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ENERGY HUB ECONOMIC DISPATCH CONTAINING BUILDING VIRTUAL STORAGE UNDER THE DEMAND RESPONSE MECHANISM

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ABSTRACT

A dispatch method with synergy and interaction between integrated energy hub and users was put forward aimed at the problems of failure to consider the thermal storage characteristics of building envelopes and demand response subsidy mechanisms for users during the operation and dispatch of integrated energy hub. First of all, a building virtual storage model was established with the indoor air and building envelope as the main part of heat transfer through comprehensive consideration of influences of indoor and outdoor disturbances on thermal process, and a mathematical model of building virtual storage with equivalent storage and discharge power was put forward; secondly, a typical equipment composition structure of integrated energy hub with supply of cooling, heating and power systems and a multi-agent interactive transaction relationship among external power companies, integrated energy hub and users were established, and a stimulating demand response mechanism based on user subsidy was put forward; thirdly, an optimized economic dispatch model of integrated energy hub was established with the maximum earnings of power station as the target, containing external power purchase expenses, incomes through selling power to users, and subsidies and with the flexible comfort level of users as constraints, and the CPLEX solver was adopted to solve the problems; finally, the practicability and effectiveness of the expressed model and method was verified through examples.

Keywords: building virtual energy storage; demand response; integrated energy hub; optimal dispatch; building envelope

1. INTRODUCTION

Energy hub is an important hinge of integrated energy system, which can improve the energy supply-demand coordination ability of the system through multi-energy complementation and integrated optimization [1]. To meet the energy supply within the service scope and realize the safe and energy-saving operation of powers, an integrated energy hub needs to formulate reasonable operation and dispatch schemes based on the cooling and heating load demands of users.

At present, some parts of researches have already applied the building heat balance model into the operation and dispatch of integrated energy systems. The first-order models based on equivalent building heat capacity and equivalent thermal resistance were established in Paper [2-3], which could represent the relationship between indoor temperature changes and cooling and heating power; the first-order equivalent model aimed at floor radiant heating and cooling system was established in Paper [4] and was applied to the optimal dispatch method for residential micro-grids with the consideration of renewable energy sources. Parts of researches also took the influence of cooling and heating demand response into the operational dispatch of integrated energy systems. The demand response model was established in Paper [5] based on price-oriented thermal loads of users to guide them to take part in the optimizing operations on micro-grids of solar-thermal power stations; a kind of energy management strategy of distributed CCHP (combined supply of cooling, heating and power) system based on demand response mechanism of user-stimulating cooling and heating load was put forward in Paper [6].

There are 2 aspects of insufficiencies in the above Papers:

(1) The stimulation of relationship between indoor temperature and cooling-heating demands of users through basic thermal resistance/capacity model or first-order model had no comprehensive consideration on the factors that affected the indoors temperature, and it ignored the internal heat transfer process of the building envelope and failed to give full expression to the influence of building thermal performances on cooling and heating demands of users;

(2) The difference in somatosensory comfort of users in different temperatures was not taken into consideration, when making use of users' "unacquaintance" towards temperature variation to adjust the indoor temperature and reduce the economic cost of power stations. As decrease of indoor temperature might cause increase of users' load in some day partings of demand response, it would lead to increase of expenditure of users on power purchase, and such process mode harmed the benefits of users on the aspects of comfort level and economic efficiency.

Aimed at the above problems, the major contributions of this paper includes:

(1) Comprehensively consider the multiple thermal disturbance factors indoors and outdoors, introduce more detailed building heat balance model of thermodynamics into the questions of dispatch so as to analyze the variation status of indoors temperature more accurately, and meanwhile a detailed modeling was made on the internal heat transfer process of the building envelope and the "virtual energy storage" characteristic of buildings was taken as a kind of usable resource to attend the economic dispatch of comprehensive energies and improve the systematic performances;

(2) Enrich and perfect the demand response subsidy mechanism between energy hub and users, forming a synergic coupling relationship between them to make overall planning and invoke the resources of both of them and take part in the transactions with the superior energy companies, then the subsidy mechanism and optimal dispatch processes were deeply combined based on the building virtual storage to realize benefit sharing between energy hub and users.

2. BUILDING VIRTUAL STORAGE MODEL

Building virtual storage model takes building heat balance theory as basis and it contains indoor air heat balance and building envelope structure heat balance.

