Reserve Improvement by Load Curtailment Service for Gas-Electric Systems Integrated with Wind Power

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Abstract. A new model is proposed for the optimal scheduling of gas-electric integrated energy systems, considering the incentive demand response (IBDR) to provide the reserve ancillary service. By incorporating the IBDR, one hand, the system can give full play to the complementary functions of different energy sources to enhance the efficiency of the system; on the other hand, more flexibility can be utilized to cope with the uncertainty of wind power with IBDR providing reserves with conventional units simultaneously. We establish the IBDR model with segmental price-quantity curves, and the transient gas flow and steady state power flow are combined to formulate the operation model of gas-electric integrated systems. A 6-node power network and a 12-node natural gas network were selected to construct a gas-electric integrated energy system. The simulation results show that the IBDR can improve the flexibility of the system and decrease the total operation cost of the gas-electric integrated energy system.

Introduction

The integrated energy system is the development trend of energy utilization in the future. Among the system, the power system and natural gas system are most closely linked, due to the rapid growth of natural gas fuel consumption and the new emerging power-to-gas (P2G) technology [1]. The main benefit of gas-electric systems is that the electrical energy can be converted to gas by the P2G process, which provides the possibility of using existing natural gas networks for storing and transporting energy [2].

As the electric power system and the natural gas system are interdependent with each other, the security and economic efficiency of one system would be directly influenced by the other. To enhance the secure and economic operation of the integrated energy system, some fundamental researches have been done about the co-optimization scheduling of the gas-electric systems. Ref. [3] focuses on an integrated formulation to analyze the steady-state operation of electricity and natural gas coupled systems. Ref. [4] introduces the P2G technology and formulates the day-ahead optimization model of a multi-energy system, considering the characteristics of P2G devices, power system, and natural gas systems. Ref. [5] developed a unified modeling and solution framework to solve the coupled gas and power flow equations. Ref. [6] proposes a security-constrained bi-level economic dispatch model for integrated gas and electricity systems considering wind power and P2G process.

To relieve the global energy crisis and reduce carbon dioxide emissions, the world has witnessed the rapid increase of renewable energy represented by wind power. The wind power characterizes uncertainty and intermittence, and therefore brings challenges to the safe and stable operation of the integrated gas-electric systems. In this context, adequate flexibility has been a necessity to improve
system security. Traditionally, the flexibility is mainly provided by the reserve of conventional units. However, purely depending on conventional units may cause the deficiency of the flexibility.

As one of the important measures to improve flexibility, the demand response (DR) has been a promising way due to its low cost and broad potential capabilities [7]. In general, the DR programs can be classified into the price-based demand response (PBDR) and the incentive-based demand response (IBDR) [8]. The PBDR can reshape the load profile by time-varying electricity price and reduce the operation cost. However, the PBDR is the voluntary behavior of consumers and cannot be directly controlled by the system operator. In contrast, the IBDR has the flexibility of being dispatched and can participate in both the energy and reserve market. A lot of researches about IBDR has been done in the power systems, including the IBDR modeling [9, 10], the co-optimization with conventional units [11]. However, these works are mainly conducted in the power system, without considering the natural gas system.

A few references have considered the impact of DR on the integrated energy systems. Ref. [12] formulates the IBDR model as a linear function between the compensation price and reduced electricity load, and incorporates the IBDR program into the gas-electric integrated energy system to enhance the system operation. Ref. [13] analyzes the impact of DR on the electricity and gas supply systems in Great Britain in a long time horizon from 2010 to 2050s. Ref. [14] proposes an integrated stochastic scheduling model to dispatch resources and deploy flexible ramp awards from both thermal units and PBDR, considering a full frame natural gas transportation network.

