A Day-Ahead Scheduling Model of Electricity-Gas Integrated System with Power-to-Gas

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Abstract—In recent years, with the increasing of gas-fired power plants and the development of power-to-gas (P2G) technology, and the interdependence between the power system and the natural gas system has gradually deepened. This paper proposes a day-ahead optimal scheduling model for an electricity-gas integrated system. Based on P2G, it can realize the two-way movement of energy between the power system and the natural gas system, promote the coordinated and optimized operation of the two energy systems, and improve energy utilization. The model proposed in this paper minimizes the total cost of both systems. Firstly, the power system sub-model and the natural gas system sub-model in the collaborative optimization model are studied separately, and the constraints between the two systems are considered. Then, the piecewise linearization method and DC power flow simplification method are adopted, the nonlinear problem is transformed into a mixed integer linear programming problem. Finally, the load forecast value of the day-ahead dispatch is loaded, and the 24-hour dispatch result is obtained through the simulation platform, and the P2G is used for joint dispatch.

1. INTRODUCTION

With the increasing in the scale of new energy, the randomness, volatility of wind power have caused a lot of energy waste. The gradual development of power-to-gas (P2G) technology provides a new solution, making it possible for the two-way flow of energy between the power system and the natural gas system, becoming one of the options that can solve the problem of long-term power storage. And in theory, it can alleviate grid congestion [1]. In recent years, the proportion of natural gas power generation capacity has been increasing. Compared with traditional thermal power plants, gas power generation is in line with the general trend of low-carbonization. It is estimated that by 2035, Chinese total natural gas power generation is expected to increase to 760 billion kWh. With the large-scale coverage of gas networks, natural gas power generation will become an important part of the future energy system[2][3]. The combination of power system and natural gas system through P2G is an optimized configuration of energy. Compared with traditional energy storage equipment, the electricity-to-gas technology has large storage capacity and long discharge time [4][5], which can effectively absorb large-scale wind power and realize long-term, large-scale space-time translation of energy [6].

In recent years, research has mainly focused on the impact of the joint operation of power and natural gas networks on the safety and steady state of the power system. In [21][22], a steady-state flow model of natural gas networks is proposed, through the natural gas system and gas turbine generator sets. Perform short-term combination to analyze the impact of natural gas system on the short-term dispatch of power system unit combination. In [23] the increasing degree of coupling between the power system and the natural gas system is analyzed, and corresponding countermeasures to the potential security threats caused by the production scheduling and safe operation of the power system is proposed. In
addition, most of the existing papers are limited to the analysis of the impact of electricity-to-gas devices on the power system and natural gas system[25], the economic analysis of electricity-to-gas devices[26], the capacity setting and selection of electricity-to-gas facilities site[26][27], and comparison of electricity-to-gas devices and other energy storage methods [28].

In summary, it is possible to consider the integration of electrical systems and natural gas systems, and the introduction of wind power and electricity-to-gas facilities has less research on optimization scheduling. Therefore, how to maximize the use of new energy, improve energy utilization, and achieve economic optimization under the constraints of the power grid and gas grid, is an urgent problem to be solved.

2. PRINCIPLES AND ADVANTAGES OF P2G TECHNOLOGY

P2G technology includes two types of electricity to hydrogen and electricity to methane. The chemical reaction principle of electro-hydrogen conversion is electrolysis of water; the chemical reaction principle of electro-conversion of methane is electrolysis of water and methanation.

The water electrolysis reaction is to electrolyze water to generate \( H_2 \) and \( O_2 \). There are three main methods for producing hydrogen from electrolyzed water, which are alkaline electrolysis of water to produce hydrogen, solid polymer electrolysis of water to produce hydrogen, and high temperature solid oxide electrolysis of water to produce hydrogen. At present, the efficiency of the electrolysis water reaction is about 56% to 73%[7][8].

The methanation reaction in which \( CO_2 \) and hydrogen are added to the catalyst is one of the effective ways to utilize \( CO_2 \). The main reaction products are \( CH_4 \) and \( H_2O \). At present, the efficiency of the methanation reaction is about 75% to 80% [9].

