind power to LA at lower price during a specified period of time. LA uses electric boiler to convert wind power into heat, part of which is stored in thermal storage device for auxiliary peak cutting, and the other part is directly supplied to user.

(3) LA-user

LA will issue additional subsidy for load reduction, and pass the heating costs of other typical users to encourage more users to participate in DR. Users dynamically adjust their own energy consumption patterns with reference to the expenditure of other typical users.

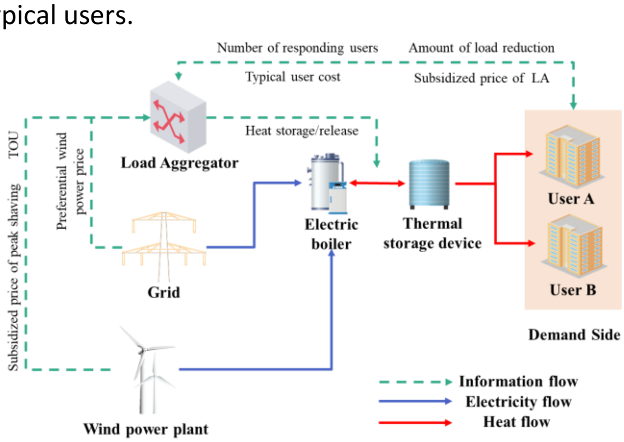


Fig. 1 Regenerative electric heating system model

2.2 Revenue model

(1) wind power plant

During the period of excess wind power, the revenue of wind power plant comes from the power consumed by LA, which includes consumption from directly heating the user and storing heat into thermal storage device. The consumption of wind power F_W^i and the revenue of wind power plant E_W^i at time i are as follows:

$$F_W^i = \left(\sum_{m=1}^{M} N_m^i \cdot L_m^i + L_C^i\right) \cdot \Delta t \tag{1}$$

$$E_W^i = F_W^i \cdot P_W^i \tag{2}$$

In formula (1), Δt is the time step. L_C^i is the heat storage power (kW). N_m^i is the number of users participating in DR. L_m^i is the load of user (kW). In formula (2), P_W^i is the preferential price of wind power (yuan/kW).

(2) LA

The revenue of LA comes from the peak cutting reward given by grid and the income of the thermal storage device. The expenditure part includes the subsidy given to user and the heat storage cost of thermal storage device. The revenue of LA E_{LA}^i at time i is as follows:

$$E_{LA}^i = (P_R^i \cdot L_A^i + P^i \cdot L_{DC}^i - P_B^i \cdot L_X^i - P_W^i \cdot L_C^i) \cdot \Delta t \tag{3}$$

In formula (3), L_A^i is the total amount of load reduction (kW), which includes the reduction of user L_X^i (kW) and the heat release power L_{DC}^i (kW). P_R^i is the subsidy price of peak cutting given by grid (yuan/kW). P^i is the TOU electricity price (yuan/kW). P_B^i is the subsidy price given to user (yuan/kW).

(3) user

The revenue of user comes from the subsidy given by LA and the cost saved by load reduction. In order to further increase user's income, LA directly provides heat to user at preferential wind power price during periods of excess wind power. Therefore, the revenue of user also includes the heat consumption saved during this period. The revenue of user E_U^i at time i is as follows:

$$E_U^i = \left[\left(P_B^i + P^i\right) \cdot L_{X,m}^i + \left(P^i - P_W^i\right) \cdot L_m^i\right] \cdot \Delta t \tag{4}$$

In formula (4), $L_{X,m}^i$ is the load that user actively reduces (kW). During the periods other than excess wind power, $\left(P^i - P_W^i\right) \cdot L_m^i = 0$.

(4) grid

Grid will improve its security and reduce capacity expansion costs by spending a portion of incentive subsidies. The benefit of grid is mainly reflected in the amount of load reduction. Therefore, the revenue of grid is measured by the amount of load reduction during peak hour of electricity consumption. The load reduction ratio θ at time i is as follows:

$$\theta = \frac{L_A^i}{\sum_{m=1}^{M} N_m^i L_m^i} \tag{5}$$

3. CASE

3.1 Parameter setting

This paper analyzes the regenerative electric heating system in Lanzhou City, Gansu Province, China as a case. The demand side includes 1,000 residential users. Taking one week in the heating season as a cycle, the peak cutting situation of grid and the revenue of all parties are studied after user participates in intraday scheduling and real-time scheduling. For thermal demand response, intraday scheduling is performed every 1 hour, and real-time scheduling is performed every 15 minutes.

