Optimal Dispatch of Integrated Energy System Considering Demand Response and Load Inertia

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Abstract. Renewable energy has the characteristics of strong anti-peak regulation and uncertainty, which cause severe challenges to system peak shaving and renewable energy accommodation. To cope with the challenges of system peak shaving and renewable energy accommodation, this paper proposes an optimal dispatch model of integrated energy system (IES), which considers the price-based demand response and load inertia. Firstly, the impact of changes in energy price on users' energy consumption is analyzed, and the cool and heat loads inertias are considered in their unbalanced constraints. Secondly, the objective function of the minimum operation costs of the IES is established, including the penalty cost of wind power and photovoltaics curtailments, and operation costs. Finally, the optimal dispatch model of IES is established and solved by YALMIP and GUROBI, respectively. The proposed model is compared with other conventional models. The accommodation capacity of renewable energy with the proposed model is enhanced.

1. Introduction

Renewable energy power accommodation is limited due to its uncertainty [1]. Peak loads are shifted to the valley with the demand response and the cooling and heating loads inertias in the integrated energy system (IES) [2]. Therefore, it is of great significance to study the impact of demand response and heat and cool loads inertias on improving renewable energy accommodation in the IES.

Users adjust their energy consumption behaviors and habits according to changes in energy price with the demand response [3]. The effect of electricity price demand response on users’ electricity consumption behaviors is analyzed [4]. However, the effects of gas price changes on user gas consumption and renewable energy accommodation are not considered. References [5] study the effect of gas price on user gas consumption behaviors, but the effects of gas price changes on user electricity consumption are not studied. Reference [6] analyzed the impact of changes in gas price on user electricity consumption and electricity price on user gas consumption. However, the impact of price-based demand response on renewable energy accommodation is not studied.

The supply and demand of the cool and heat loads can be staggered in time with the cool and heat loads inertias [7]. The supply and demand of the cool and heat loads are balanced at all times, which limits the renewable energy accommodation [8]. References [9] study the effects of the cool and heat loads inertias on the renewable energy accommodation and the operation costs of the IES. However, the effects of price-based demand response and cool and heat loads inertias on renewable energy accommodation and operation costs of the IES are not studied.
On the basis of the abovementioned studies, in this paper, we propose an optimal dispatch model of IES that considers the demand response and load inertia to enhance renewable energy accommodation. The effects of demand response and load inertia on renewable energy accommodation are fully considered.

2. Optimal dispatch model

2.1 Price-based demand response

The price-based demand response includes self-price elasticity and cross-price elasticity demand response. The electric load demand response is obtained by (1).

\[ P_{{el,t}}' = P_{{el,t}} + \Delta P_{{el,t}} \]  

where \( P_{{el,t}}' \) is the electric load demand, \( P_{{el,t}} \) is the electric load demand without demand response, and \( \Delta P_{{el,t}} \) is the electricity price-based load changes.

The gas load demand response is expressed by (2).

\[ P_{{gl,t}}' = P_{{gl,t}} + \Delta P_{{gl,t}} \]  

where \( P_{{gl,t}}' \) is the gas load demand, \( P_{{gl,t}} \) is the gas load demand without the demand response, and \( \Delta P_{{gl,t}} \) is the price-based load changes.

The elastic loads can be shown in (3).

\[ \Delta P_{{el,t}} = \Delta P_{{el,t}}' + \Delta P_{{el,t}}'' \quad \Delta P_{{gl,t}} = \Delta P_{{gl,t}}' + \Delta P_{{gl,t}}'' \]  

where \( \Delta P_{{el,t}}' \) and \( \Delta P_{{el,t}}'' \) are the self-price and cross-price elastic electric load change, \( \Delta P_{{gl,t}}' \) and \( \Delta P_{{gl,t}}'' \) are the self-price and cross price elastic gas load change.