The electro-hydrogen conversion only requires the electrolysis of water, which avoids the energy loss caused by the subsequent methanation reaction and reduces the equipment construction costs related to the methanation reaction. However, the injection of hydrogen into the natural gas pipeline will cause risks in the transportation pipeline. At present, the maximum allowable volume fraction of hydrogen in natural gas pipelines is about 10% to 15%, and the maximum allowable volume fraction of hydrogen in gas turbine fuel is about 5% [12].
The whole process of electric conversion to methane includes two steps of electrolysis of water reaction and methanation reaction, the efficiency is about 42% to 58% [13], and the efficiency is lower than that of electric conversion to hydrogen. But the most important advantage of methane is that it can be directly injected into existing natural gas pipelines and storage devices for direct production and consumption.

The current power system development has many systems for storing electrical energy, all of which have different storage principles, and there are big differences in capacity, energy storage efficiency, construction and operation costs, etc. [14]. Compared with other energy storage methods, we can see from Fig. 1 that P2G technology has obvious advantages in terms of capacity. The rated power can reach the gigawatt level, and the discharge time can last for several days or even months.

![Fig.1. Comparison of energy storage capacity.](image-url)
3. Optimization Model

Electricity-gas integrated system proposed in this chapter not only considers the economic and technical constraints of power system dispatch, but also considers the economic and technical constraints of natural gas system dispatch, so as to realize the optimal day-ahead dispatch of the joint system.

3.1 Nomenclature

- $a, g, j, s$ stand for P2G facility, natural gas load, gas supply point, and gas storage facility, respectively.
- $d, i, t, w$ represent power load, power generation unit, time and wind power plant, respectively.
- $m, n$ represents the index of the natural gas network nodes.
- $F_i^c$ is cost curve of power generation unit.
- $G_j^g$ is the gas production at gas supply point.
- $i_{at}^b$ are the status of the facility, 0 means closed, 1 means open, respectively.
- $P_{it}^b$ are the output active power of each units, respectively.
- $S_{Ui}^b, S_{Di}^b$ are start and stop costs of unit, respectively.
- $X_{on}, X_{off}$ are on/off time counter with unit $i$ at time $t$, respectively.
- $E_s$ is the gas storage capacity of $s$ at time $t$.
- $P_{mt}$ is the pressure of the natural gas system.
- $Q_{mn}^i$ is the average gas flow rate of pipeline $mn$.
- $G_{it}^u$ is the gas consumption of gas-fired units.
- $G_{at}^g$ is the gas production of P2G facility $a$ at time $t$.
- $C_{if}^fuel$, $C_w^b$, $C_j^g$, $C_s^g$ are each corresponds to the fuel price of power generation unit $i$, the cost of wind power overflow, the price of natural gas produced at gas supply points, and the price of natural gas stored at gas storage point $s$.
- $P_{f,wt}$, $P_{at}^b$, $G_{gt}$ correspond to the predicted output, power load and gas load of the wind power plant at $t$, respectively.
- $SR_t$ is the reserve at time $t$.
- $T_{on}^i$, $T_{off}^i$ is the minimum on/off time of unit $i$.
- $UR_{it}$, $DR_{it}$ are ramp up/down rate of power generation unit $i$, respectively.
- $K_{mn}^f$, $K_{mn}^p$ are constant of pipeline flow characteristic and pipeline characteristic.
- $\eta_{at}^{ptg}$ is the efficiency of P2G equipment $a$.
- $GU$ is the gas unit equipment.
- $K_a, K_d$ are relation matrix of P2G equipment and load, respectively.
- $K_p, K_w$ are the relation matrix of power generation unit and wind power, respectively.
- $PL_{max}$ is the maximum power flow (vector).
- $SF$ is the transfer factor matrix.

3.2 Objective Function

The model aims to minimize the overall energy cost, which includes non-gas turbine operating costs, wind spillover costs, natural gas production costs, and natural gas storage costs. The objective function is shown as follows.

$$\min = \sum_{i \in GU} C_{if}^{fuel} [F_i^c (P_{it}^b) + SU_{it}^b + SD_{it}^b] + \sum_{i \in W} C_{iw}^w (P_{f,wt} - P_{at}^b) + \sum_{j \in G} C_{j}^g \cdot G_{jt}^g + \sum_{s} C_{s}^g \cdot Q_{s,}^{out}$$ (1)
3.3 Model of Power System

\[
\sum_i p_i^b + \sum_w p_w^b - \sum_a p_{at}^{bptg} = \sum_d p_d^b
\]

(2)

\[p_{i(t)}^b \leq P_i^b \leq P_i^{max} \cdot I_{i(t)}^b\]

