An optimal dispatch model based on load aggregator associated with energy hub

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Abstract. With the open of demand side, the demand response will increase the flexibility of power system. As an intermediate between electricity market sellers and demand side users, load aggregator (LA) has more choices in the load shedding transactions with a large amount of demand side resources. This paper considers the impact of energy hub (including electricity energy and heat energy) to the trade strategy of load aggregator and proposes the trading framework of load aggregator based on energy hub (EH), then a load aggregator trading model based on transaction cost is established. Through the linear optimization with trading model, the transaction costs of load aggregator are compared whether the energy hub is used or not, and the influence of efficiency of different modules in energy hub on their supply proportion is analysed, and finally the trading strategy of load aggregator is studied when the demand side resources take part in load shedding.

1. Introduction

With the reform of Chinese power market, the flexibility of demand side attracts significant researches. Through the development of the demand response management (DRM) [1, 2], the security and reliability of power grid will be improved during the peak load period, and the demand side will benefit from the incentive price policy. However, due to the large scales of users and the difference of response capacities, the optimal dispatch of power grid will be challenging by the complexity of the dispatch model.

To cope with the high-order optimization problem, load aggregator (LA), a load management model, is established. The (LA) integrates the diversity of users while serving as the traditional electricity sale companies. The small and medium-sized users are unable to participate in market transactions because of their small response capacity. Through the role of load aggregators, they will be provided with opportunities for bilateral transactions, and hence the rate of system energy resource utilization will be improved. Reference [3] summarizes the opportunities and challenges brought by demand side resources the ancillary market. From the perspective of game theory, the reference [4] proposes a multi-layer structure based on load aggregator, which allows users to participate in the ancillary service market through the price incentive compatibility mechanism, so that both users and systems benefit. Reference [5] introduces different loads demand response, and comes up with the optimal bidding strategy in peak regulation market. In [6], the uncertainties of energy resources are introduced, and a Model Predictive Control (MPC)-based scheduling is proposed to obtain the optimal
LAs’ operation decision. In [7], considering participation of the demand response in the power wholesale market, the LA provides a variety of contract content for small and medium-sized users, and obtains the optimal strategy combination. In [8], through the interaction of source and load, the upper layer optimizes the cost of the system, and the lower layer optimize the scheduling of load shedding based on the active load power consumption characteristics.

Although load aggregator inspires the enthusiasm of demand side, the user's electricity experience is still affected, and the enthusiasm of demand response is greatly affected by the weather, which brings uncertainty to the optimization of power grid dispatching. It is urgent to find a better solution. With the concept of Energy Internet being put forward, researchers begin to study various energy-using modes in order to couple all kinds of energy networks, forming integrated energy networks and improving energy utilization efficiency. Among the research results, energy hub plays a vital role in realizing the transformation of multi-energy. Reference [9] gives a detailed analysis of the mathematical model of energy hub and its application in Energy Internet planning and scheduling. Reference [10] constructs a framework for multi-energy system to participate in ancillary service market, taking into account the power transfer potential of multi-energy system and the rate of return to participate in ancillary service market. Reference [11] proposes an energy hub transformation model based on adjustable hot spot ratio. On this basis, considering economic and environmental factors as the upper objective and unit efficiency as the lower objective, a double-level optimization model of micro-energy network is constructed. In [12], based on the smart grid technology and energy hub, a smart energy hub applied in thermoelctric coupled network is proposed. The Nash equilibrium of smart energy hub participating in the market is verified, and the bidding strategies of each hub are obtained through cases.

In this paper, the concept of energy hub and load aggregator is combined. During the normal operation, the operation costs of the dispatch model is optimized with the optimal energy flow ratio in the energy hub. When the system needs load shedding response from the load aggregator, the optimal operation costs can be achieved by directly signing the load shedding contract submitted by the users, or by changing the form of energy flow to meet the system load shedding requirement. The combination of the two concepts can overcome some shortcomings of traditional load aggregators in demand side response.

