Optimal utilization of load side power and heat resources based on aggregator mode

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Abstract. Combined cooling, heating and power system (CCHP) can realize the cascade utilization of energy and improve the energy utilization efficiency. Focusing on the phenomenon that the traditional self-sufficiency mode is easy to cause insufficient or excess regional energy supply, considering the complementarity between different regional load characteristics, an internal multi-region interconnected complementary energy supply method based on aggregator mode was proposed. In order to solve the problem of uncertainty in the optimal dispatching of multiple resources in the region under the aggregator mode, an optimal dispatching model based on interval linear programming was constructed, which took the minimum operation cost of aggregator as the objective function. The feasibility and effectiveness of the method are verified by analyzing the aggregator mode in residential area, commercial area, office area and industrial area. The results show that the operation cost can be reduced and the economic benefit can be improved under the aggregator mode.

1. Introduction

Combined cooling, heating and power system (CCHP) is a comprehensive energy system based on cascade utilization of energy, making the energy utilization rate as high as 70% - 90% [1]. Reference [2] summarized and analyzed the application status of CCHP in microgrid from the perspective of modeling, planning and energy management. Literature [3] optimized the economic dispatch of microgrids with the goal of minimizing production costs, environmental costs, and cooling, heating and power coordination costs. However, as the load characteristics of a single region are relatively single, it is easy to have some phenomenon of insufficient or excessive energy while meeting various load demands, which restricts the system optimization results to a certain extent [4].

Considering the complementary characteristics between different regional loads, the model of load aggregator can be adopted to manage several nearby regions, and the power balance among several regions can be realized through the interconnection and complementation of several regional energies, so as to achieve the purpose of improving economic benefits. Literature [5] elaborated on the load aggregator from the aspects of business, scheduling control strategy and operation mechanism. Literature [6] proposed a joint optimal scheduling model for multiple resources under the aggregator model, which considers the impact of uncertainties based on fuzzy chance constraints. Literature [7] solved the optimal scheduling problem under multiple uncertainties by building an optimal scheduling model based on interval programming and robust programming.
In this paper, several zones are jointly optimized for scheduling under the aggregator mode, and the interval linear programming method is adopted to transform the equality constraint into the interval form to construct the optimal scheduling model to solve the impact of uncertainty. A case study is conducted for the region containing four partitions to verify the feasibility and rationality of the model.

2. An aggregator optimization model based on interval linear programming

2.1. Interval linear programming model

The general form of interval linear programming model is as follows.

\[
\begin{aligned}
\min [f] &= [C][X] \\
\text{s.t.} [A][X] &\leq [B] \\
[X] &\geq 0
\end{aligned}
\]  

\( [f] = [f^-, f^+] \) is the optimal target value interval of the objective function. \( [C] = ([c^-, c^+]_{1 \times n}] \) is the coefficient matrix. \( [X] = ([x^-, x^+]_{1 \times n}] \) is the decision variable. \( [A] = ([a^-, a^+]_{m \times n}] \) is coefficient matrix in unequal constraints. \( [B] = ([b^-, b^+]_{m \times 1}] \) represents the prediction interval of photovoltaic output and cooling, heat and electrical load.

2.2. Optimization model

\[
\min F^i = \left( c_{\text{lp}} P_{\text{hp}}^{\text{max}} + c_{\text{rc}} S_{\text{r}}^{\text{max}} \right) T_e^{-1} + \sum_{t=1}^{T_e} \sum_{i=1}^{I} G_{\text{Mt},i}(t) c_{\text{gas}} + \sum_{t=1}^{T_e} P_{\text{grid, buy}}^i(t) c_{\text{elec}}(t) - \sum_{t=1}^{T_e} P_{\text{grid, sell}}^i(t) c_{\text{sell}}(t)
\]  

\( c_{\text{gas}} \) is the unit price of gas. \( c_{\text{elec}}(t) \) is the power purchase price of the grid. \( c_{\text{sell}}(t) \) is the price of electricity sold to the grid. \( G_{\text{Mt},i}(t), P_{\text{grid, buy}}^i(t) \) and \( P_{\text{grid, sell}}^i(t) \) are the interval value of gas purchase, electricity purchase and electricity sales respectively. \( c_{\text{lp}} \) and \( c_{\text{rc}} \) are the unit power cost and unit capacity cost of heat pump and heat storage device respectively. \( P_{\text{hp}}^{\text{max}} \) is the maximum power of heat pump. \( S_{\text{r}}^{\text{max}} \) is the maximum heat storage capacity of the heat storage device. \( T_e \) represents the life days of the heat pump and heat storage device.

