Day-ahead Scheduling of Park Integrated Energy System Considering the Demand Response

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Abstract. The Park Integrated Energy System (PIES) is essential to increase the economic energy supply for the coupling of multiple energy sources. Thus, this paper firstly analyzed the integrated demand response function of park energy users, and then constructed the optimal scheduling model of PIES aiming at the economy of PIES. Finally, an improved non-dominated scheduling genetic algorithm with elite strategy (NSGA-II) was proposed to solve the optimization problem. The results show that the model can effectively solve the optimal scheduling problem of PIES, and the integrated demand response can effectively improve the economic figure of PIES.

Keywords: Park Integrated Energy System, Integrated Demand Response, Economic Scheduling

1. Introduction
The park integrated energy system (PIES) can effectively increase the overall energy efficiency and operation economic efficiency of the system through complementary coupling between multiple energy sources [1-2]. Thus, the scheduling of the PIES considering the integrated demand response has become a key issue [3].

Literature [4] established a day-ahead economic dispatching model regarding to the randomness of wind power and users’ participation in the grid interactive response. Cases were used to verify the effectiveness of this day-ahead economic scheduling model in improving the system economic efficiency. Literature [5] established a security economic scheduling model considering the distribution switch status and the power-heat integrated demand response and verified its effectiveness with the IEEE 33-node system for the case analysis. Literature [6] studied the scheduling optimization model of the park microgrid under the multi-energy coordination and complementation as well as the power-heat integrated demand response. Literature [7] studied the optimal operation of the commercial building microgrid under the electric-thermal coupling. Literature [8] studied the optimal scheduling
of buildings considering the combined cooling-heating-power coupling and the demand response, and verified the economic efficiency. Literature [9] established a virtual power plant model aggregating the new energy power generation equipment, energy storage equipment, multi-energy coupling equipment and integrated energy load. Literature [10] proposed a new microgrid energy optimization scheduling strategy considering the incentive demand response with three time scales, namely, 24-hour ahead, 4-hour ahead and real-time.

The integrated demand-side response resources are conducive to the optimal allocation and scheduling of the PIES. Therefore, this paper first established the integrated demand-side response function of integrated energy users, then built an economic optimal scheduling model of the PIES. Finally, this paper solved the above model through the improved (NSGA-II). The integrated demand response can effectively increase the economic of the PIES dispatching.

2. Integrated Demand Response

The integrated demand response (IDR) in energy system includes the power demand response and the heat demand response. The power demand response contains two types: response based on energy price and response based on incentive.

2.1 Power Demand Response

The cost of the incentive power demand response is the economic compensation for the cluster users participating in the demand response, which is determined by the agreement signed by both parties. Generally, this cost function is a quadratic function. The specific expression is as follows:

$$C_{DR,i}(t) = \alpha_{DR,i} P_{DR,i}(t)^2 + b_{DR,i} P_{DR,i}(t)$$

(1)

$$P_{DR,i,min}(t) \leq P_{DR,i}(t) \leq P_{DR,i,max}(t)$$

(2)

Where $C_{DR,i}(t)$ indicates the demand response cost of the $i$-th incentive demand response cluster user in the $t$-th period; $P_{DR,i}(t)$ indicates the demand response reduced power of the $i$-th incentive demand response cluster user in the $t$-th period; $\alpha_{DR,i}$ indicates the quadratic coefficient of compensation amount of the $i$-th incentive demand response; $b_{DR,i}$ indicates the monomial coefficient of the compensation amount of the $i$-th incentive demand response. Among them: $P_{DR,i,max}(t)$ and $P_{DR,i,min}(t)$ indicate the largest and smallest of the demand response amount of the $i$-th cluster user in the $t$-th period. $P_{DR,i,min}(t)$ generally takes 0.