2.1 Indoor air heat balance model

The climatic environment of indoor air is affected and disturbed by several factors, there were not only the outdoor disturbance factors like heat permeated from doors and windows and temperature of outdoor air, etc., but also the indoor disturbance factors like heat convection between building envelope structure and indoor air, etc. [7, 8]. The heat balance model established with indoor air as main part was shown in Formula (1).

$$Q_1+Q_2+Q_3=Q_4+Q_5$$

$$\begin{cases} Q_1 = \sum_{i=1}^{N_i} h_i f_i (T_{in} - T_{1,i}) \\ Q_2 = Q_d + Q_w \\ \quad = \beta K_c f_c (T_{in} - T_{out}) + 0.278 c_w \rho_w V_0 n(t)(T_{in} - T_{out}) \\ Q_3 = 0.278 c_o \rho_o V_o \dfrac{dT_{in}}{dt} \\ Q_4 = \sum Q_k \end{cases} \tag{1}$$

Where, $Q_{1\text{-}5}$ are different factors that affect the indoor climatic environment; T_{in}, T_{out} and $T_{1,i}$ are temperatures of indoor air, outdoor air and internal surface of wall; Q_k is cooling/heating power. The specific meanings of other parameters in Formula (1) can be found in Paper [7], which will not be discussed in detail here.

2.2 Building envelope heat balance model

Building envelope structure is of high thermal inertia, which means that it will absorb or release heat with the changes of outdoor temperature, the temperature of its internal nodes will also rise or fall with it, so it is a dynamic heat transfer process [9]. The heat balance equation in the building envelope is shown in Formula (2).

$$\begin{cases} T_4 = T_{out} \\ (\frac{1}{2} s_2 c_2 \rho_2 \Delta x_2 + \frac{1}{2} s_3 c_3 \rho_3 \Delta x_3) \dfrac{dT_3}{dt} = \dfrac{s_2 \lambda_2}{\Delta x_2}(T_2 - T_3) + \dfrac{s_3 \lambda_3}{\Delta x_3}(T_4 - T_3) \\ (\frac{1}{2} s_1 c_1 \rho_1 \Delta x_1 + \frac{1}{2} s_2 c_2 \rho_2 \Delta x_2) \dfrac{dT_2}{dt} = \dfrac{s_1 \lambda_1}{\Delta x_1}(T_1 - T_2) + \dfrac{s_2 \lambda_2}{\Delta x_2}(T_3 - T_2) \\ \frac{1}{2} s_1 c_1 \rho_1 \Delta x_1 \dfrac{dT_1}{dt} = \dfrac{s_1 \lambda_1}{\Delta x_1}(T_1 - T_2) + q_{co} + q_{so} \end{cases} \tag{2}$$

Where, $T_{1\text{-}4}$ are the temperatures of different layers of envelope; $s_i/c_i/\rho_i/\Delta x_i/\lambda_i$ are different parameters of the layers of envelope; q_{CO} is the convective heat transfer between the envelope and the air; q_{SO} is the solar radiation heat through the outer window.

The relation between indoor temperature and cooling/heating power could be calculated from Formula (1-2). Through changing the indoor temperature of the buildings, the output power of refrigerating (heating) equipment could be adjusted to provide foundation for the building virtual storage model established under the demand response mechanism.

2.3 Mathematical model of building virtual storage equivalent power

There is thermal inertia during the process of building heat transfer, which is represented as a kind of energy storage and discharge behavior similar to the energy storing devices, and it is a kind of usable "virtual energy storage" resource. If it is integrated to the equipment scheduling models, it can improve the load curve, optimize the output power of equipment and thus improving the operating economy of energy hub

When the indoor temperature of a building T_{in} is constantly or is changing, according to Formula (1), the output power of the refrigerating (heating) equipment Q_{sta}/Q_{dyn} can be respectively presented by Formula (3).

$$Q_{sta}=hf(T_{in}-T_1)+(\beta K_c f_c+0.278c_w\rho_w V_0 n(t))*(T_{in}-T_{out})$$

$$Q_{dyn}=hf(T_{in}-T_1)+(\beta K_c f_c+0.278c_w\rho_w V_0 n(t))*(T_{in}-T_{out})+0.278c_o\rho_o V_o\frac{dT_{in}}{dt} \tag{3}$$

$$Q_{dyn}=\begin{cases}Q_{dyn} & Q_{dyn}\le 0\\ 0 & Q_{dyn}>0\end{cases}$$

The equivalent power of building virtual storage Q_{vir} can be acquired through calculating the output power deviation of refrigerating (heating) equipment before and after the indoor temperature changes, as shown in Formula (4).

$$Q_{vir}=Q_{dyn}-Q_{sta} \tag{4}$$

3. ECONOMIC DISPATCH MODEL OF ENERGY HUB UNDER DEMAND RESPONSE MECHANISM

3.1 Equipment composition and interactive relationship of typical integrated energy hub

As the energy hinge, integrated energy hub buys energy from superior electric power and natural gas companies and converts it into electric and cold energy through multi-type equipment, and then sells it to users of subordinate loading zones. The equipment composition and interactive relationship of typical integrated energy hub is shown in Figure 1.