(3)

\[0 \leq p_{at}^{bptg} \leq P_a^{max} \cdot I_{at}^{bptg}\]

(4)

\[0 \leq p_w^b \leq P_{f}^{b}\]

(5)

\[
(X_{i(t)}^{on} - T_{i(t)}^{on}) \cdot (I_{i(t)}^b - I_{i(t-1)}^b) \geq 0
\]

(6)

\[
(X_{i(t)}^{off} - T_{i(t)}^{off}) \cdot (I_{i(t)}^b - I_{i(t-1)}^b) \geq 0
\]

(7)

\[SU_{i(t)}^b \geq su_i \cdot (I_{i(t)}^b - I_{i(t-1)}), SU_{at}^b \geq 0\]

(8)

\[SD_{i(t)}^b = sd_i \cdot (I_{i(t)}^b - I_{i(t-1)}), SD_{at}^b \geq 0\]

(9)

\[
p_i^b - p_i^{b(t-1)} \leq UR_i \cdot I_{i(t-1)}^b + p_i^{min} \cdot (I_{i(t)}^b - I_{i(t-1)}^b) + p_i^{max}(1 - I_{i(t)}^b)
\]

(10)

\[
p_i^{b(t-1)} - p_i^b \leq DR_i \cdot I_{i(t)}^b + p_i^{max} \cdot (I_{i(t)}^b - I_{i(t-1)}^b) + p_i^{max}(1 - I_{i(t-1)}^b)
\]

(11)

\[
\sum_d p_d^{max} \cdot I_{d(t)}^b \geq \sum_d P_d + SR_i
\]

(12)

\[
-PL^{max} \leq SF \cdot \left( K_P \cdot P_i^b + K_w \cdot P_w^b - K_a \cdot p_{at}^{bptg} - K_d \cdot p_d^b \right) \leq PL^{max}
\]

(13)

\[I_{i(t)}^b - I_{i(t)}^{bptg} \leq 1, \text{ if } K_p(e,i) = K_a(e,a) = 1 \]

(14)

The above are the basic constraints of the power system, including the system load balance generator set, the power limit of the electric-to-gas device and the wind farm, the minimum on/off time limit, the startup and shutdown cost, the uphill and downhill limit, and the system rotation reserve requirements, DC power flow constraint.

Constraint (14) ensures that the gas-fired unit and the P2G mechanism will not operate at the same time, ensuring operational safety.

3.4 Model of Natural Gas System

In this section, the gas network model is used to describe the dynamic characteristics of the natural gas system, and the gas flow rate and line package speed are considered by changing the input and output gas flow. Constraint (15) represents the gas network node balance, which means that the total gas flow injection is equal to the total extraction amount at each node.

\[
\sum_{n \in G(m)} (Q_{in,n}^t - Q_{out,n}^t) + \sum_{s \in G(m)} (Q_{out,s}^t - Q_{in,s}) + \sum_{j \in G(m)} G_{jt}^g + \sum_{a \in G(m)} G_{at}^g = \sum_{l \in G(m)} G_{lt}^g + \sum_{g \in G(m)} G_{gt}
\]

(15)

\[G_{j(t)}^{min} \leq G_{jt}^g \leq G_{j(t)}^{max}\]

(16)

\[P_{r(t)}^{min} \leq P_{r(t)} \leq P_{r(t)}^{max}\]

(17)

\[E_{st} = E_{st(t-1)} + Q_{in,t}^s - Q_{out,t}^s\]

(18)

\[E_{st}^{min} \leq E_{st} \leq E_{st}^{max}\]

(19)

\[Q_{in,\min}^s \leq Q_{in,t}^s \leq Q_{in,\max}^s\]

(20)

\[Q_{out,\min}^s \leq Q_{out,t}^s \leq Q_{out,\max}^s\]

(21)

Constraint (16) shows the maximum and minimum amount of gas produced by the gas well, and constraint (17) represents the pressure limit of each gas node, constraint (18) represents the balance of
the storage capacity of the gas tank, and constraint (19) represents the maximum and minimum storage capacity.

\[
\tilde{Q}_{mn,t} = \text{sgn}(Pr_{rt}, Pr_{nt}) \cdot K_{mn}^{gf} \cdot \sqrt{|Pr_{rt}^2 - Pr_{nt}^2|}
\]

(22)

\[
\tilde{Q}_{mn,t} = \frac{Q_{mn,t}^\text{out} + Q_{mn,t}^\text{in}}{2}
\]