User who participates in DR will reduce load on the basis of ensuring their own comfort to obtain subsidies. However, due to the different heating and consumption habits of each user, which can be divided into two categories: price-sensitive and price-insensitive. The response parameters of two types of users are as shown in Table 1. The response participation in Table 1 represents the active degree of user's participation in DR. The response ratio in Table 1 represents user's load reduction strength.

Table 1 User's type and response characteristic parameters

Type	Number	Response participation	Response ratio
Price-sensitive (User A)	600	0.6	1.000
Price-insensitive (User B)	400	0.3	0.584

The TOU electricity price set by Lanzhou Power Grid in Gansu is as shown in Table 2.

Table 2 TOU electricity price in Lanzhou

Hour	[0,7]	[8,11] [15,16] [19,22]	[12,14] [17,18] [23]
P^i(yuan/kWh)	0.30	0.76	0.50

The subsidy price of peak cutting provided by grid is 0.4 yuan/kWh. The subsidy price of LA is 0.15 yuan/kWh. The preferential wind power price set by wind power plant is 0.28 yuan/kWh at 1:00-6:00 and 22:00-23:00 every day.

3.2 Results and Discussion

(1) Load reduction analysis

Table 3 Load reduction under different scheduling methods

Day		1	2	3	4	5	6	7
Original load (kWh)		122332.0	114247.9	113143.3	110618.8	110446.9	108956.7	109983.1
Intraday scheduling	Reduction (kWh)	18721.4	18676.4	18676.4	18745.5	18718.1	18718.6	18699.8
	Reduction ratio	0.153	0.165	0.165	0.169	0.169	0.171	0.170
Real-time scheduling	Reduction (kWh)	17636.9	17498.4	17498.4	17465.6	17470.6	17457.7	17472.7
	Reduction ratio	0.144	0.155	0.155	0.158	0.158	0.160	0.159

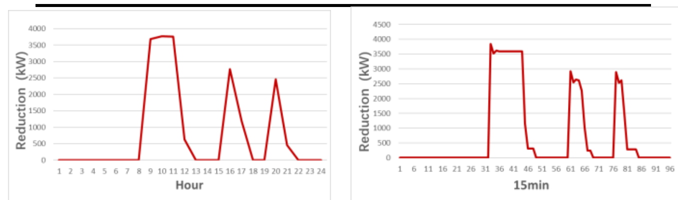


Fig. 3 Hourly load reduction under different scheduling methods
intraday scheduling (left), real-time scheduling (right)

The peak cutting effect of scheduling includes the load reduction of user and the heat release of thermal storage device during peak hour. As shown in Fig. 3, through intraday and real-time scheduling, load has been effectively reduced in the three time periods of 8-11, 15-16 and 19-22 every day. At each moment, the amount of load reduction always peaked at the beginning, then leveled off after a small decline, and then dropped significantly at the end. Under intraday scheduling, the total load reduction in a single day is higher than 18,500kWh. The load reduction ratio is higher than 15%, and the average load reduction ratio in a cycle is 16.61%. Under real-time scheduling, the total load reduction in a single day is higher than 17,000kWh. The load reduction ratio is higher than 14%, and the average load reduction ratio in a cycle is 15.53%.

(2) The revenue of wind power plant

Table 4 The revenue of wind power plant under different scheduling methods

Day		1	2	3	4	5	6	7
Intraday scheduling	Wind power consumption (kWh)	56702.7	59984.3	58381.6	58804.5	57960.2	57253.2	57426.1
	Revenue (Million yuan)	1.588	1.680	1.635	1.647	1.623	1.603	1.608
Real-time scheduling	Wind power consumption (kWh)	56702.7	59804.2	58316.7	58741.9	57865.6	57160.7	57349.6
	Revenue (Million yuan)	1.588	1.675	1.633	1.645	1.620	1.600	1.606

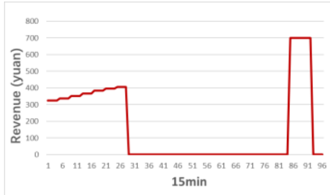


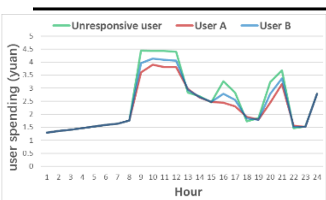
Fig. 4 Hourly revenue of wind power plant under different scheduling methods
intraday scheduling (left), real-time scheduling (right)

The revenue of wind power plant includes heating and storage benefits from curtailed wind power. As shown in Fig. 4, through intraday and real-time scheduling, wind power plant can obtain benefits from consuming abandoned wind during 1-6 and 22-23 hours of the day. The single-day income of two scheduling methods is both higher than 15,000 yuan, and the total income is higher than 113,000 yuan.