2. Optimization model
Two modular are contained in energy hub [13,14]: The single-input-single-output energy hub contains the auxiliary boiler (AB) and electric heat pump (EHP). The single-input-multi-output energy hub contains the combined heating and power (CHP). AB can convert the gas into heat and its heat conversion rate $\eta_A$ is highest among the EHP’s and CHP’s. CHP can convert the gas into heat and electricity with the efficiency of $\eta_{CHP}^{gh}$, $\eta_{CHP}^{ge}$, respectively. EHP can convert the electricity into the heat with the efficiency of $\eta_{EHP}^{eh}$.

![Figure 1. The structure of energy hub.](image-url)
The energy hub is composed of a variety of energy flow conversion models, such as the CHP, AB and EHP mentioned above. These modules communicate with each other to achieve collaborative work. The structure is as follows:

In figure 1, the blue lines represent the electricity, and the orange lines represent the heat. The mathematic model for describing the procedure of energy converting is as follows [9]:

\[
\begin{bmatrix}
L_1 \\
L_2 \\
\vdots \\
L_n
\end{bmatrix} =
\begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1m} \\
c_{21} & c_{22} & \cdots & c_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
c_{n1} & c_{n2} & \cdots & c_{nm}
\end{bmatrix}
\begin{bmatrix}
P_1 \\
P_2 \\
\vdots \\
P_m
\end{bmatrix}
\]

(1)

In equation (1), \( L_i \) represents the \( i \)th kind of energy of output. \( P_i \) represents the \( i \)th kind of energy of input. \( c_{ij} \) represents the transferring ratio of \( i \)th kind of energy into \( j \)th kind of energy.

The matrix form of equation (1) is as follows:

\[
L = CP
\]

(2)

As an energy hub, the CHP mathematic model [11] represents as equation (3):

\[
L_{CHP} = \begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} \alpha_g \eta_{CHP}^{ge} \\ \alpha_g \eta_{CHP}^{gh} \end{bmatrix} \begin{bmatrix} P_e \\ P_h \end{bmatrix}
\]

(3)

In equation (3), \( L_e \) represents the electricity output of CHP. \( L_h \) represents the heat output of CHP. \( P_g \) represents the gas input of CHP. \( \alpha_g \) represents allocation ratio of the total amount of gas into the CHP.

Same as the CHP, the EHP mathematic model [10] represents below:

\[
L_{EHP} = \eta_{EHP}^{eh} \begin{bmatrix} P_e \\ P_h \end{bmatrix}
\]

\[
L_{EHP} = \begin{bmatrix} \alpha_{CHP} \alpha_c \ (1 - \alpha_c) \eta_{EHP}^{eh} \end{bmatrix} \begin{bmatrix} P_e \\ P_h \end{bmatrix}
\]

(4)

In equation (4), \( L_{EHP} \) represents the output vector of EHP. \( \alpha_{CHP} \) represents the allocation ratio from CHP into EHP. \( \alpha_c \) represents the allocation ratio directly into the demand side. \( \eta_{EHP}^{eh} \) represents the equivalent thermoelectric conversion rate vector of EHP, the detailed mathematic model follows:

\[
\eta_{EHP}^{eh} = \eta_{EHP}^{eh} \begin{bmatrix} \eta_{CHP}^{ge} & 0 \\ 0 & 1 \end{bmatrix}
\]

(5)

For AB, the mathematic model [10] presents below:

\[
L_{AB} = (1 - \alpha_g) \eta_{AB}^{eh} \begin{bmatrix} P_e \\ P_h \end{bmatrix}
\]

(6)

In equation (6), \( L_{AB} \) represents the output vector of AB.

Combining the model of CHP, EHP and AB, the mathematic model of energy hub follows:

\[
E_{load} = \begin{bmatrix} \alpha_c & \alpha_g \ (1 - \alpha_{CHP}) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \eta_{EHP}^{eh} \end{bmatrix} \begin{bmatrix} P_e \\ P_h \end{bmatrix}
\]

(7)
\[ H_{\text{load}} = L_{AB} + [0 \ 1] L_{\text{CHP}} + L_{\text{EHP}} \]
\[ = \begin{bmatrix} (1 - \alpha_e) \eta^h_{EHP} & (1 - \alpha_g) \eta^{AB} \\ \alpha_g \eta^h_{\text{CHP}} + \alpha_{CHP} \alpha_g \eta^{ge}_{\text{CHP}} \eta^h_{EHP} \end{bmatrix} \begin{bmatrix} P_e \\ P_g \end{bmatrix} \]  

(8)

In equations (7) and (8), \( E_{\text{load}} \) represents the electricity demands and the \( H_{\text{load}} \) represents the heat demands, respectively.