In summary, the gas-electric integrated energy systems are the trend of future energy utilization, and the related research devote to formulate more deliberated models for such a system from various time scale, however, only few works have considered the impact of DR on the systems. This paper aims to incorporate the IBDR in the integrated systems to provide reserve ancillary services and analyze how the IBDR can influence the integrated systems. The main contribution of this paper is listed as follows:

- The gas-electric integrated systems and the IBDR program are combined, and the dynamic optimal energy flow are adopted on the basis of our earlier works [15]. A comprehensive optimization model is formulated, and how the IBDR program influences the final results are analyzed.
- Different with the earlier works in Ref. [12], we formulate the IBDR model with a step-wise function, which is more conformed to the practice in the bidding market. In our model, the IBDR program only provides the reserve ancillary service, and do not participate in the energy optimization. Besides, the IBDR is co-optimized with the conventional units to provide reserve simultaneously.

In the rest of this paper, Section II gives the IBDR formulation for providing ancillary service. Section III models the dynamic optimal power flow model of the integrated system considering the IBDR. Section IV gives the simulation results on the test system. Section V make the conclusions.

The IBDR Formulation for Providing Reserve Ancillary Service

![Figure 1. The offered price and quantity for IBDR program.](image-url)
The IBDR program of end users is aggregated by agents. Firstly, all agents submit their offered price and quantity as shown in Fig. 1 to the dispatching center. Fig. 1 is characterized by a step function monotonically increasing. Each step in Fig. 1 represents a range of load reduction quantity and its corresponding compensation price. Secondly, the dispatching center determines the optimal scheduling solution according to the system operating conditions and the offered price and quantity packages by DR agents.

Based on Fig. 1, the compensation to the IBDR service for agent $m$ is formulated as (1)-(5).

$$d_{m,t}^{IBDR} = \sum_{k=1}^{K} p_{cap,m}^k o_{m,t}^k x_{m,t}^k.$$  

(1)

$$0 \leq o_{m,t}^k \leq q_m^k - q_m^{k-1}.$$  

(2)

$$x_{m,t}^{k-1} \geq x_{m,t}^k.$$  

(3)

$$x_{m,t}^k \leq o_{m,t}^k Q.$$  

(4)

$$\sum_{t=1}^{N_t} x_{m,t}^i \leq \varphi_m.$$  

(5)

where $k$ is the index for load reduction levels; $m$ is the index for agents; $t$ is the index for time periods; $d_{m,t}^{IBDR}$ is the cost for IBDR proving reserve service; $p_{cap,m}^k$ is the price for providing reserve service for the $k$th level load reduction of agent $m$; $o_{m,t}^k$ is the quantity of load reduction of agent $m$ in period $t$; $x_{m,t}^k$ is a binary variable, when $x_{m,t}^k = 1$, the load reduction of $k$th level is scheduled, otherwise, it is not scheduled; $\varphi_m$ is the allowed maximum response times of agent $m$ during a day; $Q$ is a large enough constant. Eq. 1 is the capacity cost function for agent $m$; Eq. 2 is used to restrict the range of load reduction in each level; Eq. 3 is used to guarantee that the $k$th level of load reduction can be scheduled if and only if the $(k-1)$th level of load reduction is scheduled; Eq. 4 is used to guarantee that when $o_{m,t}^k$ is zero, $x_{m,t}^k$ should be zero; Eq. 5 is used to restrict the response times for an agent during a scheduling horizon, so as to guarantee the reliability of power supply for end users.

It should be noted that the formulation of IBDR is nonlinear, due to the nonlinear term $o_{m,t}^k x_{m,t}^k$ in Eq. 1. To linearize the model, we use the big-M method to transform the nonlinear term $o_{m,t}^k x_{m,t}^k$ into a linear term $\theta_{m,t}^k$, by letting $\theta_{m,t}^k = o_{m,t}^k x_{m,t}^k$, and adding constraints for $\theta_{m,t}^k$ as shown in Eq. 6 and Eq. 7.

$$-Q x_{m,t}^k \leq \theta_{m,t}^k \leq Q x_{m,t}^k.$$  

(6)

$$o_{m,t}^k - Q(1-x_{m,t}^k) \leq \theta_{m,t}^k \leq o_{m,t}^k + Q(1-x_{m,t}^k).$$  