2.2 Heat Demand Response

Since the indoor temperature is allowed to fluctuate within a certain range without influencing the comfort level, it is necessary to properly reduce the expected indoor temperature in the peak load period and reduce the heat demand; to properly increase the indoor temperature during the low load period. When the scheduling period was set as 24 hours a day, the proper optimization of the expected indoor temperature at each time period was of great significance to increase the economic value and safety of the entire PIES. Based on the thermal model of buildings, the indoor temperature of users can be presented as follows:

$$T_{in}(t+1) = T_{in}(t) e^{-\Delta t/\tau} + \left[ R Q_{load}(t) + T_{out}(t) \right] \left[ 1 - e^{-\Delta t/\tau} \right]$$

(3)

$$\tau = R \times C_{air}$$

(4)

Where $T_{in}(t)$ and $T_{out}(t)$ indicate the indoor and outdoor temperature in the $t$-th period; $\Delta t$ indicates the calculation time step; $\tau$ indicates the heat dissipation time constant; $R$ indicates the thermal resistance.
of the building; $C_{\text{air}}$ indicates the indoor heat capacity; $Q_{\text{load}}(t)$ indicates the heating power in the $t$-th period; $T_{m,\text{max}}$ and $T_{m,\text{min}}$ indicate the highest and lowest acceptable indoor temperature.

The indoor temperature should also meet the upper and lower limit constraints as shown below

$$T_{m,\text{min}} \leq T_m(t) \leq T_{m,\text{max}}$$

(5)

The heat load in the determined indoor and outdoor temperature can be obtained in accordance with Formula (3), as shown below.

$$Q_{\text{load}}(t) = \frac{1}{R} \left[ \frac{T_m(t+1) - T_m(t) \cdot e^{-\Delta t} - T_{\text{out}}(t)}{1 - e^{-\Delta t}} \right]$$

(6)

The cost function of the heat demand response is similar to the cost function model of the power demand response, both of which are quadratic functions and will not be repeated here.

3. PIES Scheduling Model
A typical centralized PIES includes the power system, the thermal system and integrated load users. The power system includes the coal-fired thermal power unit and the combined heat and power unit (CHP). The thermal system includes the coal-fired heating boiler unit and the CHP unit and other heat sources. The load of integrated load user includes the electric load and the heat load. Each user can take part in the power demand response and the heat load has a certain flexibility. The day-ahead scheduling optimization method took 24 hours as a cycle and 1 hour as a step.

3.1 Objective Function
In this paper, the optimal scheduling period was 24h with 1 hour as the unit time interval. The PIES economic efficiency objective function is:

$$f_1 = \sum_{i=1}^{24} [C_{\text{CP}}(t) + C_{\text{CB}}(t) + C_{\text{CHP}}(t)] + \sum_{i=1}^{24} C_{\text{DR},i}(t)$$

(7)

$$C_{\text{CP}}(t) = F_{\text{CP}}(t) \times c_{\text{coal}}$$

(8)

$$C_{\text{CB}}(t) = F_{\text{CB}}(t) \times c_{\text{coal}}$$

(9)

$$C_{\text{CHP}}(t) = F_{\text{CHP}}(t) \times c_{\text{gas}}$$

(10)

where $f_1$ is the total dispatching cost of the PIES; $C_{\text{CP}}(t)$ indicates the dispatching cost of the coal-fired thermal power unit at the $t$-th period; $C_{\text{CB}}(t)$ indicates the operation cost of the coal-fired heating boiler unit in the $t$-th period; $C_{\text{CHP}}(t)$ indicates the operation cost of the CHP unit in the $t$-th period; $c_{\text{coal}}$ and $c_{\text{gas}}$ indicate the unit price of the standard coal and natural gas respectively.