2.3. Constraints

\[
0 \leq P_{\text{pv},i}^+(t) \leq P_{\text{pv},i}^{\text{max}}(t)
\]  

\( P_{\text{pv},i}^+(t) \) and \( P_{\text{pv}}^{\text{max}}(t) \) are the interval value of photovoltaic predicted output and the maximum generating power in the \( i \) area respectively.

\[
P_{\text{hp},i}^+(t) = P_{\text{lp}}^+(t) \mu_{\text{hp},i}
\]  

\[
0 \leq P_{\text{lp}}^+(t) \leq P_{\text{lp}}^{\text{max}}
\]  

\( P_{\text{hp},i}^+(t) \) and \( P_{\text{lp}}^+(t) \) are the heating power and electric power interval value of the heat pump respectively. \( P_{\text{lp}}^{\text{max}} \) is the maximum electric power of the heat pump. \( \mu_{\text{hp},i} \) is the heating efficiency.

\[
0 \leq h_{ce}^+(t) \leq h_{e}^{\text{max}}
\]  

\[
0 \leq h_{cd}^+(t) \leq h_{c}^{\text{max}}
\]
$h_{c,r}(t)$ and $h_{d,r}(t)$ are the power interval value of heat storage and heat release of heat storage device respectively. $h_{r}^\text{max}$ is the maximum storage (release) power of the heat storage device.

\[
S_r^+(t) = S_r^+(t-1) + \left( h_{c,r}(t) \eta_{c,r} - h_{d,r}(t) / \eta_{d,r} \right) \Delta t
\]

\[
0 \leq S_r^+(t) \leq S_r^\text{max}
\]

$S_r(t)$ is the heat storage in the heat storage device. $\eta_{c,r}$ and $\eta_{d,r}$ are the efficiency of heat storage and heat release respectively.

\[
0 \leq P^k_{\text{grid,buy}}(t) \leq P^\text{max}_{\text{grid}}
\]

\[
0 \leq P^k_{\text{grid,sell}}(t) \leq P^\text{max}_{\text{grid}}
\]

$P^\text{max}_{\text{grid}}$ is the maximum transmission power of the transmission line.

\[
P^\pm_{\text{MT,i}}(t) + P^\text{max}_{\text{PV,i}}(t) + P^\pm_{\text{grid,buy}}(t) \geq P^\pm_{\text{load,i}}(t)
\]

\[
P^\pm_{\text{grid,buy}}(t) + \sum_i P^\pm_{\text{MT,i}}(t) + \sum_i P^\pm_{\text{PV,i}}(t) = P^\pm_{\text{hp}}(t) + \sum_i P^\pm_{\text{load,i}} + P^\pm_{\text{grid,sell}}(t)
\]

$P^\pm_{\text{MT,i}}(t)$ is the power interval value of micro gas turbine in area $i$. $P^\pm_{\text{load,i}}(t)$ is the electric load interval value of area $i$.

\[
P^\pm_{\text{hp}}(t) - h_{c,r}(t) + h_{d,r}(t) + \sum_i Q^\pm_{\text{cool,i}}(t) = \sum_i H^\pm_{\text{load,i}}(t)
\]

\[
Q^\pm_{\text{r,c}}(t) = C^\pm_{\text{load,i}}(t)
\]

$Q^\pm_{\text{cool,i}}(t)$ and $Q^\pm_{\text{r,c}}(t)$ are the heating and refrigeration power output interval values in area $i$ respectively. $H^\pm_{\text{load,i}}(t)$ and $C^\pm_{\text{load,i}}(t)$ are the heat and cooling load interval values of area $i$ respectively.

### 3. Case study

#### 3.1. Data

In this paper, an area including residential zone, commercial zone, office zone and industrial zone is analyzed. The cooling and heating load and photovoltaic output of each zone are shown in [8]. Under the aggregator mode, the aggregator charge a certain fee to each zone. Then optimize the use of load-side resources through resource integration to ensure the energy consumption of each zone and obtain certain benefits. The fees charged by the aggregator to each zone are temporarily charged according to the cost of the optimal energy supply in each zone without the aggregator model. The time-of-use electricity price is used to purchase electricity from the grid [8], and the electricity sales price is 0.4 yuan/kWh for distributed on-grid. The price of natural gas is 2.05 yuan/m³. To improve the efficiency of energy utilization, the aggregator added a simple heat network within the area and configured a heat pump and a heat storage device. The parameters are shown in [9].