(7)

**Optimal Power Flow Model for Integrated Energy Systems with IBDR**

**Objective function.** The basic idea of the dynamic optimal energy flow in the integrated systems is to combine the steady-state load flow model in power system and the dynamic gas flow in difference form of the gas system. The objective function is to minimize the operating cost of the integrated system with IBDR:
\[
\min \sum_{i=1}^{N_g} \sum_{j=1}^{N_N} c_{ij}^p (P_{ij}^s \Delta t) + \sum_{i=1}^{N_g} \left( c_{ij}^{\text{cur}} P_{ij}^{\text{cur}} + c_{ij}^{\text{dr}} P_{ij}^{\text{dr}} \right) + \sum_{i=1}^{N_g} c_{ij}^{\text{gas}} (3600 \cdot M_{ij}^{\text{gas}} \cdot \Delta t) + \sum_{m=1}^{N_m} d_{m,j}^{\text{IBDR}} + \\
\sum_{i=1}^{N_g} c_{ij}^{\text{wcur}} (P_{ij}^{\text{wcur}} \cdot \Delta t) + \sum_{i=1}^{N_g} c_{ij}^{\text{load}} (L_{ij}^{\text{load}} \cdot \Delta t) \]
\]

where \( T_N \) is the total time periods during the scheduling horizon; \( N_g, N_{\text{gas}}, N_w, N_{\text{DR}} \) are the total number of coal-fired units, gas-fired units, wind turbines and DR agents, respectively. \( c_{ij}^p \) and \( P_{ij}^s \) are the cost coefficient and the output of the \( i \)-th coal-fired unit at period \( t \), respectively. \( c_{ij}^{\text{gas}} \) and \( M_{ij}^{\text{gas}} \) are the natural gas price and the consumed mass flow rate of natural gas of the \( i \)-th gas-fired unit at period \( t \), respectively. \( P_{ij}^{\text{wcur}} \) and \( c_{ij}^{\text{load}} \) are the wind power curtailment and the penalty price of the \( i \)-th wind turbine at period \( t \), respectively. \( N_{\text{load}} \) is the total load buses in the system. \( L_{ij}^{\text{cur}} \) and \( c_{ij}^{\text{load}} \) are the quantity of load shedding and its penalty price for the \( i \)-th load bus at period \( t \); \( \Delta t \) is the duration of one period, and it is set as one hour in this paper.

**Natural gas system constraints.** The natural gas system includes the following constraints in this paper.

1) **Boundary Conditions**

Boundary conditions are set at the ends of the pipes.

At sink nodes, the incoming mass flow rate \( M_{ij} \) is equal to the outgoing mass flow rate \( M_{ij}^L \) consumed by the gas loads:

\[
M_{ij} = M_{ij}^L \quad \forall i \in \text{sink nodes} .
\]

The gas density \( \rho_{ij} \) and pressure \( p_{ij} \) at source nodes at each period \( t \) are constant values \( \rho_{i,0} \) and \( p_{i,0} \), respectively.

\[
\begin{cases}
\rho_{ij} = \rho_{i,0} & \forall i \in \text{source nodes}, t \leq T_N \\
p_{ij} = p_{i,0} &
\end{cases}
\]

The mass flow rate at the intersections should be balanced among the incoming and outgoing pipelines:

\[
\sum_j M_{ij} = 0 \quad \forall i \in \text{the intersections}, \forall t .
\]

For the observation node \( i \) in the gas system, the gas state equation for gas pressure \( p_{ij} \) and density \( \rho_{ij} \) as shown in Eq. (12) should be satisfied.

\[
p_{ij} = c^2 \rho_{ij} \quad \forall i .
\]

2) **The Material-balance Equation**

The material-balance equation with the Wendroff difference form\(^{[15]}\) is shown in Eq. 13, it represents the conservation of the mass in the gas pipeline.

\[
\rho_{ij,t+1} + \rho_{ij,t} - \rho_{ij} + \frac{\Delta t}{L_j A_j} [M_{ij,t+1} - M_{ij,t} + M_{ij,t} - M_{ij,t}] = 0 .
\]

where \( L_j \) is the pipe length between node \( i \) and node \( j \), \( A_j \) is the cross-sectional area.

