Research on Rolling Optimal Scheduling Model of Integrated Energy System for Park Energy Internet

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Abstract. As the physical carrier of the energy internet, the reasonable scheduling of the integrated energy system has become the focus of current research. In this paper, based on the demand for energy internet construction, renewable energy and demand-side load fluctuations are considered, and the price-type and substitution-type demand side response characteristics are utilized to establish day-ahead and intra-day optimization scheduling model, which takes into account the demand side response. According to the difference of electricity, cold/heat and gas dispatching time, a three-layer rolling optimal dispatching model is proposed. The case study shows that the multi-time scale optimal scheduling model with demand-side response can restrain the fluctuation of intraday renewable energy and load, improve the stability of the system, and further reduce the operating cost of the system.

1. Introduction

Since the 21st century, energy consumption and global environmental problems have become increasingly prominent, and many countries are seeking for the transformation of the energy industry [1-2]. Integrated Energy System (IES), a modern energy system with electric power system as the core and cold/hot natural gas system Integrated, has become the focus of research [3]. IES can meet users' energy needs and improve energy efficiency. However, the randomness of renewable energy and the volatility of demand-side loads make it harder to operate and manage IES. Therefore, the research on IES with multiple time scales of demand-side response is of great significance to the optimization of China's energy consumption structure and the construction of a low-carbon society [4].

In order to achieve reasonable scheduling of IES and reduce operating costs, existing researches mainly focus on multi-energy coupling, multi-time scale and demand-side response for scheduling analysis. In [5], a regional IES joint scheduling model containing renewable energy, CCHP and energy storage systems is established, and finally the model is solved by Cplex solver. In the literature [6], the authors consider multiple types of power generation and energy storage constraints to establish an operation model containing renewable energy and multiple energy forms of cooling, heating and power, to achieve comprehensive utilization and collaborative optimization of multi-energy flows. The existing
researches have established a day-ahead and intra-day scheduling model, but there are few researches focusing on the difference of different energy scheduling times within a day.

To address the above issues, this paper takes into account the advantages of demand-side response to establish an intra-day receding horizon optimal scheduling model. According to the difference in scheduling time of electric cooling/heating and other energy sources, the model establishes an intra-day optimization model including three sub-layers of slow control, intermediate control and fast control, which effectively suppresses the intra-day forecast errors and realizes the economic and stable operation of the system.

2. Multi-time scale optimal operation model of integrated energy system

2.1. Structural diagram of the regional IES.

The structural diagram of the regional IES is shown in Fig. 1. The generation side includes air conditioning (AC), combined cooling heating and power (CCHP), including micro-gas turbine (MT), waste heat boiler (WHB), absorption refrigerator (AR) and other cold sources, gas boiler (GB), electric boiler (EB) and other heat sources, power grid, wind turbine (WT), photovoltaic (PV), fuel cell (FC) and other power sources, natural gas network, power to gas (PtG) and other gas sources. The network side includes transmission and distribution, heating/cooling, gas supply and other networks. The storage side includes energy storage (ES), cold energy storage (CS), heat storage (HS), gas storage (GS) and other power storage, cold/heat and gas storage equipment. The demand side includes cold/heat, electricity, gas and other loads.

![Figure 1. Regional IES operational structure.](image)

2.2. Intra-day rolling optimal scheduling.

Intra-day rolling optimal scheduling has three control sub-layers: the slow control sub-layer is used to optimize the scheduling of cold/heat load with a long duration, the control time domain $k_1$ is 1h, and the scheduling time window is 2h. The intermediate control sub-layer is used to optimize the natural gas energy with shorter scheduling time. The control time domain $k_2$ is 30min and the scheduling time window is 1h. The fast control sub-layer is used to optimize the power with the shortest scheduling time. The control time domain $k_3$ is 5min and the scheduling time window is 30min.
As shown in Fig. 2, during the control period \( t_0 \), the system predicts the cold/heat energy from \( t_0 + 1 \) to \( t_0 + 3 \) and adjusts the power from \( t_0 + 1 \) to \( t_0 + 2 \); predicts the natural gas energy from \( t_0 + k_2 \) to \( t_0 + k_2 + 1 \) and adjusts the power from \( t_0 + k_2 \) to \( t_0 + k_2 + 1 \); predicts the cold/heat energy from \( t_0 + k_3 \) to \( t_0 + k_3 + 1 \) and adjusts the power from \( t_0 + k_3 \) to \( t_0 + 2k_3 \).

1) Slow control sub-layer scheduling model
Follow the day-ahead MT operating status and cold/heat energy scheduling strategy, and adjust the output of each unit of the system according to the changes in the cold/heat load during the period \( t \).

