Research on Multiple Demand Response in Integrated Energy System Containing Power, Gas and Heat

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Abstract. Integrated demand response provides an important direction for realizing the bidirectional-interaction between supply and demand in the integrated energy system. In view of the differences in the time, space, cost and other aspects of users' demand for multi-energy, an integrated demand response method based on the energy pricing strategy of the integrated energy system is proposed. Firstly, the characteristics of integrated demand response resources are analyzed, and various integrated demand response models are established. Secondly, based on the nodal energy price, considering the energy response potential, and taking the user energy cost as the optimization goal, an energy cost model that takes into account the load change of the user's integrated demand response is established. Finally, an example is used to analyze the multi-energy load response under the integrated energy system nodal energy price strategy, which is beneficial to promote the rational use of energy by multi-energy users and reduce energy costs.

1. Introduction
The integrated energy system is an effective way to promote efficient and clean utilization of energy. With the increasing degree of coupling between power, gas and heat and other energy sources, demand-side resources are becoming more abundant, and the adjustable capacity of users is no longer limited to the power load regulation mode of traditional demand response. The integrated demand response method can further fully tap the demand response potential of multi-energy users, make users' energy use more economical and flexible, and achieve a win-win situation between the energy network and users. Therefore, considering the response potential between users of different energy sources, the study of integrated demand response is of great significance to ensure the economic and efficient operation of the integrated energy system.

At present, the research on integrated demand response mainly focuses on the system level and the user level. At the system level, existing studies can take the energy consumption characteristics of power, gas and heat loads and different demand response implementation mechanisms as the constraint conditions for the optimal operation of multi-energy system, and put forward the gas-electricity cooperative optimal operation strategy considering the integrated demand response resources at the micro grid level [1, 2]. At the user level, existing research can analyze demand response interaction patterns from the perspective of industrial users, propose multi-agent oriented interaction mechanism of integrated energy system in industrial parks [3], and establish interactive optimization model...
considering demand response based on multi-energy complementation [4], it is also possible to establish a load-side model with multi-energy flow, multi-form and multi-response type [5]. However, most are still considering the impact of integrated demand-side resources on the overall energy efficiency of the system and the optimal economic operating cost, or analyzing how demand-side resources respond under the conditions of energy prices and the response behavior of various demand entities. Few studies have been conducted on the coordinated response of multiple energy sources based on the node energy price of the integrated energy system. Multi-energy users are only passive receivers of energy prices.

In response to the above problems, considering the uniqueness and similarity of different load types in energy consumption characteristics, integrated demand response research based on the energy pricing strategy of integrated energy system is conducted. The innovations of this paper are as follows:

1. In terms of integrated demand response method, considering the response characteristics of the integrated demand response resources on the day-ahead time scale, the response strategies for various flexible loads under the guidance of the energy pricing mechanism of power-gas-heat integrated energy system are proposed, which is conducive to improving the response resource capacity.

2. At the energy price level, considering the nodal energy price, a method for calculating the nodal energy price of power-gas-heat integrated energy system with wind power generation is proposed, which is beneficial to promote the interaction between supply and demand.

The structure of this paper is as follows. Section 2 considers multi-load integrated demand response, proposes an integrated energy system operation mode, and establishes an integrated demand response model. Section 3, the optimal operation model of the integrated energy system with multiple demand side load responses is established. Section 4 analyzes the response results of nodal energy prices to the integrated demand of multi-energy users through calculation examples, and verifies the effectiveness of the proposed method. Section 5 summarizes the main findings of paper.

2. Integrated energy system operation mode considering multi-load integrated demand response

2.1. Integrated energy system price decision process

Firstly, the power, gas and heat loads of each node of the integrated energy system are predicted. Secondly, an integrated energy system scheduling model is constructed, and the energy price of nodes is determined by the energy balance equations of power, gas and heat. Then, taking the multi-energy load users of the system coupling nodes as the object, considering the response characteristics of multi-flexible loads, a multi-load integrated demand response model was established. Finally, the user-side response feeds back the load demand to the system side, thus forming the transfer relationship between system scheduling, nodal energy price and integrated demand response.

Figure 1. Integrated energy system price decision process
2.2. Characteristic analysis and model establishment of integrated demand response resources

Flexible load refers to the load that can be adjusted according to energy prices and load reduction, and has the characteristics of flexible scheduling. According to the difference and complementarity in price, energy characteristics of multiple energy sources such as power, gas, and heat, flexible loads can be divided into three categories: shiftable loads, transferable loads and curtailable loads.