The relationship between load changes and price changes are shown in (4)-(5).

\[ \Delta P_{{el,t}} = P_{{el,t}}' \epsilon_{{el}}' \frac{\Delta P_{{ec,t}}}{P_{{ec,t}}} \quad \Delta P_{{el,t}} = P_{{el,t}}' \epsilon_{{el}}'' \frac{\Delta P_{{ec,t}}}{P_{{ec,t}}} \]  

\[ \Delta P_{{gl,t}} = P_{{gl,t}}' \epsilon_{{gl}}' \frac{\Delta P_{{gc,t}}}{P_{{gc,t}}} \quad \Delta P_{{gl,t}} = P_{{gl,t}}' \epsilon_{{gl}}'' \frac{\Delta P_{{gc,t}}}{P_{{gc,t}}} \]  

where \( \epsilon_{{el}}' \) and \( \epsilon_{{el}}'' \) are the self-price and cross-price elasticity matrix of electric load, \( \epsilon_{{gl}}' \) and \( \epsilon_{{gl}}'' \) are the self-price and cross-price elasticity matrix of gas load, \( \Delta P_{{ec,t}} \) is the electricity price change in period \( t \), \( P_{{ec,t}} \) is the electricity price in period \( t \) without demand response, \( \Delta P_{{gc,t}} \) is the gas price change in period \( t \) and \( P_{{gc,t}} \) is the gas price in period \( t \) without demand response.

2.2 Load inertia

The actual temperature of heat load may be higher or lower than the standard temperature, due to the heat inertia. The heat power of the heating system considering thermal inertia is limited by (6).

\[ \mu P_{{hl,t}} \leq P_{{hl,t}} \leq \nu P_{{hl,t}} \]  

where \( P_{{hl,t}} \) is the heat power of the heating system at time \( t \), \( \mu \) and \( \nu \) are the inertia coefficients of the heating system, \( P_{{hl,t}} \) is the heat power load.

The elasticity of human thermal comfort can be expressed by the predicted mean vote (PMV) index. The PMV index calculation formula is expressed by (7).

\[ \lambda_{{PMV}} = 2.43 \frac{3.76(t_{{c,t}} - t_{{e,t}})}{M(t_{{e,t}} + 0.1)} \]
where $M$ is the human metabolic rate, $t_r$ is the average temperature of the human skin in a comfortable state, $t_a$ is the ambient temperature of the human body, $t_{cl}$ is the thermal resistance of the clothing.

The heating power of the heating system is obtained by (8) with the flexibility of thermal comfort.

$$P_{h,i,t} = (1 - \frac{T - T_{i,\text{min}}}{T_{i}}) P_{h,i,t} \leq P_{h,i,t} \leq (1 - \frac{T_{i,\text{max}} - T}{T}) P_{h,i,t}$$

(8)

where $T$ is the standard heating temperature.

The heat power unbalance is calculated by (9).

$$\max(\mu P_{e,i,\text{min}},(1 - \frac{T - T_{e,\text{min}}}{T}) P_{e,i}) \leq P_{e,i} \leq \min(\nu P_{e,i},(1 - \frac{T_{e,\text{max}} - T}{T}) P_{e,i})$$

(9)

The cool load, similar as the heat load, has the inertia. The cool power unbalance is limited by (10).

$$\psi P_{c,i,t} \leq P_{c,i,t} \leq \omega P_{c,i,t}$$

(10)

where $P_{c,i,t}$ is the cooling power of the cooling system at time $t$, $\psi$ and $\omega$ are the inertia coefficients of the cooling system, $P_{c,i,t}$ is the cool power load.

2.3 Integrated energy system model

1) Combined heat and power (CHP) model.

The CHP has the constraint of “setting power with heat”. The electric-heat characteristics of CHP can be described in (11) [10].

$$\max\{P_{c,i,\text{min}} - C_{e,i}P_{h,i} - C_{r,i}(P_{h,i} - P_{h,\text{min}})\} \leq P_{e,i} \leq P_{c,i,\text{max}} - C_{e,i}P_{h,i}$$

(11)

where $P_{e,i,t}$ is the electric power of CHP at time $t$, $P_{e,\text{min}}$ and $P_{e,\text{max}}$ are the min and max electrical power of CHP, $P_{h,i}$ is the heat power of CHP at time $t$.

The constraints of CHP are expressed by (12).

$$P_{e,\text{min}} \leq P_{e,i,t} \leq P_{e,\text{max}} \quad P_{h,\text{min}} \leq P_{h,i,t} \leq P_{h,\text{max}} \quad r_l \leq P_{h,i,t} - P_{h,i,t-1} \leq r_u$$

(12)

where $r_l$ and $r_u$ are the lower and upper ramp rate limits.

2) Power to gas (P2G) model [11].

$$P_{g,t} = \alpha P_{e,t}$$

(13)

where $P_{g,t}$ is the gas power generated by P2G at time $t$, and $\alpha$ is a conversion coefficient.