The objective function is:

\[
F_1 = \min \sum_{i=r}^{k+k} (F_{g,i} + F_{e,i})
\]

The cost of natural gas is:

\[
F_{g,i} = R'_{gas} \left( F_{MT}^T + \Delta F_{MT}^T + F_{GB}^T + \Delta F_{GB}^T \right) + \mu_{MT} \left( \Delta P_{MT}^T \right)^2 + \mu_{GB} \left( \Delta P_{GB}^T \right)^2 \Delta t
\]

where \( R'_{gas} \) is the unit price of natural gas in \( t \) period; \( \Delta F_{MT}^T, \Delta F_{GB}^T \) are the consumption changes of MT and GB respectively in \( t \) period,; \( \mu_{MT}, \mu_{GB} \) are the unit adjustment cost of MT and GB; \( \Delta P_{MT}^T, \Delta P_{GB}^T \) are the MT and GB adjustment power in \( t \) period; \( \Delta t \) is the unit dispatch period.

The cost of electrical equipment change is:

\[
F_{e,i} = \mu_{EB} \left( \Delta P_{EB}^T \right)^2 \Delta t + \mu_{AC} \left( \Delta P_{AC}^T \right)^2 \Delta t
\]

where \( \mu_{EB}, \mu_{AC} \) are the unit adjustment cost of EB and AC; \( \Delta P_{EB}, \Delta P_{AC} \) are the adjustment power of EB and AC in \( t \) period.

There are also cooling/heating supply and demand balance constraints and related coupling equipment.

2) Intermediate control sub-layer scheduling model
Follow the day-ahead GS suction and discharge conditions, and adjust the output of each unit of the system according to the natural gas load in the time period \( t \) and the equipment changes in the slow control layer.

The objective function is:

\[
F_2 = \min \sum_{t=k}^{k+k} (F_{g,2} + F_{e,2})
\]

The cost of interaction with the natural gas network is:

\[
F_{g,2} = R'_{gas} \left( C_{source}^T + \Delta G_{source}^T \right) \Delta t
\]
Where $\Delta G_{source}^t$ is the amount of change in the power of interaction with the natural gas network during $t$ period.

The cost of electrical equipment change is:

$$F_{e,2} = \mu_{PtG} \left( \Delta P_{PtG}^t \right)^2 \Delta t$$

(6)

Where $\mu_{PtG}$ is the unit adjustment cost of PtG; $\Delta P_{PtG}^t$ is the adjustment power of PtG during $t$ period.

There are also natural gas supply and demand balance constraint and power constraint of interaction with the natural gas source.

3) Fast control sub-layer scheduling model

Follow the day-ahead ES charging and discharging state, according to the fluctuation of the new energy in the time period $t$ and the power changes of the demand side and the above two sub-layers, the day-ahead scheduling is revised.

The objective function is:

$$F_3 = \min \sum_{i=1}^{k+1} (F_{e,3} + F_{g,3} + F_{ES})$$

(7)

The cost of interaction with the grid is

$$F_{e,3} = \left[ R_{grid}^t \left( P_{grid}^t + \Delta P_{grid}^t \right) + \mu_{grid} \left( \Delta P_{grid}^t \right)^2 \right] \Delta t$$

(8)

Where $R_{grid}^t$ is the electricity price in period $t$; $\Delta P_{grid}^t$ is the amount of change in the interactive power with the grid in period $t$; $\mu_{grid}$ is the adjustment cost of the interactive power unit.

The cost of natural gas is:

$$F_{g,3} = \left[ R_{gas}^t \left( F_{FC}^t + \Delta F_{FC}^t \right) + \mu_{FC} \left( \Delta F_{FC}^t \right)^2 \right] \Delta t$$

(9)

Where $\Delta F_{FC}^t$ is the change in consumption during $t$ period; $\mu_{FC}$ is the FC unit adjustment cost; $\Delta P_{FC}^t$ is FC adjustment power during $t$ period.

The ES charge and discharge change cost is

$$F_{ES} = \mu_{ES} \left[ \left( \Delta P_{c}^t \right)^2 + \left( \Delta P_{f}^t \right)^2 \right] \Delta t$$

(10)

Where $\mu_{ES}$ is the ES unit adjustment cost; $\Delta P_{c}^t, \Delta P_{f}^t$ are the ES charging and discharging adjustment power in $t$ period.

The power supply and demand balance constraint and the power constraint for interaction with the grid will not be repeated here.