3) **The Momentum Equation**

The momentum equation is utilized to describe the momentum transport in the continuum of natural gas. The momentum equation with the Wendroff difference form is expressed as Eq. 14.
\[
\frac{1}{A_j}(M_{j,t+1} + M_{j,t-1} - M_{j,t} - M_{j,t}) + \frac{\Delta t}{L_j} [p_{j,t+1} - p_{j,t-1} + p_{j,t} - p_{j,t}] + \\
\lambda \bar{\omega}_j \Delta t \left( M_{j,t+1} + M_{j,t-1} + M_{j,t} + M_{j,t} \right) = 0
\]

where \( \lambda \) is the friction coefficient, \( \bar{\omega}_j \) is the average gas velocity, \( d_j \) is the diameter of the pipe.

4) Min-max value of the mass flow and gas pressure

For those source nodes in the natural gas network, the mass flow should satisfy:

\[
M_{i,t} \geq 0 \quad \forall i \in \text{source nodes}, \quad \forall t.
\]

For those non-source nodes, the gas pressure should satisfy:

\[
p_{i,t} \leq p_{i,t} \leq p_{i,t} \quad \forall i \notin \text{source nodes}, \quad \forall t.
\]

\( p_{i,t} \) and \( p_{i,t} \) are the lower and upper gas pressure, respectively.

**Power System Constraints.** The power system constraints considered the following constraints in this paper.

1) Power Balancing Constraints

\[
\sum_{i=1}^{N_p} P_{i,t}^{\text{gas}} + \sum_{i=1}^{N_w} P_{i,t}^{\text{wind}} + \sum_{i=1}^{N_t} P_{i,t}^{\text{load}} = \sum_{i=1}^{N_p} P_{i,t}^{\text{b}} + L_t + \sum_{i=1}^{N_t} P_{i,t}^{\text{cur}} - \sum_{i=1}^{N_t} L_{i,t} \quad \forall t.
\]

where \( P_{i,t}^{\text{gas}} \), \( P_{i,t}^{\text{wind}} \) are the output of the \( i \)-th gas-fired unit and the \( i \)-th wind turbine at period \( t \), respectively. \( P_{i,t}^{\text{b}} \) is the consumed energy of the \( i \)-th P2G at period \( t \). \( N_p \) is the total number of P2Gs, \( L_t \) is the total load at period \( t \).

2) Transmission Line Constraints

\[
f_{\text{lim}} \leq Sp \leq f_{\text{lim}}.
\]

where \( p \) is the net injection of node power, \( S \) is the sensitivity matrix of node injection power and line power, \( f_{\text{lim}} \) is the capacity of transmission lines.

3) Generation Limit Constraints

\[
P_{i,t} \leq P_{i,t} \leq \overline{P}_{i,t}.
\]

where \( P_{i,t} \) and \( \overline{P}_{i,t} \) are the lower and upper outputs of the \( i \)-th unit, respectively. And \( P_{i,t} \) for coal-fired units is usually set as 30% of its rated capacity, and gas-fired units can operate from zero to its rated capacity.

4) Ramping Limit Constraints

\[
| P_{i,t} - P_{i,t-1} | \leq P_{\text{ramp},i}.
\]

where \( P_{\text{ramp},i} \) is the ramping limits of the \( i \)-th generator.