The constraints of P2G are expressed by (14).

$$P_{e,\text{min}} \leq P_{e,t} \leq P_{e,\text{max}}$$

(14)

3) Micro gas turbine model.

The micro-gas turbine model is obtained by (15) [12].

$$P_{m,t} = \eta_{m} P_{m,t}$$

(15)

where $P_{m,t}$ is the gas power consumed at time $t$, $\eta_{m}$ is a conversion coefficient, $P_{m,\text{th,t}}$ is the heat power .

The power and ramp rate constraints of the micro gas turbine are as follows.

$$\begin{cases} P_{m,\text{min}} \leq P_{m,t} \leq P_{m,\text{max}} \\ r_{m,t} \leq P_{m,t} - P_{m,t-1} \leq r_{m,\text{max}} \end{cases}$$

(16)

where $P_{m,\text{min}}$ and $P_{m,\text{max}}$ are the lower and upper power limits for the micro-gas turbine, $r_{m,t}$ and $r_{m,\text{max}}$ are the lower and upper ramp rate limits, respectively.
3. Objective function and constraints

3.1. Objective function
The objective function of the minimum operation costs of the IES are established by (17).

\[
\min(C) = C_1(P_{\text{el},t}) + C_2(P_{\text{el},t}) + C_4(P_{\text{wind},t}) + C_5(P_{\text{pv},t})
\]

where \( C \) is the minimum operation cost of IES.

1) Operation cost of CHP \(^{[13]}\).

\[
C_1 = \sum_{t=1}^{T} \left[ a_1(P_{\text{el},t} + C_{11}P_{\text{el},t}) + b_1 \left( P_{\text{el},t} + C_{13}P_{\text{el},t} \right)^2 + g \right]
\]

where \( C_1 \) is the operation cost of CHP, \( a_1, b_1 \) and \( g \) are the operation cost coefficients of CHP.

2) Operation cost of P2G.

\[
C_2 = \sum_{t=1}^{T} c_1P_{\text{el},t}
\]

where \( C_2 \) is the operation costs, \( c_1 \) is the operation costs coefficients of P2G.

3) Operation costs of micro gas turbine.

\[
C_3 = \sum_{t=1}^{T} a_3P_{\text{mg},t}
\]

where \( C_3 \) is the fuel cost of the micro gas turbine, and \( a_3 \) is a cost coefficient of the micro-gas turbine.

4) Cost of wind power curtailment.
The cost of wind power curtailment is obtained by (21).

\[
C_4 = \sum_{t=1}^{T} a_4P_{\text{wind},t}
\]

where \( C_4 \) is the cost of wind curtailment, \( a_4 \) is a cost coefficient of wind power curtailment, and \( P_{\text{wind},t} \) is the wind power curtailment at time \( t \).

5) Cost of photovoltaics curtailment.

\[
C_5 = \sum_{t=1}^{T} a_5P_{\text{pv},t}
\]

where \( C_5 \) is the cost of photovoltaics curtailment, \( a_5 \) is a cost coefficient of photovoltaics curtailment, and \( P_{\text{pv},t} \) is the wind power curtailment at time \( t \).

3.2. Constraints

1) Electric power balance.
Total generations and electric loads must be balanced at each operation period as described in (23).

\[
P_{\text{wind},t} + P_{\text{pv},t} + P_{\text{el},t} + P_{\text{mg},t} = P_{\text{el},t} + \Delta P_{\text{el}}
\]

2) Heat power unbalance as shown in (9).
3) Gas power balance.
Total gas supply and demand are balanced at each operation period as described in (24).

\[
P_{\text{g},t} + P_{\text{el},t} = P_{\text{el},t} + P_{\text{mg},t} + \Delta P_{\text{g}}
\]

4) Cold power unbalance as shown in (10).
5) Constraints of user satisfaction.
\[ 1 - \frac{\Delta P_e}{P_{e}\text{min}} \geq S_p^{\text{min}} \quad 1 - \frac{\Delta P_g}{P_{g}\text{min}} \geq S_g^{\text{min}} \]  

(25)

where \( S_p^{\text{min}} \) and \( S_g^{\text{min}} \) are the mi values of power and gas purchase satisfaction, respectively.

6) Constraints on price changes.