2.2.1. Shiftable load model.

Shiftable load refers to a load that requires high continuity of utilization time. Although its utilization time can also be adjusted, the overall translation can only be carried out in a fixed continuous time period, and it cannot be shifted in time periods and does not have elastic changes in demand. The shiftable load can be expressed mathematically as shown in formula 1.

\[ \Delta P_{i,t+N}^{\text{shift}} = \Delta P_{i,t}^{\text{shift}} \quad \forall i \in N_{\text{shift}} \]

Where \( \Delta P_{i,t}^{\text{shift}} \) is the shiftable amount of load \( i \) in the original time \( t \); \( \Delta P_{i,t+N}^{\text{shift}} \) is the load increment at that time after the load is translated to the time \( t + N \); \( N_{\text{shift}} \) is the total number of shiftable loads.

2.2.2. Transferable load model.

The transferable load meets a certain total load within a specified time interval, and the energy consumption power at each time is not limited, so it has certain virtual energy storage characteristics. Assuming that the transferable time interval in the scheduling period is \([t_{tr-}, t_{tr+}]\), the transferable load can be expressed mathematically as shown in formula 2.

\[ \sum_{t = t_{tr-}}^{t_{tr+}} P_{i,t}^{\text{trans}} \Delta T = W_{T}^{\text{trans}} \]

Where \( P_{i,t}^{\text{trans}} \) is the load after scheduling; \( \Delta T \) is the load unit scheduling period time; \( W_{T}^{\text{trans}} \) is the total power consumed during the transfer-type load scheduling period.

2.2.3. Curtailable load model.

Curtailable load mainly refers to the change in the size of user demand caused by price changes. It is the elastic load that requires the reliability of energy supply in a specific period of time. The curtailable load can be expressed as shown in formula 3 and formula 4.

\[ P_{i,\tau}^{\text{cut}} = (1 - \beta_{i,\tau}\lambda_{i}) P_{i,\tau}^{\text{cut}} \]

\[ \sum_{\tau = 1}^{T} \beta_{i,\tau} \leq N_{\text{max}}^{\text{cut}} \]

Where \( P_{i,\tau}^{\text{cut}} \) and \( P_{i,\tau}^{\text{cut}} \) are the load power of the load \( i \) before and after the scheduling period \( \tau \) respectively; \( u_{i,\tau} \) is a 0-1 variable, which represents the reduction state; \( \lambda_{i} \) is the load reduction coefficient.

3. Optimal operation model of integrated energy system with multiple demand-side load response

In the integrated energy system, the load can be a variety of rich energy forms such as power, gas, and heat. The integrated demand response can further tap the response potential of multi-energy users, and reduce energy costs by changing users' energy consumption habits or optimizing energy matching. This paper mainly guides the integrated energy consumption behavior of multi-energy users through nodal energy prices, studies the adjustability of multi-energy flexible load in integrated energy system, and analyzes the energy consumption behavior of the user side participating in demand response.

3.1. Optimal scheduling model for integrated energy systems

The integrated energy system scheduling model established in this paper aims to minimize the daily operating cost of the integrated energy system, and its total operating costs include the cost of power generator set, the operating cost of gas turbine set, the output cost of gas well and the operating cost of CHP unit. The objective function is shown in formula (5).
\[
\min F = \sum_{g \in \Omega_g} f_1 \left( P_{g,j}^G \right) + \sum_{k \in \Omega_k, 2} f_2 \left( P_{k,j}^{2G} \right) + \sum_{m \in \Omega_m} f_3 \left( Q_{n,j}^N \right) + f_4 \left( P_{m,t}^{chp}, Q_{m,t}^{chp} \right)
\]

Where, \( F \) is the total operating cost of integrated energy system; \( T \) is the operation cycle; \( P_{g,j}^G \) is the active power of power generator; \( P_{k,j}^{2G} \) is the gas turbine; \( Q_{n,j}^N \) is the output value of gas well at time \( t \); \( P_{m,t}^{chp} \) and \( Q_{m,t}^{chp} \) are the power and heat emitted by CHP unit. \( \gamma_p \) and \( \gamma_h \) respectively represent the fuel consumed by CHP unit to emit unit power and heat. The specific model is shown in formula (6) - (9).