(3) The revenue of user

Table 5 The revenue of user under different scheduling methods

	Day	1	2	3	4	5	6	7
Intraday scheduling	Unresponsive user	60.1	54.4	54.0	52.3	52.5	51.7	52.4
	User A	55.1	49.4	49.0	47.4	47.5	46.8	47.4
	User B	57.3	51.6	51.1	49.4	49.6	48.9	49.5
Real-time scheduling	Unresponsive user	60.06	54.38	53.97	52.30	52.45	51.73	52.36
	User A	54.73	48.93	48.53				
	User B	55.83	50.07	49.68				



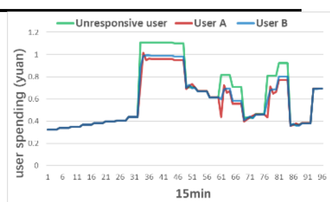


Fig. 5. Hourly revenue of user under different scheduling methods
intraday scheduling (left), real-time scheduling (right)

Table 5 shows the heating cost of different types of users under the condition of maintaining their own comfort. As shown in Fig. 5, through intraday and real-time scheduling, the single-day cost of user A is lower than user B than unresponsive user. The different cost between different types of users arises from the peak hour of electricity consumption. The heating cost of user who participate in response will be lower than other users. and the higher the response ratio, the greater the savings. The higher the response ratio, the greater the savings.

(4) The revenue of LA

Table 6 The revenue of LA under different scheduling methods

Day	1	2	3	4	5	6	7
Intraday scheduling	1.326	1.281	1.302	1.304	1.303	1.303	1.302
Real-time scheduling	1.296	1.253	1.272	1.272	1.272	1.271	1.272

As shown in Table 5, under intraday scheduling, the revenue of LA in a single day is about 13,000 yuan. The total income in a cycle is reach up to 91,200 yuan. Under real-time scheduling, the revenue of LA in a single day is about 12,800 yuan. The total income in a cycle is reach up to 89,100 yuan.

4. CONCLUSION

(1) In this paper, the authors study the intraday and real-time scheduling strategies for demand-side heat load in the context of grid demand response. It can be seen from the result of revenue that the dispatching strategy can improve consumption of wind power and benefit all participants on the basis of meeting the peak cutting requirement and ensuring user's comfort. Through intraday scheduling, the grid effectively reduced the load by 16.61%, the wind power plant absorbed 406.5MWh of abandoned wind power and obtained a profit of 113,823 yuan, and LA received a profit of 91,200 yuan. Through real-time scheduling, the grid effectively reduced the load by 15.53%, the wind power plant absorbed 405.9MWh of abandoned wind power and obtained a profit of 113,663 yuan, and LA received a profit of 89,100 yuan.

(2) By comparing the result of intraday scheduling and real-time scheduling, it can be seen that although the execution frequency of real-time scheduling is faster, the final load reduction effect and revenue of all parties are not significantly better than those of intraday scheduling. Due to the limitation of thermal response speed and building thermal inertia, shortening the scheduling time interval cannot achieve better results in thermal demand response scheduling.

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REFERENCE

[1] Ling H, He J; Xu Y. Status and prospect of thermal energy storage technology for clean heating. Energy Storage Science and Technology 2020;9(3):861-868.

[2] Chen L, Xu F, Wang X. Implementation and effect analysis of heat storage to improve wind power consumption capacity. Proceedings of the CSEE 2015;35(17):4283-4290.

[3] Shang Q, Sun M. Research on grid optimization scheduling based on wind power and storage (heat) heating system. Acta Energiae Solaris Sinica 2021;42(07):65-70.

[4] Li C, Xu Z, Ma Z. Time-of-use electricity price optimization model considering user demand response. Proceedings of the CSU-EPSA 2015;27(03):11-16.

[5] Xu H, Dong S, He Z. Electro-thermal Comprehensive Demand Response Based on Multi-energy Complementarity. Power System Technology 2019;43(02):480-487.

[6] Pan G, Gu W, Wu Z. Optimal design and operation of multi-energy system with load aggregator considering nodal energy prices. Applied Energy 2019;239:280-295.

[7] Li B, Shen J, Wang X. From controllable loads to generalized demand-side resources: A review on developments of demand-side resources. Renewable and Sustainable Energy Reviews 2016;53: 936-944.

[8] Zhao D, Song Y, Wang Y. Multi-time scale coordination scheduling model considering flexible load response uncertainty. Automation of Electric Power Systems 2019;43(22):21-30.

[9] Li X, Zhao D. Multi-time scale optimal scheduling strategy of multi-microgrid based on market mechanism. Electric Machines and Control 2020;24(7):29-38.