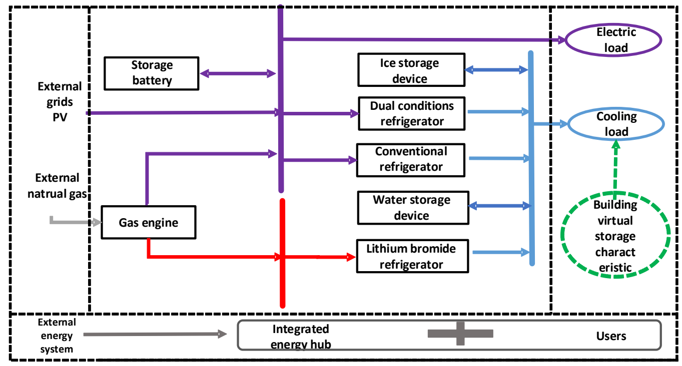

Fig 1 the equipment composition and interactive relationship of typical integrated energy hub

3.2 Demand response mechanism of users

Requirements of users on comfort level of indoor temperature can be expressed with PMV index, which means the average scale prediction of thermal sensation. The simplified formula of PMV index is shown as Formula (5):

$$\Gamma^{PMV}(t)=2.43-3.76\times\frac{33.5-T^{in}(t)}{M(I^{cl}+0.1)} \tag{5}$$

Where, Γ^{PMV} is the PMV index; M is the metabolic rate of human body; I_{cl} is the thermal resistance of clothing.

The range of PMV index recommended in ISO7730 criterion is:

$$-0.5\le\Gamma^{PMV}(t)\le 0.5 \tag{6}$$

Based on Formula (5) and (6), the acceptable temperature comfort level range of users can be acquired through calculation.

The operator of energy hub ensures the information including maximum adjustable temperature range and subsidy measures through signing agreements with users in advance. The agreement is as follows: ladder-type temperature subsidies can be realized for the users that take part in the demand response based on the response degree. The expenditures of subsidies are shown in Formula (7).

$$c_{bonus}(t)=\alpha\times(P_L(t)c_e(t)+Q_L(t)c_{cold})$$

$$\alpha=\begin{cases}\alpha_1 & 0<|T_{in}(t)-T_{set}|\le\varepsilon\\ \alpha_2 & |T_{in}(t)-T_{set}|>\varepsilon\end{cases},\quad \alpha_1<\alpha_2 \tag{7}$$

Where, $c_{bonus}(t)$ is the subsidy fee for users at time t; P_L and Q_L are the power and cooling load demand of users; c_e is the time-sharing price for energy hub; c_{cold} is the unit cold price for energy hub; and α is the temperature subsidy coefficient, which varies according to the temperature deviation from the set temperature, T_{set} is the set temperature.

3.3 Objective function

Considering from the aspect of integrated energy hub operators, the goal of the energy hub on joint economic cooling-heating electric dispatch is to reasonably arrange the output power of equipment in the hub and realize earnings maximization in the operation of energy hub. The operational earnings of the energy hub consist of external energy purchase expenses, incomes through selling energy to users, subsidies, as shown in Formula (8).

$$\begin{aligned} \max C_{func} &= C_{sale} - C_{buy} - C_{bonus} \\ &= \sum_{t=1}^{T} [P_L(t)c_e(t) + Q_L(t)c_{cold} - P_{buy}(t)c_e(t) - G_{buy}(t)c_g \\ &\quad - c_{bonus}(t)]\Delta t \end{aligned} \tag{8}$$

Where, C_{func} is the operating earnings of energy hub; C_{sale} is the income through selling energy to users; C_{buy} is external energy purchase expenses; C_{bonus} is the subsidies for users; P_{buy} and G_{buy} are the electric power and gas power purchased for energy hub; Cg is the unit price of gas.

3.4 Constraint conditions

Economic dispatch of equipment in the energy hub needs to meet the restrictions of energy balance, indoor temperature comfort level, etc.