\[
f_1 \left( P_{g,j}^G \right) = a_g \left( P_{g,j}^G \right)^2 + b_g P_{g,j}^G + c_g
\]
\[
f_2 \left( P_{k,j}^{2G} \right) = C_{k,j} P_{k,j}^{2G}
\]
\[
f_3 \left( Q_{n,j}^N \right) = C_{n,j}^N Q_{n,j}^N
\]
\[
f_4 \left( P_{m,t}^{chp}, Q_{m,t}^{chp} \right) = \kappa_{chp} \gamma_p P_{m,t}^{chp} + \gamma_h Q_{m,t}^{chp}
\]

Where, \( a_g, b_g \) and \( c_g \) are the power generation cost coefficients of power generator; \( C_{k,j}^{2G} \) is the operating cost of the gas turbine \( k \) at time \( t \), excluding the gas cost; \( C_{n,j}^N \) is the natural gas price at the gas well \( n \) at time \( t \); \( kCHP \) is the fuel cost coefficient.

Constraint conditions mainly include power subsystem constraints, gas subsystem constraints, heat subsystem constraints and coupling constraints. Specific constraints are shown in Literature [6-9]. In addition, the system meets the energy balance constraints of power, gas and heat loads.

### 3.2. nodal energy price calculation model of integrated energy system

The integrated energy system contains various resources such as power, gas and heat. Besides power price, the nodal price of integrated energy system also includes nodal gas price and nodal heat price, which are collectively referred to as nodal energy price. Nodal energy price is the expansion and extension of nodal power price in the integrated energy system. Energy prices in the form of nodal price from the network to each node, as a price signal is sent to user groups. Based on the research of the nodal energy price, it can provide the basis for the research of integrated energy system demand response. By calculating the energy balance constraint of power, gas and heat nodes, the energy price of nodes can be determined. Taking coupling nodes as an example, this section establishes the power, gas and heat node balance constraint, as shown in formulas (10) - (12).

\[
P_{x,j}^G + P_{x,j}^W + P_{x,j}^{2G} - P_{x,j}^L - \sum_{y \in \Omega_y} P_{x,j}^L = P_{x,j}^L
\]
\[
Q_{x,j}^N + \sum_{y \in \Omega_y} Q_{x,j}^L + Q_{x,j}^{2G} - Q_{x,j}^L = Q_{x,j}^L
\]
\[
\phi_{x,j} = C_p m_{x,j} \left( T_{x,j}^s - T_{x,j}^o \right)
\]

### 3.3. Integrated demand response model based on the nodal energy price of integrated energy system

To minimize the energy cost of node users, the model is established as shown in formulas (13) - (15).

\[
\min \quad C_i = C_e + C_g + C_h
\]
\[
C_i = \sum_{t=1}^{24} P_{i,t} \cdot price_{i,t}
\]
\[
P_{i,t} = P_{i,t}^s + P_{i,t}^{shift} + P_{i,t}^{trans} + P_{i,t}^{cut}
\]

Where, \( C_i \) represents the cost of different energy types \( i \) of users, and \( price_{i,t} \) represents the corresponding load price in time period \( t \); \( P_{i,t}^s \) represents the \( i \)-type rigid load, \( P_{i,t}^{shift} \) represents the i-
type shiftable load, $P^{\text{trans}}_{i,t}$ represents the i-type transferable load, and $P^{\text{cut}}_{i,t}$ represents the i-type curtailable load.

Satisfying constraints are as follows, including shiftable load constraints, transferable load constraints, and curtailable load power constraints [10].

4. Optimal solution

In order to reduce the difficulty of solving and the need for follow-up research, the nonlinear model is dealt with in this paper. Regarding the power system, since the power model considering active and reactive power needs to solve a large number of nonlinear equations, a DC power flow model is used to solve it [11]. Regarding the heat system, the method of quality adjustment is adopted to decouple the thermal conditions and hydraulic conditions, and the dynamic model of the heating network is linearized for solution [12]. At the same time, due to the non-linear power flow constraints of the natural gas system, the feasible region of the problem will be non-convex, and it is often much more difficult to obtain the global optimal solution. Therefore, considering the coupling complexity of the system, the incremental linearization method [13] is used to linearize the nonlinear natural gas system flow model, and finally the model in this paper is transformed into a mixed integer programming model, which is solved by calling Cplex solver through GAMS software.