5) Reserve Constraints

\[
0 \leq P_{i,t}^{\text{pow}} \leq \min\{P_{i,t} - P_{i,t}, P_{\text{ramp},i}\}.
\]

\[
0 \leq P_{i,t}^{\text{wind}} \leq \min\{P_{i,t} - P_{i,t}, P_{\text{ramp},i}\}.
\]

\[
\sum_{j=1}^{N_j} P_{i,j} + \sum_{m=1}^{N_m} \sum_{k=1}^{K} P_{i,k} \geq R_{i,t}^{\text{cur}}.
\]
\[
\sum_{i=1}^{N_i+N_g} P_{i,t}^{dr} \geq R_i^{dr}.
\]

where \( R_i^{ur} \) and \( R_i^{dr} \) are the needed upward and downward reserve, respectively.

**Energy Conversion Constraints.** Bi-directional energy conversion is considered in this paper. The gas-fired generators consume natural gas to produce electricity while the P2G power stations consume electricity to produce natural gas.

For the P2G power stations, the relationship between the produced natural gas and consumed electricity can be expressed as:

\[
M_{i,j}^S = \eta_{i,j} P_{i,j}^P.
\]

where the subscription \( ki \) indicates that the energy from node \( k \) in the power system is converted to natural gas sent to node \( i \) in the gas system by the P2G power stations; \( \eta_{i,j} \) is the energy conversion efficiency and the unit is \( \text{kg} \cdot \text{s} / \text{MW} \); \( P_{i,j}^P \) is the consumed power by the P2G power stations at bus \( k \) in the power system at period \( t \), \( M_{i,j}^S \) is the converted gas mass flow by the P2G power stations at node \( i \) in the natural gas system.

The relationship between the produced electricity and the consumed natural gas by the gas-fired units can be expressed as:

\[
P_{i,j}^{gas} = \eta_{i,j} M_{i,j}^{gas}.
\]

where the subscription \( in \) connects the mass flow rate at node \( i \) in the gas system and the generator at node \( n \) in the power system; \( \eta_{i,j} \) is the conversion efficiency of the devices and the unit is \( \text{MW} \cdot \text{s/kg} \); \( P_{i,j}^{gas} \) is the active power of the \( n \)th gas-fired unit at period \( t \); \( M_{i,j}^{gas} \) is the consumed gas from node \( i \) at moment \( t \).

**Simulation Results**

**Test System.** To verify the effectiveness of the proposed method, the Graver 6-bus power system and 12-bus natural gas system are combined to construct the gas-electric integrated energy systems, as shown in Figure 2. For the natural gas system, there are one source node (node 1) and two load nodes (nodes 8 and 10). For the power system, there are one thermal power unit (node 1), one wind farm (node 6), one gas-fired unit (node 3), and 5 load buses. The gas-fired unit is connected to node 11 of the natural gas system. There are two P2G power stations in the integrated system, which correspond to nodes 4 and 5 of the power system and nodes 9 and 12 of the natural gas system. We assume that each load bus has one IBDR agent to provide reserve ancillary service.

![Figure 2. Gas-electric integrated energy system.](image-url)
The parameters adopted for gas load, wind power output and power system load of the integrated energy systems are all from the actual data of the Danish national natural gas system and the power system during one week in 2015, with an interval of 1 hour, as shown in Figure 3.

In the objective function, the operating cost for the coal-fired unit is 200 yuan/MW·h. The price for the gas-fired unit is 800 yuan/MW·h. \( \eta_{li} \) in Eq. 25 is set as 0.11 kg/(s·MW), and \( \eta_{lu} \) in Eq. 26 is set as 1.8 MW·s/kg. The penalty price for wind power curtailment and load shedding are set as 1000 yuan/MW·h and 2000 yuan/MW·h, respectively. To analyze how the IBDR reserve ancillary service influences the integrated energy systems, we set four comparative cases as shown in Table 1 with different response times for IBDR.