3.5 Optimal objects and solutions

The above optimal dispatch model is a linear programing model, and the optimal objects contain: output power of energy conversion equipment of an integrated energy hub within 24h, variation of cooling-heating loads of user, the amount of electric power and natural gas purchased by energy hub from superior energy companies. At present, there have been mature solution algorithms for the linear programming models. Based on the YALMIP platform and through invoking the mature commercial solver CPLEX [10], optimization on objective function can be realized in the MATLAB environment in this paper.

4. ANALYSIS OF EXAMPLES

4.1 Basic status of examples

There were 11 independent 4-floor high buildings in a park of Southern China, whose layer height was 3m, and each building took an area of about 400m^2. The valley period of electric price of the power company was 00:00-08:00, 14:00-17:00 and 19:00-22:00 were the peak periods of power price, and others were the ordinary periods of power price. The price of natural gas was RMB 4.57/ m^3, and the unit cold price of energy hub for the users was RMB 0.2/ kWh [11]. The user subsidy coefficient α_1 was 3% and α_2 was 5%. Set temperature of users was 26℃, and the indoor temperature could fluctuate within the range of ±2℃ of the set temperature.

4.2 Comparison scheme of examples

To verify the effectiveness of the method mentioned in this paper, the following schemes were set to make contrast explanation.

Scheme 1: indoor temperature changed from 24-28 ℃, subsidies for user response were given with consideration of refined building virtual storage model.

Scheme 2: indoor temperature changed from 24-28 ℃, subsidies for user response were given with consideration of simplified building virtual storage model.

Scheme 3: indoor temperature changed from 24-28 ℃, refined building virtual storage model was considered without consideration of subsidies.

Scheme 4: indoor temperature changed from 24-28 ℃, simplified building virtual storage model was considered without consideration of subsidies.

Scheme 5: indoor temperature maintains 26℃, building virtual storage model and subsidies for user response were both not taken into consideration.

4.3 Result of example schemes

The economic comparison of the 5 kinds of schemes within a dispatch cycle was shown in Table 1.

Table 1 Cost components of Scheme 1-5(RMB)

Scheme	Operational earnings of EH	Power purchase expense of EH	Expenditure of users
1	76590	252630	330110
2	69460	259120	329480
3	85030	254160	340080
4	79700	260930	341530
5	68140	266840	335890

Scheme 5 showed that without considering the characters of building virtual storage and demand response of users, the total power purchase expenses of the energy hub and the total expenditure of users were both at high price;

On the basis of Scheme 5, character of refined and simplified building virtual storage were taken into consideration in Scheme 3 and 4 separately, then transfer and reduction occurred in the cooling load of users, which improved the load curve of users, and the overall power purchase expense of the energy hub reduced, but as the economic subsidies for users were not taken into consideration, the expenditure of users increased by 1.25% and 1.68% when the temperature comfort level decreased, which harmed the users' benefit on the contrary;

Based on Scheme 3 and 4, after taking the demand response subsidy mechanism of users into consideration in Scheme 1 and 2, it encouraged users to take part in the demand response with economy as orientation, and the total expense of users reduced by 2.93% and 3.53%;

Based on Scheme 2 and 4, refined building virtual storage model was taken into consideration in Scheme 1 and 3, through which the total power purchase expense of the energy hub reduced by 2.50% and 2.59%;

Figure 2 showed the variation of users' cooling demand and the equivalent energy storage and discharge power of building virtual storage after taking building virtual storage into consideration in Scheme 1, positive numbers represented the building energy storage power, and negative numbers represented the building discharge power. The main operational mode of building virtual storage was that: building virtual storage stored certain heat through lowering the temperature to increase the cooling load of users at the valley period at night when the power price was low; and building virtual storage discharged the stored heat through raising the temperature at day time to reduce the cooling load of users in peak periods. The energy storage and discharge character of building virtual storage is similar to that of actual energy storage devices, which reduce the power expenses for cooling equipment and improve the economic efficiency of the system through transferring the loads at the peak time to others.