The fuel consumption characteristics of the CHP unit are determined by the power generation and heating power of the unit, which is usually presented by the following formula:

$$F_{\text{CHP}}(t) = a_{\text{CHP},P} P_{\text{CHP}}^2(t) + b_{\text{CHP},P} P_{\text{CHP}}(t) + c_{\text{CHP},P} + a_{\text{CHP},H} Q_{\text{CHP}}^2(t) + b_{\text{CHP},H} Q_{\text{CHP}}(t) + c_{\text{CHP},H}$$

(11)

where $F_{\text{CHP}}(t)$ indicates the natural gas consumption of the CHP unit in the $t$-th period; $P_{\text{CHP}}(t)$ and $Q_{\text{CHP}}(t)$ indicate the power generation and heating power of the CHP unit in the $t$-th period; $a_{\text{CHP},P}$ and $a_{\text{CHP},H}$ indicate the quadratic coefficient of the power generation and heating power in their fuel consumption characteristics; $b_{\text{CHP},P}$ and $b_{\text{CHP},H}$ indicate the linear coefficient of power generation and
heating power in their fuel consumption characteristics; \( c_{\text{CHP,P}} \) and \( c_{\text{CHP,H}} \) indicate the constant of their fuel consumption characteristics.

The fuel consumption characteristics of the coal-fired thermal power unit are determined by the output of the unit in real time, which is usually presented by the quadratic function shown below:

\[
F_{CP}(t) = a_{CP} P_{CP}^2(t) + b_{CP} P_{CP}(t) + c_{CP}
\]

Where \( F_{CP}(t) \) indicates the standard coal consumption of the coal-fired thermal power unit in the \( t \)-th period, \( P_{CP}(t) \) indicates the power generation of the coal-fired thermal power unit in the \( t \)-th period, and \( a_{CP}, b_{CP}, c_{CP} \) indicate the quadratic coefficient, the linear coefficient and the constant of the fuel consumption characteristics, respectively.

The fuel consumption characteristics of the coal-fired heating boiler unit are also determined by the heating power of the unit in real time, which is usually presented by the following quadratic function:

\[
F_{CB}(t) = a_{CB} Q_{CB}^2(t) + b_{CB} Q_{CB}(t) + c_{CB}
\]

where \( F_{CB}(t) \) indicates the standard coal consumption of the coal-fired heating boiler unit in the \( t \)-th period, \( Q_{CB}(t) \) indicates the heating power of the coal-fired heating boiler unit in the \( t \)-th period, and \( a_{CB}, b_{CB}, c_{CB} \) indicate the quadratic coefficient, the linear coefficient and the constant of the fuel consumption characteristics, respectively.

3.2 Constraint Condition

The CHP unit constraints [11] are as shown in Formula (14). The CHP unit generates power by burning the natural gas. The exhausted high-temperature flue gas passes through the bromine cooler for heating.

\[
Q_{\text{CHP}}(t) = \frac{\eta^h \delta_{\text{CHP}} P_{\text{CHP}}(t)(1 - \eta^\text{MT} - \eta^l)}{\eta^\text{MT}}
\]

where \( Q_{\text{CHP}}(t) \) is the residual heat of the CHP unit in the \( t \)-th period; \( \eta^\text{MT} \) is the power generation efficiency of the micro-burner in the \( t \)-th period; \( \eta^l \) is the heat loss rate; \( \delta_{\text{CHP}} \) is the thermal coefficient of the bromine cooling mechanism; \( \eta^h \) is the flue gas recovery rate.

The output upper and lower limit constraints of the coal-fired thermal power unit, the coal-fired heating boiler unit and the CHP unit are shown below.

\[
P_{CP,\text{min}} \leq P_{CP}(t) \leq P_{CP,\text{max}}
\]

\[
Q_{CB,\text{min}} \leq Q_{CB}(t) \leq Q_{CB,\text{max}}
\]

\[
P_{\text{CHP,\text{min}}} \leq P_{\text{CHP}}(t) \leq P_{\text{CHP,\text{max}}}
\]

\[
Q_{\text{CHP,\text{min}}} \leq Q_{\text{CHP}}(t) \leq Q_{\text{CHP,\text{max}}}
\]

where \( P_{CP,\text{min}}, Q_{CB,\text{min}}, P_{\text{CHP,\text{min}}}, Q_{\text{CHP,\text{min}}} \) indicate the power supply of the coal-fired thermal power unit, the heating power of the coal-fired heating boiler unit, the power supply and heating power lower limits of the CHP unit. \( P_{CP,\text{max}}, Q_{CB,\text{max}}, P_{\text{CHP,\text{max}}}, Q_{\text{CHP,\text{max}}} \) indicate the power supply of the coal-fired thermal power unit, the heating power of the coal-fired heating boiler unit, the power supply and heating power upper limits of the CHP unit.
The upper and lower limit constraints of users’ incentive demand response are shown in equation (19).

\[ P_{DR,i,min}(t) \leq P_{DR,i}(t) \leq P_{DR,i,max}(t) \]  

Where \( P_{DR,i,min}(t) \) and \( P_{DR,i,max}(t) \) indicate the limits of the power demand response capability of the i-th cluster user in the t-th period.