### 3. Demand side response strategy of integrated energy system

The introduction of demand-side response can change the user’s energy consumption behavior curve, reduce system operating costs and improve system operating efficiency. In this paper, the load in the system is divided into traditional load and energy coupling load. Traditional loads are classified into unavoidable loads and price-based loads according to their sensitivity to prices, such as some electrical loads in this paper. Energy coupling loads can be replaced by other energy sources to achieve the same energy effect, such as all loads in this paper, which is called alternative loads. In order to reduce the complexity of the model, the influence of the alternative load on the price response is not considered in this paper.
3.1. Price-based demand response

The widely used electricity price-elasticity matrix is used to solve the demand side electricity load, and the amount of electricity consumption relative to the corresponding price change, to obtain the elasticity coefficient of the electricity price.

The self-elasticity coefficient \( \eta_{aa} \) represents the response of electricity to changes in electricity prices at that time, and the cross-elasticity coefficient \( \eta_{ab} \) represents the response of electricity to changes in electricity prices in other periods.

\[
\Delta q_{pq} / \Delta p_q = \eta_{aa} \quad \text{where a and b represent different time periods.}
\]

\[
\Delta q_{pq} / \Delta p_q = \eta_{ab} \quad \text{where a and b represent different time periods.}
\]

Therefore, the following equation holds for the period 1 to n.

\[
\begin{bmatrix} \Delta q_1 & \Delta q_2 & \ldots & \Delta q_n \\ q_1 & q_2 & \ldots & q_n \end{bmatrix}^T = E_q \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \\ \ldots \\ \Delta p_n \end{bmatrix}
\]

where \( E_q \) is the electricity price-elasticity matrix.

The total power \( q_z \) after the demand side response is:

\[
q_z = q_s + \Delta q_n = \left[ q_1 \cdots q_n \right] + \left[ q_1 \cdots q_n \right] E_q \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \\ \ldots \\ \Delta p_n \end{bmatrix}
\]

where \( q_s \) is the load power in the n periods before the demand side responds, \( \Delta q_n \) is the load power change in the n periods after the demand side responds.

Considering that natural gas has the same commodity attributes as electric energy, the method of calculating the natural gas load is obtained by analogy with the time-of-use electricity price method of the above electric load.

The natural gas self-elasticity coefficient \( \omega_{aa} \) and cross-elasticity coefficient \( \omega_{ab} \) are:

\[
\omega_{aa} = \frac{\Delta g_s}{\Delta r_s} 
\]

\[
\omega_{ab} = \frac{\Delta g_s}{\Delta r_s}
\]

Therefore, there are the following equations for the period 1-n:

\[
\begin{bmatrix} \Delta g_1 & \Delta g_2 & \ldots & \Delta g_n \\ g_1 & g_2 & \ldots & g_n \end{bmatrix}^T = E_g \begin{bmatrix} \Delta r_1 & \Delta r_2 & \ldots & \Delta r_n \\ r_1 & r_2 & \ldots & r_n \end{bmatrix}
\]

where \( E_g \) is the natural gas volume and price matrix.

The total amount of natural gas \( g_z \) after the demand side response is obtained:
\[ g_s = g_n + \Delta g_n = \left[ g_1, \cdots, g_n \right] E_s \left[ \frac{\Delta r_i}{r_i}, \cdots, \frac{\Delta r_n}{r_n} \right] \]  

(18)

where \( g_s \) is the load natural gas volume \( n \) period before the demand side response; \( \Delta g_n \) is the change value of the load natural gas volume \( n \) period after the demand side response.

3.2. Alternative demand response

In IES, energy sources such as electricity, natural gas, and cold/heat can be converted between different energy sources through related coupling devices. Users can use other energy sources to replace the required energy, so that the system can operate more stably. The conversion between energy sources follows the law of conservation of energy. The alternative demand response conversion relationship is described as follows:

\[ \Delta R_i = -\gamma_{i,j} \Delta R_j \]  

(19)

\[ \gamma_{i,j} = \frac{W_i \cdot \eta_i}{W_j \cdot \eta_j} \]  

(20)

\[ \Delta R_i^{\min} \leq \Delta R_i \leq \Delta R_i^{\max} \quad s = i, j \]  

(21)

where \( i \) and \( j \) represent two kinds of energy in electricity, natural gas, cold and heat; \( \Delta R_i, \Delta R_j \) are the load increments of certain two kinds of energy; \( \gamma_{i,j} \) is the conversion coefficients between energies; \( W_i, W_j \) are the unit heat of energy \( i \) and \( j \); \( \eta_i, \eta_j \) are the utilization rates of energy \( i \) and \( j \) respectively; \( \Delta R_i^{\min}, \Delta R_i^{\max} \) are the minimum and maximum load increments of energy \( i \) and \( j \).