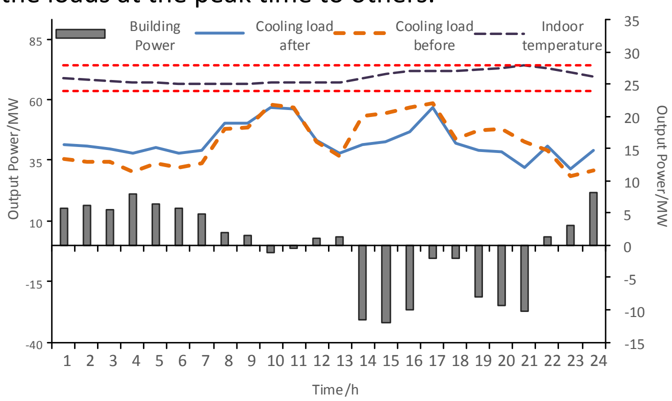

Fig 2 the variation of users' cooling demand and the equivalent energy storage and discharge power of building virtual storage in Scheme 1

The optimal dispatch results of cooling systems in Scheme 1 and 5 were respectively shown in Figure 3 and 4. The indoor temperature of Scheme 1 was low at night and gradually rose in daytime, and the maximum temperature was up to 28℃. As there was certain time-delay characteristics in the changes of building temperature, the time that the highest temperature occurred was later than that of outdoor temperature. Compared with Scheme 5, as the changes of indoor temperature in Scheme 1, there were relevant changes in the output power of refrigeration equipment. The refrigerating power of equipment increased at night when the power price was at valley period, and the refrigerating power at the peak time obviously lowered, large amount of the cooling power was transferred from daytime to night-periods, and the daily operating benefits were increased by 12.40%.

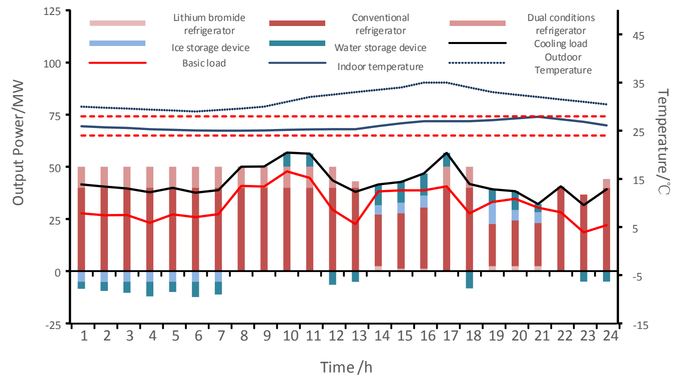

Fig 3 the optimal dispatch results of cooling systems in Scheme 1

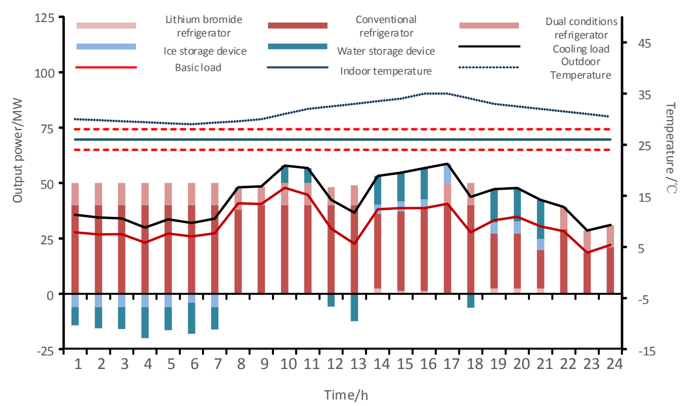

Fig 4 the optimal dispatch results of cooling systems in Scheme 5

5. CONCLUSION

The integrated energy hub optimal dispatch model containing building virtual storage under demand response mechanism was established in this paper, and

5 kinds of schemes were made to compare whether the building virtual storage model and demand response subsidy mechanism should be adopted, and the conclusions were as follows:

(1) The refined building virtual storage model established in this paper based on detailed building heat balance could take multiple heat disturbance factors into consideration and analyze the variation of indoor temperature more accurately, and it could sufficiently mobilize the "virtual energy storage" characters of buildings to attend the comprehensive energy operational dispatch, save the economic expenses of the energy hub by 2.5%-2.6%.

(2) The ladder-type demand response subsidy mechanism between energy hub and users put forward in this paper could realize the deep combination with the optimal dispatch process based on building virtual storage. With the premise of not harming the users' benefit, it could reduce the operating expense of users by 2.9%-3.6%.

This paper focused on how to improve the economic performance of integrated energy system by utilizing the virtual energy storage characteristics of refined buildings and the demand response mechanism based on ladder subsidy, which has a certain guiding significance for practical application and theoretical exploration. Follow-up work will describe the response characteristics of different types of users as accurately as possible in the demand response model, and realize the detailed consideration of load.

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