5. Example analysis

5.1. Basic data

In this section, a integrated energy system coupled by an improved IEEE 24-node power system, Belgian 20-node natural gas system and 6-node heating system is adopted for simulation study, as shown in Fig. 2. Among them, generators at nodes 18 and 22 of IEEE 24-node power system are set as gas turbines, which are respectively connected to Anderlues and Mons nodes of the natural gas system.

The generator set of node 2 is CHP generator, which is connected to the node 1 of the heating system as a heat source. Nodes 8, 19 and 21 are connected to wind power generation unit with rated output of 100MW, and P2G equipment is connected to the Loenhout, Peronnes and Voeren nodes of the natural gas system. The natural gas system has six wells, two compressors and 21 pipelines. The power system and the natural gas system are coupled bidirectional through the P2G equipment and gas turbines. The heat source of the heating subsystem includes a CHP unit and a heat pump. The energy efficiency of the heat pump is 0.8, and the power consumed is provided by the CHP unit. The CHP unit is set as a gas-fired CHP unit, which deepens the coupling degree of the electric, gas and thermal systems. Among them, the parameters of the heating subsystem are referred to Literature [14], and the specific parameters of Belgian 20-node gas system in are referred to Literature [15].

![Figure 2. Integrated energy system example diagram.](image-url)
5.1.1. Equipment parameters. The relevant parameters of gas turbine, P2G equipment and other coupling equipment are shown in Table 1, Table 2 and Table 3.

Table 1. Gas turbine related parameters.

| Generator | Power network node | Gas network node | Upper limit of active power (MW) | Lower active limit (MW) | Conversion efficiency (%) | Operating costs ($/MW) |
|-----------|--------------------|-----------------|----------------------------------|------------------------|--------------------------|------------------------|
| GT1       | 2                  | Anderlues       | 500                              | 0                      | 43%                      | 5.47                   |
| GT2       | 22                 | Mons            | 300                              | 0                      | 43%                      | 5.47                   |

Table 2. P2G related parameters.

| Generator | Power network node | Gas network node | Input upper limit (MW) | Input lower limit (MW) | Operating costs ($/MW) |
|-----------|--------------------|-----------------|------------------------|------------------------|------------------------|
| P2G1      | 8                  | Loenhout        | 200                    | 0                      | 12.33                  |
| P2G2      | 19                 | Peronnes        | 180                    | 0                      | 12.33                  |
| P2G3      | 21                 | Voeren          | 160                    | 0                      | 12.33                  |

Table 3. CHP related parameters.

| Name | Maximum output (MW) | Output lower limit (MW) | Power generation efficiency (%) | γp | γh | kchp ($/MW) |
|------|---------------------|-------------------------|-------------------------------|----|----|-------------|
| CHP  | 200                 | 0                       | 130                           | 0.31 | 2.4 | 24          |

5.1.2. Load parameters. The total power, gas and heat load curves of users in integrated energy system are shown in Fig. 3.

Figure 3. Load of system curve.

5.2. Results analysis

Considering integrated demand response scenario with demand transfer characteristics of multi-energy loads, the power/gas/heat coupling nodes are studied. Through the analysis of the optimal energy flow of the integrated energy system, the energy prices of the integrated energy system nodes are obtained.

Figure 4. Nodal energy prices diagram.
As for the nodal power price, when transmission congestion is not taken into account, the power price at each node of the power system is equal. It can be seen from Figure 3 that the variation trend of the nodal power price curve is basically the same as that of the power load curve. The power price is higher when the load is high, and the power price is lower when the load is low. The nodal gas price in the gas system is also affected by the peak-valley value of the multi-energy load in the nodal gas system, showing an obvious peak-valley shape. As for the nodal heat price, the hot water flowing in the pipeline is accompanied by heat loss, so it is affected by heat loss, and the nodal heat price is not the same. For a single hot node, the change of heat price is more complex because of the different temperature of supply and return water network.

The power load, gas load and heat load of multi-energy users of coupling nodes are unified into the power unit for measurement, and the initial load curve of power-gas-heat nodes is shown in Fig. 5.