The ramping rate constraints of the coal-fired thermal power unit, the coal-fired heating boiler unit and the CHP unit are as follows.

\[ V_{CP,min} \leq \frac{P_{CP}(t+1) - P_{CP}(t)}{T} \leq V_{CP,max} \]  
\[ V_{CB,min} \leq \frac{Q_{CB}(t+1) - Q_{CB}(t)}{T} \leq V_{CB,max} \]  
\[ V_{CHP,P,min} \leq \frac{P_{CHP}(t+1) - P_{CHP}(t)}{T} \leq V_{CHP,P,max} \]  
\[ V_{CHP,H,min} \leq \frac{Q_{CHP}(t+1) - Q_{CHP}(t)}{T} \leq V_{CHP,H,max} \]

Where \( V_{CP,min} \), \( V_{CB,min} \), \( V_{CHP,P,min} \), \( V_{CHP,H,min} \) indicate the power reduction rate limit of the coal-fired thermal power unit, the coal-fired heating boiler unit and the CHP unit. \( V_{CP,max} \), \( V_{CB,max} \), \( V_{CHP,P,max} \), \( V_{CHP,H,max} \) indicate the power increase rate limit of the coal-fired thermal power unit, the coal-fired heating boiler unit and the CHP unit.

The reserve constraint is a necessary for the security of the system, as shown below.

\[ P_{G,max} \geq P_{load}(t) \times (1 + k_r) \]  
\[ P_{G,max} = P_{CP,max} + P_{CHP,max} \]

Where \( P_{G,max} \) indicates the maximum output of the system power supply unit, \( k_r \) indicates the system reserve capacity coefficient.

At each scheduling moment in the scheduling cycle, the power and heat load balance of each user should be satisfied. The load balancing constraints are shown below.

\[ P_{CP}(t) + P_{CHP}(t) + \sum_{i=1}^{n} P_{DR,i}(t) = P_{load}(t) \]  
\[ Q_{CH}(t) + Q_{CHP}(t) = Q_{load}(t) \]

where \( P_{load}(t) \) and \( Q_{load}(t) \) indicate the predicted electric load and the predicted heat demand in the t-th period.

3.3 Solution Algorithm

The scheduling optimization model established in the paper was an optimization issue in terms of mathematical solution. The scheduling optimization model of the PIES had a large number of constraint conditions Therefore; this paper improved the above algorithm to solve the park comprehensive energy optimization model.
First, the constraint violation value was defined to quantitatively describe the degree of solution violation of the constraint. The equality and inequality constraints of the scheduling model can be indicated as follows:

\[
\begin{align*}
\begin{cases}
g_j(x) & \leq 0, \quad j = 1, 2, \ldots, J \\
h_k(x) & = 0, \quad k = 1, 2, \ldots, K
\end{cases}
\end{align*}
\]  

(28)

Where \( x \) indicates the solution matrix composed of various optimization variables, \( J \) and \( K \) indicate the number of constraint conditions in various forms.

Secondly, the constraint violation value was defined to quantitatively describe the degree to which a solution violated the constraint condition. Taking the solution matrix as an example, the constraint violation value of the solution can be indicated as follows:

\[
CV(x) = \sum_{j=1}^{J} \left| g_j(x) \right| + \sum_{k=1}^{K} \left| h_k(x) \right|
\]  

(29)

Where \( e < g_j(x) > \) indicates that if \( g_j(x) < 0 \) or \( g_j(x) = 0 \), its value is 0, if \( g_j(x) > 0 \), its value is itself. If the constraint violation indicator of a solution is 0, the solution fully satisfies the constraint condition and is feasible; if the constraint violation indicator of a solution is more than 0, the solution is infeasible.