The constraints on electricity and gas price changes are given by (26).

\[ \Delta P_{e}\text{min} \leq \Delta P_e \leq \Delta P_{e}\text{max} \quad \Delta P_{g}\text{min} \leq \Delta P_g \leq \Delta P_{g}\text{max} \]  

(26)

The upper and lower limits of the electricity price and the gas price change range do not exceed ±50%. The load and air load response do not exceed 10% of the load.

4. Analysis of examples

4.1. The setup of simulation

The simulation parameters of the IES are shown in Table 1. Fig. 1 shows the forecasts of load demand, wind power and photovoltaics, and forecasts data are taken from the comprehensive demonstration area in Liaoning Province, China.

![Figure 1. Load demand and renewable energy forecasting curves.](image)

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( \varepsilon_e \) | -0.3  | \( \varepsilon_g \) | -0.4  |
| \( \varepsilon_e \) | 0.1   | \( \varepsilon_g \) | 0.1   |
| a4(USD/MW) | 120  | a5(USD/MW) | 120   |

4.2. Optimization model dispatch results analysis

To verify the effectiveness of the proposed optimal dispatch model, two models are compared in this paper.

Model 1: An optimal dispatch model that with demand response and load inertia.

Model 2: An optimized dispatch model that without demand response and load inertia.

Figs. 2-5 show the comparison of electricity price, gas price, electric load, and gas load with two models. During the high-wind power and low-electric load period of (1:00 -4:00) and (22:00 -24:00), the electricity price is reduced and the gas price is increased, and the electric load demand is increased. Users transfer the self-elastic response electric load demand to the trough, and transfer the cross-elastic response gas load demand to the electric load, which increase the wind power accommodation.

During the period of (5:00 -6:00), (15:00), (20:00), the electricity price and gas price are increased, and the user reduce the electricity and gas consumption according to the increase in the electricity and gas price. The self-elastic response power load and gas load are transferred to the trough period, so the electric load demand and the gas load demand are reduced. Therefore, the effect of peak shaving is achieved. During the high-electric and low-gas period load demand of (7:00 -10:00), (16:00 -19:00) and (21:00), the electricity price is increased and gas price is reduced. User transfers the self-elastic response electric load during this period to the trough period. The self-elastic response gas load in other peak periods is transferred to this time period, and the electric load of the cross-elastic response is transferred to the gas load. The electric load demand is reduced and the gas load demand is increased, which has a peak-shaving effect on electric load demand, and the demand for gas load has
the effect of filling the valley. During the high-wind power, high-photovoltaics, high-electric load demand and high-gas load demand period of (11:00 -14:00), the electricity price is reduced and the gas price is increased, user transfer the self-elastic response electric load of other peak periods to this period, so the electric load demand is increased. According to the comparison of electricity price and gas price, the user transfers the gas load demand of the cross-elastic response during this period to the electric load demand. Therefore, the electric load demand is increased and the gas load demand is reduced, and the wind power and photovoltaic accommodation are enhanced.

Figure 2. Comparison of electricity price with two models.

Figure 3. Comparison of gas price with two models.

Figure 4. Comparison of electric load optimization with two models.

Figure 5 Comparison of gas load optimization with two models.

Figs. 6-7 show the comparison of heat load and cool load optimization with two models. During the high wind power and heat load period, the heat load demand is reduced due to the heat load inertia. The heat output of is reduced, and wind power accommodation is improved. During the high-wind power and photovoltaic period, the heat load demand is lower, the heat load demand and the heat output is reduced, and photovoltaic accommodation is improved.
Figs. 8-9 show the comparison of wind power and photovoltaics accommodation with two models. With the demand response, the electricity price and gas price are optimized, and users are guided to transfer the electric energy during peak hours to the low period. The electric load and gas load during this period are transferred, which improve wind power and photovoltaics accommodation.

5. Conclusion

Aiming at improve the wind power and photovoltaics accommodation, an optimal dispatch model of IES based on demand response and the cool and heat loads inertias is proposed in this paper. The proposed model can reduce the peak load, fill the trough load, and the supply and demand of the cool and heat loads fluctuate within a certain range, so the wind power and photovoltaics accommodation are increased. The simulation results show that, with the proposed model, the wind power and photovoltaics accommodation are increased. Compared Model 1 with Model 2, the wind power and photovoltaics accommodation are increased due to the demand response and the cool and heat loads inertias.

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