![Node Initial load curve](image)

**Figure 5.** Node Initial load curve.

It is assumed that the power load includes the rigid power load, the shiftable power load 1 and the shiftable power load 2, the transferable power load and the curtailable power load. The heat load includes rigid heat load, shiftable heat load and curtailable thermal load. The gas load includes the rigid gas load and the curtailable gas load. The conditions of each flexible power, gas and heat loads before optimization are shown in Tables 4 to 6. Among, the load translation time range represents the difference between the transferable period before and after and the original period of load.

| The load properties | The cluster | Shiftable duration range (h) |
|---------------------|-------------|-----------------------------|
| Power load          | 1           | [-1, 1]                     |
|                     | 2           | [0, 2]                      |
| Heat load           | 1           | [-3, 3]                     |

**Table 4.** Parameters of shiftable load.

| The load properties | \( T_{\text{trans,start}} \sim T_{\text{trans,end}} \) | \( P_{\text{trans,min}} \sim P_{\text{trans,max}} \) |
|---------------------|---------------------------------------------------|---------------------------------------------------|
| Power load          | 4:00~24:00                                        | 8~26.7KW                                          |

**Table 5.** Parameters of transferable load.

| The load properties | \( T_{\text{cut,min}} \sim T_{\text{cut,max}} \) | \( N_{\text{cut,max}} \) |
|---------------------|---------------------------------------------------|--------------------------|
| Power load          | 2~5                                               | 8                        |
| Heat load           | 2~5                                               | 8                        |
| Gas load            | 2~5                                               | 8                        |

**Table 6.** Parameters of curtailable load.

The analysis of user response of flexible load can be divided into shiftable load analysis, transferable load analysis and curtailable load analysis.
5.2.1. Shiftable load response. Firstly, the shiftable power load is analyzed. The responses of the shiftable power load cluster 1 and the shiftable power load cluster 2 are shown in Fig. 6. Comparing the response of the shiftable power load, the shiftable load 1 is 1 hour before and after the current period, and the shiftable load 2 is 2 hour after the current period, so the response amount will vary with the forward and backward shift ranges. There are differences, but because the shiftable range includes two hours, the response curves have the same trend. Due to the small load regulation time range, the load response has limitations. It can only be shifted in a small period before and after, and the peak load occurs in a period of lower power price compared to the period before and after.

![Figure 6. Response of shiftable power load diagram.](image1)

There is only one cluster of shiftable heat load, and the response of the shiftable heat load is analyzed, as shown in Fig. 7. As can be seen from the figure, the response is relatively concentrated because the shiftable heat load has a long period of shiftable range and can be translated in the three periods before and after the current period. The peak period of load occurs at 01:00, 10:00 and 21:00, and the heat price of nodes in these three periods is lower than that in other periods. Among them, since the heat price is the lowest at 21:00, the load is the highest at this time.

![Figure 7. Response of shiftable heat load diagram.](image2)

5.2.2. Transferable load response. The transferable load in this section only includes the power load, and the situation before and after the response of the transferable power load is shown in Table 7. It can be seen that the splitting period of transferable load does not change, but the power does, which is optimized from the original four periods of 13:00~16:00 to four periods of 6:00~7:00, 16:00 and 23:00. Compared with the shiftable power load, the response is more flexible. The load is shifted to the period when the power price is low, and the total amount of transferable load remains unchanged.
| Flexible load | Condition before load optimization | Condition after load optimization |
|---------------|-----------------------------------|----------------------------------|
| transferable load | time frame 13:00–16:00 | time frame 6:00, 7:00, 16:00, 23:00 |
| Power (MW) | 8.4452, 8.0922, 7.9204, 7.9481 | 9, 9, 5.4060, 9 |

5.2.3. Curtailable load response. Loads that can be reduced in this section include power loads, heat loads and natural gas loads, as shown in Fig. 8 before and after optimization. As can be seen from the figure, the power load was reduced during the two peak periods of power price, effectively avoiding the peak power price. However, due to the restriction of continuous cutting time and cutting times, the load cannot be continuously and infinitely reduced. In addition, although the specific time of reduction of heat and gas loads is different, they are concentrated in the period of time when power prices are higher, when the reduction is more cost-effective.

5.2.4. Changes in Multi-user Load Curves. Because load shifting and load transfer do not affect the total load, but load shedding will reduce the total load and affect the load curve, the flexible load curve optimized by nodal energy price is shown in figure 10. It can be seen from the diagram that the peak and valley difference of energy demand of multi-energy load users decreases, and the change of load curve is opposite to the trend of nodal energy price. At this point, the cost of multi-energy users reduced by 11548.02$. Therefore, by calculating the nodal energy price of the integrated energy system, including power price, heat price and gas price, the nodal price signal can be used to guide the user's energy consumption behavior, which can stimulate the flexibility of the user side and reduce the user's energy consumption cost.