Finally, the constrained dominance relationship was adopted to change the non-dominated sorting method. The dominance relationship was determined by the individual constraint violation value.

4. Case Analysis

4.1 Case Scenario and Data

To verify the model proposed in this paper, a PIES in a northern place in China was selected. The test took 24 hours as the scheduling period with 1 hour as the unit scheduling time. The performance indicators and economic parameters of the key power and heating equipment of the PIES system are listed in Table 1.

| Equipment | Parameter | Value |
|-----------|-----------|-------|
| Power Generation of Combined Heat and Power Unit | Quadratic Coefficient | 0.0006 |
| | Monomial Coefficient | 0.25 |
| | Constant | 2 |
| | Largest Output | 100MW |
| | Smallest Output | 30MW |
| Heat Generation of Combined Heat and Power Unit | Quadratic Coefficient | 0.0002 |
| | Monomial Coefficient | 0.1 |
| | Constant | 2 |
| | Largest Output | 300MW |
| | Smallest Output | 0 |
| Coal-Fired Heating Boiler Unit | Quadratic Coefficient | 0.0004 |
| | Monomial Coefficient | 0.1 |
| | Constant | 3 |
| | Largest Output | 200MW |
| | Smallest Output | 50MW |
| Coal-Fired Thermal Power Unit | Quadratic Coefficient | 0.0005 |
| | Monomial Coefficient | 0.3 |
Figure 1 shows the electric load prediction curve of various types of users. In this case, six cluster users participating in the grid demand response were set up, which can be divided into residential, commercial, and industrial cluster users. There were two demand response users of each type. The quadratic coefficient of the demand response cost function was 20 and the monomial coefficient was 500. The equivalent thermal resistance $R$ of the building was set to 0.2 $°C/MW$, and the heat dissipation time constant was set to 2 hours.

After investigation, the demand response time period and the agreed response volume of three different types of loads can be seen in Table 2.

**Table 2. Demand response periods and response volumes**

| User          | Response Time   | Agreed Response Volume (MW) |
|---------------|-----------------|-----------------------------|
| Residential 1 | 8:00–20:00      | 2                           |
| Residential 2 | 8:00–20:00      | 2                           |
| Commercial 1  | 8:00–20:00      | 1                           |
| Commercial 2  | 8:00–20:00      | 1                           |
| Industrial 1  | 8:00–20:00      | 3                           |
| Industrial 2  | 1:00–24:00      | 3                           |

4.2 Optimization Results and Analysis
Two running scenarios were set in the case to verify the proposed model. Scenario 1 optimized the scheduling without considering the power-heat integrated demand response; Scenario 2 optimized the
scheduling considering the power-heat demand response. The optimized scheduling results between two scenario were compared to verify the effectiveness of the model proposed in this paper.

The optimal solutions in the two scenarios were selected for comparison, as shown in Table 3. From the analysis and comparison of the above table, it illustrates the Scenario 2 considering the demand response improved the optimal result by 1.2%, indicating that the integrated demand response is helpful to improve the optimal dispatching of PIES.

Table 3. Comparison of Optimization Results in Two Scenarios

| Scenario | Economic Efficiency/Yuan |
|----------|--------------------------|
| Scenario 1 | 1692972 |
| Scenario 2 | 1673737 |

5. Conclusion
To solve the scheduling optimization of the PIES, this paper analyzed the power demand response and the heat demand response method of users and proposed the optimal scheduling model for the PIES. The improved NSGA-II algorithm was used to solve the math problem and the case analysis was used to verify that the model can be used to analyze the scheduling of the PIES so as to provide the optimal scheduling scheme. Compared with the optimal scheduling not considering the power-heat integrated demand response, the model proposed in this paper improved the economic efficiency of PIES by 1.2%. It can be concluded that the power-heat integrated demand response can effectively improve the economic efficiency of the PIES.

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