(23)

\[
\text{sgn}(Pr_{rt}, Pr_{nt}) = \begin{cases} 
1, & Pr_{rt} \geq Pr_{nt} \\
-1, & Pr_{rt} \leq Pr_{nt}
\end{cases}
\]

(24)

(22)-(24) are low simulation in natural gas pipeline.

\[
LP_{mn,t} = K_{mn}^{lp} \cdot \tilde{P}_{mn,t}
\]

(25)

\[
LP_{mn,t} = LP_{mn,t-1} + \tilde{Q}_{mn,t} - \tilde{Q}_{mn,t}^\text{out}
\]

(26)

\[
\tilde{P}_{mn,t} = \frac{Pr_{rt} + Pr_{nt}}{2}
\]

(27)

LP represents the amount of natural gas contained in the pipeline, and LP can be regarded as proportional to the average pressure of the gas pipeline and pipeline characteristics. Since the uncertainty of real-time gas load can actually be balanced by LP, the uncertainty of natural gas load is not considered in the proposed joint day-ahead optimal scheduling model.

3.5 Joint Constraint

\[
G_{it}^u = \left[ F_i^c(P_{it}^b) + SU_{it}^b + SD_{it}^b \right] / HHV, \quad \forall i \in GU.
\]

(28)

\[
G_{it}^{p2g} = \phi \cdot a_{it}^{p2g} \cdot \eta_a^{p2g} / HHV, \forall a \in PtG
\]

(29)

Gas generators and P2G facilities establish a connection between the power system and the natural gas system. Constraint (28) is the relationship between gas power generation dispatch and gas consumption unit. Constraint (29) represents a P2G facility, where the higher heating value (HHV) is 1.026 MBtu/kcf and the energy conversion factor $\phi$ is 3.4 MBtu/MWh.

Finally, the optimal model of electricity-gas integrated system is established.

4 STRATEGY OF SOLUTION

4.1 Linear Method

The piecewise linearization method is utilized to simplified the objective function (1), whose principle is shown in Fig. 2.

![fig2](image)

Fig.2. Piecewise linearization of fuel cost

Linearized model of fuel costs is shown as follows:

\[
\tilde{f}(t) = \sum_{i=1}^{N} (\alpha_i P_i(t) + \beta_i B_i(t))
\]

(30)

\[
\alpha_i = \frac{f(P_{i+1}) - f(P_i)}{P_{i+1} - P_i}
\]

(31)

\[
\beta_i = f(P_i) - P_i \alpha_i
\]

(32)
\[
P_i B_i(t) \leq P_i(t) \leq P_{i+1} B_i(t)
\]
\[
U(t) = \sum_{i=1}^{N} B_i(t) \leq 1
\]
\[
-M(1 - \delta_{mn,t}) \leq \bar{Q}_{mn,t} \cdot K_{mn}^2 \cdot (\bar{P}_{mt}^2 - \bar{P}_{nt}^2) 
\leq M(1 - \delta_{mn,t})
\]
\[
-M \delta_{mn,t} \leq -\bar{Q}_{mn,t} \cdot K_{mn}^2 \cdot (\bar{P}_{mt}^2 - \bar{P}_{nt}^2) \leq M \delta_{mn,t}
\]
\[
-M(1 - \delta_{mn,t}) \leq P_{mt} + P_{nt} \leq M(1 - \delta_{mn,t})
\]

The linearization of \( A \) is completed through (35)-(37), and the linearization of \( P_{mt}^2 \) and \( P_{nt}^2 \) are completed in the same way.

### 4.2 Power Transfer Distribution Factor

\( B_{bus} \) represents the non-full rank node admittance matrix, \( \theta \) represents the voltage phase angle matrix, \( P_{flow} \) represents the node injection active column vector, \( C \) represents the branch-node correlation matrix, and \( B_{branch} \) represents the non-full rank branch susceptance matrix.

\[
P_{inj} = B_{bus} \theta
\]
\[
P_{flow} = B_{branch} C \theta
\]
\[
P_{flow} = P_{g}^T P_{flow} = P_{flow}^T \begin{bmatrix} p_{int}^T \\ p_{flow}^T \end{bmatrix}
\]
\[
P_{inj} = P_{g}^T P_{g} P_{inj} = P_{injection}^T
\]

Where, \( P_{f} \) represents the permutation matrix sorted by intra-class road flow, \( P_{g} \) represents the permutation matrix sorted by injection classification, and \( P_{injection} \) represents the active injection vector arranged according to the classification order [21].