The electric, natural gas, and cold/heat substitute load after response can be obtained by:

\[ L_i = L_i^0 + \Delta L_i \]  

(22)

where \( L_i^0 \) represents the alternative load before response, \( \Delta L_i \) represents the change in load response.

In order to ensure that the load in the above system does not increase or decrease, and to meet user requirements, the load conversion volume balance constraint is introduced:

\[ \sum_{i=1}^{N} \Delta L_i = 0 \]  

(23)

where \( N \) represents the collection of all types of energy in energy coupling.

4. Case Study

4.1. Parameter setting

This article selects a certain area IES for analysis. The system structure is shown in Fig. 1. The self-elasticity coefficient of electricity price is selected to be -0.2. The cross-elasticity coefficient is selected to be 0.03. The self-elasticity coefficient of price-based natural gas is -0.58. The cross-elasticity coefficient is 0.15. The IES operating parameters are shown in Table 1. The time-of-use electricity price is shown in Table 2. The natural gas time-of-use price is shown in Table 3. The parameters of each energy storage system are shown in Table 4.

| Type | \( P_{\text{min}} \) / kW | \( P_{\text{max}} \) / kW | Type | \( P_{\text{min}} \) / kW | \( P_{\text{max}} \) / kW |
|------|-------------------|-------------------|------|-------------------|-------------------|
| MT   | 15                | 60                | AR   | 10                | 30                |
| GB   | 0                 | 50                | WHB  | 10                | 35                |
| AC   | 0                 | 45                | PtG  | 0                 | 20                |
| EB   | 0                 | 50                | Grid | -80               | 80                |
Table 2. Time-of-use price

| Period     | Time                  | Power purchase price (yuan/kWh) | Power selling price (yuan/kWh) |
|------------|-----------------------|---------------------------------|-----------------------------|
| Peak period| 10:00-15:00 18:00-21:00| 1.1                             | 0.76                        |
| Normal time| 07:00-10:00 15:00-18:00 21:00-23:00| 0.8                             | 0.56                        |
| Valley time| 00:00-07:00 23:00-24:00     | 0.5                             | 0.35                        |

Table 3. Time-sharing natural gas price

| Period     | Time                  | Gas purchase price(yuan/m³) |
|------------|-----------------------|-----------------------------|
| Peak period| 08:00-12:00 16:00-19:00| 2.2                         |
| Normal time| 06:00-08:00 12:00-16:00 19:00-22:00| 2.1                         |
| Valley time| 22:00-06:00            | 1.2                         |

Table 4. Parameters of each energy storage system

| Parameter | Electric energy storage | Gas energy storage | Cooling energy storage | Heating energy storage |
|-----------|-------------------------|--------------------|------------------------|------------------------|
| $C_{ES,AC}$ | 0.25                    | 0.25               | 0.25                   | 0.25                   |
| $C_{ES,EB}$ | 0.25                    | 0.25               | 0.25                   | 0.25                   |
| $\lambda_{min}$ | 0.2                     | 0.1                | 0.1                    | 0.1                    |
| $\lambda_{max}$ | 0.8                     | 0.8                | 0.8                    | 0.8                    |
| $C_{ES}$ | 150                     | 150                | 100                    | 100                    |

Fig. 3 Multi-time scale optimization results

4.2. Intra-day rolling optimal scheduling analysis

The results of day-ahead and intra-day optimal scheduling are shown in Fig. 3. The output of coupling equipment and the interactive power between electrical and external network are revised in intra-day period. The interacting power curve with the grid fluctuates with changes of the electricity price, and the electricity purchased during peak hours is significantly reduced to achieve better economic efficiency. Natural gas, which has a longer scheduling time than electric energy, drives MT to generate
electricity when the electricity price is high, so as to maintain the system's supply and demand balance. The day-to-day optimization of cold/heat energy with an hourly scheduling time scale is more accurate, and the output of equipment will also change.

5. Conclusions
Based on the characteristics of price-based and alternative demand-side response, this paper considers the differences in scheduling time of electricity, cooling/heating and gas, and proposes an IES multi-time-scale optimization scheduling model taking into account the demand-side response. The following conclusions are drawn:

Demand-side response is related to the scheduling efficiency of IES. When the system is scheduled in accordance with the model proposed in this paper, its operating cost is optimal, which can better reflect the advantages of demand-side response.

The multi-time scale optimization scheduling of IES, on the basis of day-ahead optimization results, the intra-day optimization further shortens the time scale, improves the accuracy of system decision-making.

The intra-day three-layer rolling optimal scheduling model can dispatch electricity, cold/heat and gas on different time scales, so that the fluctuation of supply and demand can be suppressed and the stable operation of the power system can be guaranteed.

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