![Figure 3. Natural gas system.](image)

**Table 1. Case settings.**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>IBDR considered</th>
<th>Maximum response times of IBDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>NO</td>
<td>--</td>
</tr>
<tr>
<td>Case 2</td>
<td>YES</td>
<td>8</td>
</tr>
<tr>
<td>Case 3</td>
<td>YES</td>
<td>16</td>
</tr>
<tr>
<td>Case 4</td>
<td>YES</td>
<td>24</td>
</tr>
</tbody>
</table>

The simulation results for each cost in different cases are shown in Table 2. As can be seen from Table 2, when the IBDR service are not considered in Case 1, the system occurs to the phenomenon of load shedding with a penalty cost of \( 1.3207 \times 10^4 \) yuan. With the IBDR program providing reserve service in Case 2, 3 and 4, the load shedding can be voided. In addition, with the increase of response times of IBDR, the total operation cost of the integrated energy system decreases, due to the decrease of the energy cost of gas power units, the total reserve cost and the penalty cost for load shedding. However, the adequate response times for an IBDR agent during one day should be set according to the will of end users by considering the reliability of electricity usage.

**Table 2. Each cost for integrated energy systems in different cases.**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy cost for coal-fired unit (10^6 yuan)</td>
<td>2.212917</td>
<td>2.212917</td>
<td>2.212917</td>
<td>2.212917</td>
</tr>
<tr>
<td>Energy cost for gas-fired unit (10^5 yuan)</td>
<td>7.00164</td>
<td>7.05447</td>
<td>7.05447</td>
<td>7.05446</td>
</tr>
<tr>
<td>Reserve cost for IBDR (10^4 yuan)</td>
<td>--</td>
<td>5.0107</td>
<td>8.9173</td>
<td>1.0347</td>
</tr>
<tr>
<td>Reserve cost for gas unit (10^2 yuan)</td>
<td>2.38289</td>
<td>1.78406</td>
<td>1.76785</td>
<td>1.76361</td>
</tr>
<tr>
<td>Reserve cost for thermal power unit (10^2 yuan)</td>
<td>2.61674</td>
<td>2.21805</td>
<td>1.78384</td>
<td>1.54188</td>
</tr>
<tr>
<td>Penalty cost for wind power curtailment (10^2 yuan)</td>
<td>1.18110</td>
<td>1.18110</td>
<td>1.18110</td>
<td>1.18110</td>
</tr>
<tr>
<td>Penalty cost for load shedding (10^2 yuan)</td>
<td>1.3207</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total operation cost (10^6 yuan)</td>
<td>3.544362</td>
<td>3.486792</td>
<td>3.480816</td>
<td>3.477371</td>
</tr>
</tbody>
</table>

Take Case 2 as an example, the outputs for gas-fired and coal-fired units and consumed energy for P2G station are given in Fig.4. To further validate how the IBDR service can improve the flexibility of the system operation, we give the comparison results of output curves for gas-fired units and load shedding curves between Case 1 and Case 2 in Fig. 5.
As can be seen from Fig. 4, the output of coal-fired and gas-fired units and the consumed energy of P2G stations have complementary characteristics. When the wind power has a large output, the P2G stations consumed energy to storage the wind power and the output of the units are in their minimum output level; while when the wind power has a low level of output, the P2G stations no longer consumed energy and the units produce power at a large level. As can be seen from Fig. 5, the outputs of coal-fired units at periods 59 and 60 have reached to its maximal level in Case 1, therefore the coal-fired unit cannot provide the upward reserve for the system. Then, the gas-fired unit needs to lower its output to provide the needed upward reserve, which results in the load shedding at periods 59 and 60. In contrast, when the IBDR service is incorporated into the integrated energy system in Case 2, the flexibility for proving reserve has been improved, and the feasible region for the system operation has been enlarged. As the IBDR can provide service at periods 59 and 60, then the output of the gas-fired unit can be increased, and then the load shedding can be avoided.

**Conclusions**

This paper investigated the role of incentive-based demand response to facilitate the flexibility improvement in the gas-electric integrated energy system. A comprehensive model has been proposed considering the IBDR program providing reserve ancillary service. The simulation results show that the IBDR service can improve the flexibility of the system operation and decrease the total operating cost.
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