#### 3.2. No consideration of uncertainty

Without considering the fluctuation of cooling, heating and electric load in the area and the uncertainty of photovoltaic output, the unit output, power purchase and heat network heating of each zone is shown in figure 1. The negative ordinate in figure 1 represents the electrical or heating power delivered to the aggregator.
Figure 1. Power interaction between each zone and aggregator

Figure 1 shows the electrical and heating interaction power between the aggregator and each district. It can be seen from figure 1 that during most period of the night, each zone needs to be supplied by the aggregator with electric power and heating power. From figure 1(a), the industrial zone outputs electric power to the aggregator on the basis of meeting its own electrical load demand. Commercial and office zones need to be supplied with partial power by the aggregator each period, while residential zone needs to be supplied with partial power by the aggregators during peak load periods. The electric power between the industrial zone and the other three zones is complementary in the daytime. From figure 1(b), it can be seen that the three zones with heat load at night need to be supplied by the aggregator through the heating network. There is surplus heat input into the heat network in some periods. Apart from the industrial zone, the other zones need to be supplied with some heat by the aggregator. The heating power output in the industrial zone from 18:00 to 23:00 is larger than the heating power required by the other three zones. Therefore, under the aggregator mode, the heating power among the zones is complementary.

Figure 2. Power of heat pump and purchase under aggregator mode

Figure 2 shows the total amount of electricity the aggregator needs to purchase from or sell to the grid and the output of heat pumps and heat storage devices. From the figure that the aggregator purchases electricity from the grid during the valley periods of electricity price. In other periods, the internal micro-gas turbine optimizes the output to achieve the electric power balance in the zone. During the periods from 18:00 to 23:00, the overall heat load demand in the area decreases significantly. The heat pump is in non-operating state, and the surplus heat of the industrial zone would be stored on the basis of meeting part of the heat load demand of other zones.
3.3. Consider the uncertainty

Due to the volatility of photovoltaic power generation and the randomness of user-side load, this paper assumes that the fluctuation range of load and photovoltaic is [90%, 110%].

![Figure 3](image1.png)

Figure 3. Operation results of the sub-model $f^-$

![Figure 4](image2.png)

Figure 4. Operation results of the sub-model $f^+$

Figure 3 show the optimized operation results of each micro gas turbine and aggregator’s equipment in sub model $f^-$. Combined with figure 3(a) and figure 3(b), it can be seen that during the valley periods of electricity price, the electric load demand is mainly met by the aggregator purchasing from power grid. Since the generation cost of gas turbine is higher than the power purchase cost from power grid. The overall heat load demand at night is relatively low, relying on the heat network to use heat pump to meet the overall heat load demand. During the daytime, the electricity price is high, and the electric power balance is mainly achieved through the interaction of electric energy in the area. Since the electrical load in the commercial zone is higher than the heat load, if the micro-gas turbine in the commercial zone is operated at a higher power, the resources cannot be fully utilized. In the evening, the overall heat load decreases greatly. At this time, the electricity price is at its peak, and the heat pump is in a non-operating state in order to save electricity purchase cost. Except for residential zone, three zones are mainly used to meet the electrical load demand of the area. On the basis of meeting the heat demand of the area, part of the heat is stored for heat release when the heat load gap is large.

Figure 4 show the optimized operation results of each micro gas turbine and aggregator’s equipment in sub model $f^+$. By comparing the results of sub model $f^+$ and $f^-$, it can be seen that the power purchase and heat pump operation of the aggregator are less affected by the fluctuation of load and photovoltaic output. In the sub-model $f^+$, no electricity is sold to the grid from 11:00-12:00.
The non-operating periods of the heat pump are shortened from the five periods of 18:00-23:00 in the sub-model $f^-$ to two periods of 19:00-21:00. The other three periods run at low power. In sub model $f^+$, the cooling, heating and electrical loads are greater than that of sub model $f^-$, and the operation power of micro gas turbine in each zone increases.

Table 1. Operating costs in various cases

|                      | No consideration of uncertainty | Consider the uncertainty |
|----------------------|---------------------------------|--------------------------|
| cost/yuan            | 194 149.8                      | [169 065.1, 223 273.7]   |
| income/yuan          | 23 242.4                       | [-5 881.5, 48 327.1]     |

By comparing and analyzing the data in Table 2, when the fluctuation of load and photovoltaic output is not considered, the aggregator can have a yield of 10.7%. When the fluctuation of load and photovoltaic output is considered, the yield of the aggregator is [-2.7%, 22.2%]. When the volatility of load and photovoltaic output is considered, the yield of the aggregator is [-2.7%, 22.2%]. It can be seen that the aggregator has the possibility of loss, but the loss rate is not large and it is an abnormal extreme situation at this time, so it can be considered that the loss rate is far less than the yield.

4. Conclusions

- (1) Under the aggregator mode, economic benefits can be improved through the interconnection and complementation of energy between several regions.
- (2) The optimal solution of interval form based on interval programming can more truly reflect the impact of uncertainty on the income of the aggregator.
- (3) Under the aggregator mode, the loss rate is far less than the yield.

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