6. Conclusion
In this paper, considering the uniqueness and similarity of different load types in energy use characteristics, the operation mode of integrated energy system considering multiple demand response is first proposed. Secondly, the optimal operation model of integrated energy system with multiple demand side load response is established. Based on the test example constructed in this paper, the following conclusions are drawn:

1) Under the nodal energy price strategy of the integrated energy system, the integrated energy system considering the demand response load has lower operating cost than the integrated energy system.
which is not involved in the demand response load, which accords with the idea of energy saving and emission reduction. The energy utilization rate is improved.

2) A variety of demand side loads participate in the scheduling, and users adjust their energy demand according to the nodal energy price, which not only makes the supply and demand more balanced, but also can cut the peak and fill the valley, reduce the load difference, and provide a new direction for the development of the integrated energy system.

3) In the follow-up work, the uncertainty model is established considering the randomness of wind power output, and the influence of network dynamic characteristics and user side load substitution on the optimal operation of the system is further considered.

References

[1] ZHAO Na, LI Xiangyu, ZHU Yongqiang, et al. Gas and electric collaborative optimization strategy for demand side of micro energy internet [J]. Electric Power Construction, 2017, 38(12): 60-67.

[2] LIU Jichun, ZHOU Chunyan, GAO Hongjun, et al. A day-ahead economic dispatch optimization model of integrated electricity-natural gas system considering hydrogen-gas energy storage system in microgrid [J]. Power System Technology, 2018, 42(1): 170-179.

[3] JIANG Ziqing, LIU Yuquan, AI Qian, et al. Multi-agent oriented interaction mechanism of integrated energy system in industrial parks [J]. Southern Power System Technology, 2018, 12(3):18-26.

[4] XU Hang, DONG Shufeng, HE Zhongxiao, et al. Electro-thermal comprehensive demand response based on multi-energy complementarity [J]. Power System Technology, 2019, 43(2): 480-489.

[5] Xu Zheng, Sun Hongbin, Guo Qinglai. Review and prospect of integrated demand response[J]. Proceedings of the CSEE, 2018, 38(24):7194-7205, 7446 (in Chinese).

[6] Correaposada C M, Sánchez Martin, Pedro. Integrated power and natural gas model for energy adequacy in short-term operation [J]. IEEE Transactions on Power Systems, 2015, 30(6): 3347-3355.

[7] Zhong Yongjie, Sun Yonghui, Xie Dongliang, et al. Multi-scenario optimal dispatch of integrated community energy system with power-heating-gas-cooling subsystems[J]. Automation of Electric Power Systems, 2019, 43(12): 76-84 (in Chinese).

[8] HUANG Guori. Optional collaborative planning and operation strategy of integrated energy systems with power to gas technology [D]. Zhejiang University, 2017.

[9] Dong Shuai, Wang Chengfu, Xu Shijie, et al. Day-ahead optimal scheduling of electricity-gas-heat integrated energy system considering dynamic characteristics of networks [J]. Automation of Electric Power Systems, 2018, 42(13): 12-19 (in Chinese).

[10] LANG Yizihe. Study on price mechanism of multi-energy system considering interaction between source and load [D]. Nanjing: Southeast University, 2018.

[11] Correaposada C M, Sánchez Martin, Pedro. Integrated power and natural gas model for energy adequacy in short-term operation [J]. IEEE Transactions on Power Systems, 2015, 30(6): 3347-3355.

[12] YANG Zijuan, GAO Ciwei, ZHAO Ming. Summary of research on power-natural gas network coupling system [J]. Automation of Electric Power Systems, 2018, 42(16): 21-31, 56.

[13] CORREA-POSADA C M, SANCHEZ-MARTIN P. Integrated power and natural gas model for energy adequacy in short term operation [J]. IEEE Transactions on Power Systems, 2015, 30(6): 3347-3355.

[14] Li Z, Wu W, Shahidehpour M, et al. Combined heat and power dispatch considering pipeline energy storage of district heating network[J]. IEEE Tran. Sustain. Energy, 2016,7(1): 12-22.

[15] Wolf D D, Smeers Y. The Gas Transmission Problem Solved by an Extension of the Simplex Algorithm[J]. Management Science, 2000, 46(11):1454-1465.