### 5 Case Analysis

The six-bus power system on the left includes three generators G2-G4, two gas turbines G1, G5, a P2G device, a wind farm, seven transmission lines and three loads, which is shown in Fig. 3. The P2G equipment has a capacity of 37.5 MW and an efficiency of 0.64 [22]. The fuel price of G2-G4 is $2.5/MBtu. The seven-node gas system includes two gas wells W1 and W2, a gas storage S1, six pipelines PL1-PL6, and five gas loads. Both the initial and final bus packages are set to 106800 kcf. And the forecast values of wind power and loads in next 24 hours are shown in Fig. 4.

The optimal result of output active power of P2G devices is shown Table I according to the day-ahead optimal dispatch model proposed in this paper.

![Fig. 3. 6-node power system/7-node natural gas system.](image-url)
Fig. 4. Forecast values of wind power and loads in the next 24 hours.

Table I. Output active power of P2G devices (MW)

|     | t4   | t5   | t6   |
|-----|------|------|------|
| m1  | 77.481 | 79.532 | 6.676 |
| i3  | 36.533 | 37.500 | 4.148 |

Table I shows that the P2G equipment at node 1 of the natural gas system has consumed 77.471 MW, 79.532 MW and 6.676 MW of wind power during t4, t5, t6, respectively. The P2G equipment at node 3 of the left power system also consumed 36.533 MW, 37.500 MW, 3.148 MW of wind power during t4, t5, t6. The P2G equipment converts this wind energy into natural gas and stores it in the natural gas system when the power load is low, as shown in Fig 4. It can also be seen that the power load from t3 to t6 is at a trough, the output of wind farm is at its peak at this time, and the generated electric energy cannot be consumed by the electric load, so it is converted into natural gas through the P2G equipment and enters the natural gas system.

In the time period from t3 to t6, the gas load increased by about 250kcf. Firstly, if the natural gas system is taken out independently, the increase in the system gas load will inevitably increase the amount of natural gas entering the system from the gas wells W1 and W2, or the gas storage tank Gas enters the system, and in this model, the gas output of the gas storage tank is 0 during the period from t3 to t6, and the intake of the gas wells W1 and W2 into the only channels PL5 and PL6 of the natural gas system does not show much fluctuation. The natural gas volume of the PL5 pipeline was maintained at 2000kcf, and the intake volume of the PL6 pipeline did not increase but decreased, from 4148.443kcf to 3939.483kcf.

Combined with the previous analysis, it can be seen that during this period of time, the natural gas produced by the P2G facility enters the natural gas system, which offsets the increase in gas load and reduces the speed requirements of the gas well in response to load fluctuations.

Combining Fig. 4 and Simulation results from GAMS, we find that when natural gas load is low and the electric load rises (t14-t16), the electric load increases by about 90 MW. At same time, the operation result of the optimal dispatch model shows that the gas turbine G5 at i3 increased its output from 10 MWh to 50 MWh. The output of the gas turbine at i1 increased by 12 MWh. At this time, the output of non-gas turbine G2 at i2 and non-gas turbine G4 at i6 increased by 35 MWh.

If the power system and the natural gas system are completely independent at this time, the additional load about 90 MW needs to be fully borne by the non-gas turbine unit, which will greatly increase the power generation cost of the non-gas generator unit, leading to the activation of the backup generator unit, resulting in a further increase in power generation costs.

The operation results show that the minimum value of the objective function, that is, the lowest comprehensive energy cost is 537,995.392 USD. If the P2G equipment are removed from the model, the energy cost will be 597,756.862 USD. By contrast, P2G saves about 10% of economic costs and creates a good Economic benefits.

P2G technology plays a significant role in eliminating wind power, it can reduce the impact of load fluctuations on both power system and natural gas system, can save power generation costs.
6 CONCLUSION
The electricity-gas integrated system day ahead scheduling model makes the time characteristic curve of power load and gas load more stable, effectively reducing the difficulty of responding to load fluctuations in the power system, alleviating the pressure of power dispatch, reducing the cost of power generation. At the same time, it also effectively relieves the congestion of the natural gas network, and has a very positive impact on the optimal dispatch of the natural gas system. The model in this paper realized optimal economy and efficient use of energy. The subject has great research value in the future.

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