Through the analysis and model constructing of the energy hub above, we can conclude that in a multi-energy system, even if the output energy is fixed, different schemes can be obtained through different energy allocation ratios, which facilitates the load aggregator. In the case of traditional load aggregator and system load-shedding contract, it is possible that the user cannot respond during peak period, which makes the contract unable to perform and LA will suffer losses. In the case of load aggregator with energy hub, the load aggregator will have a variety of solutions to solve this problem.

A mathematical model of load aggregator based on energy hub is established, which is as follows:

\[
\min \sum_{t=1}^{T} \sum_{i=1}^{I} \rho_{\text{da},e}^t P_{\text{da},e}^{in,t} + \rho_{rt,e}^t P_{rt,e}^{in,t} + \rho_{g}^t P_{g}^{in,t} + \rho_{ci}^t \Delta P_{i}^t \]
\[
\text{s.t.} \quad f(P) = 0 \quad \quad g(P) \leq 0 \quad \quad P \leq P \leq \bar{P} \]
\[
P = [P_{\text{da},e}^{in,t} \ P_{rt,e}^{in,t} \ P_{g}^{in,t} \ \Delta P_{i}^t] \]

(9)

In the equation (9), \( \rho_{\text{da},e}^t \) represents the trading price in day-ahead market, \( \rho_{rt,e}^t \) and \( \rho_{g}^t \) represents the price in real-time market and gas price, respectively. \( P_{\text{da},e}^{in,t} \) represents the trading electricity energy in day-ahead market. \( P_{rt,e}^{in,t} \) represents the trading electricity energy in real-time market. \( P_{g}^{in,t} \) represents the trading gas amount. \( \rho_{ci}^t \) represents the \( i \)th electricity contract price signed with demand side. \( \Delta P_{i}^t \) represents the \( i \)th electricity contract capacity. \( P \) represents the energy input vector.

In the equation (10), the inequality constraints are followed [9]:

\[
E_{\text{load}}^{t} - \sum_{i=1}^{I} \Delta P_{i}^t = \alpha_e P_{e}^{in,t} + \alpha_g (1-\alpha_{CHP}) \eta^{ge}_{\text{CHP}} P_{g}^{in,t} \]

(12)

\[
\begin{align*}
0 & \leq P_{\text{CHP}}^{in,t} \leq P_{\text{CHP}}^{\max} \\
0 & \leq P_{EHP}^{in,t} \leq P_{EHP}^{\max} \\
0 & \leq P_{BOI}^{in,t} \leq P_{BOI}^{\max}
\end{align*}
\]

(13)

Equation (12) represents the electricity balance between the supply and demand. Equation (13) represents the energy output limitation constraints of CHP, EHP and AB.

In the equation (10), the inequality constraints are followed [14]:

\[
(1 - \alpha_e) \eta^h_{EHP} P_{e}^{in,t} + \alpha_g \eta^{ge}_{\text{CHP}} \alpha_{\text{CHP}} \eta^h_{EHP} + \alpha_s \eta^h_{\text{g}} + (1-\alpha_g) P_{g}^{in,t} \eta^{AB} \geq H_{\text{load}}^{t} \]

(14)

Equation (14) represents the heat supply inequality constraints, considering the heat loss during the transportation.
3. Solution algorithm
The proposed mathematic model based on the combination of energy hub and LA is a non-linear optimization problem. The decision vector contains $X=[a, p]$. In this paper, through fixing the vector $a$ by Monte Carlo method, the non-linear optimization problem is transformed into mix-integer linear problem, then the problem is solved by MATLAB and CPLEX.

Step 1: Averagely generate $N$ groups of allocation ratio vector in the horizon of 0-1: $a_1, a_2, \ldots, a_N$. Initialize the iteration number $k$ and $k=1$;
Step 2: Import $a_k$ into the proposed model (2-9) - (2-14) and optimize the model by MATLAB and CPLEX. Keep the solution and corresponding objective in the array $RemK$;
Step 3: Judgement procedure. If $k>N$, go to the Step 4, else $k=k+1$, and go to the Step 2;
Step 4: Select the minimum value of objective of $RemK$ and the corresponding solution. Output.

4. Cases analysis
The case studies are implemented using MATLAB R2015b and CPLEX 12.8.0 on a Windows 10 Professional Intel i5-3210M CPU 2.5 GHz 8GB RAM.

The study case is based on actual user data in Henan Province. The winter load curve is contained in the figure 2. The value of $\eta_{CHP}^h$ is 0.35. The value of $\eta_{CHP}^e$ is 0.40. The value of $\eta_{AB}$ is 0.90. The value of $\eta_{EHP}^e$ is 0.5. The maximum limitation of power output of CHP is 50 MW. The maximum limitation of power output of EHP is 50 MW and the AB’s is 30 MW. The price of gas is 6.5$/kcf. The electricity price of day-ahead market and real-time market is selected from the PJM history data (AECO 30/12/2015).

![Figure 2. Curve of energy loads.](image1)

![Figure 3. Costs of purchasing electricity in two modes.](image2)

![Figure 4. Costs of purchasing natural gas in two modes.](image3)
From figures 3, 4 and 5, the total purchasing energy cost of LA with EH is less than the LA’s without EH at most time. During the 8-12 hours, the heat energy output of CHP and AB reaches the upper limitation, however, the supply supported by CHP and AB doesn’t meet the amount of demand, so the extra electricity is purchased to be converted into heat energy through EHP, which results the improvement of purchasing cost during the period.

Figure 5. Costs of purchasing natural gas in two modes.

Also, the gas purchasing cost of LA with EH is higher than the LA’s without EH. The main reason is the gas price is cheaper than the electricity price and the LA purchases the extra nature gas to support electricity loads with the assistant of conversion energy form of EH. In total, although the gas purchasing cost of LA with EH is higher, the total energy purchasing cost (2051.1072 M$) of LA with EH is still less than the LA’s without EH (2118.2873 M$).

The demand response and the load shedding contract are not discussed in the case study above. The following simulations will present the impact to dispatch scheme when considering load shedding contract with demand side.

Considering the participation of the demand side, the load aggregator collects the information of the demand side response before the operation day, including the amount of load shedding, available time, compensation price and so on. Subsequently, during the operation day, in order to meet the requirement of total amount of load shedding from independent system operator (ISO), the load aggregator optimizes the purchase cost of electricity, gas and the load shedding contracts.

It is assumed that three users sign the load shedding contract, and the information is assumed as follows, as shown in Table 1:

| Users | The mount of load shedding (MW) | available time (h) | compensation price ($/MW) |
|-------|-------------------------------|--------------------|---------------------------|
| 1     | 80                            | 7-10,12-14,17,20-22| 20                        |
| 2     | 60                            | 8-9,11-13,17,20-22 | 21                        |
| 3     | 100                           | 9-14,17,20-23      | 18                        |

The requirement amount of load shedding from ISO is bellowed as shown in Table 2:

| Time (h) | The mount of load shedding (MW) | Allocation ratio $\alpha_e$ | Equivalent amount of load shedding (MW) |
|----------|--------------------------------|-----------------------------|----------------------------------------|
| 11       | 220                            | 0.7                         | 154                                    |
| 12       | 250                            | 1                           | 250                                    |


From figure 6, the contracts of user 2 and user 3 are dispatched at 11:00, however, the amount of load shedding requirement is still higher than the summarization of contracts. In this situation, LA without EH cannot meet requirements of ISO and suffers losses. LA with EH can purchase natural gas in gas market to actively reduce the electricity purchasing amount and convert gas into the electricity to meet the vacancy of demand side.

5. Conclusions
Based on the multi-energy conversion characteristics of energy hubs, a transaction optimization model of load aggregator has been established. Relevant conclusions are drawn as follows. Energy hub helps reduce the cost of LA effectively through satisfying the power and heat demand locally. Also, LA with energy hub helps improve the power system reliability, especially for the peak load period. Moreover, electricity pricing mechanism plays a key role in LA’s trading strategy. Consequently, sensitivity of LA to the price of energies in the market need to be further studied.

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