Research on unit commitment optimization of high permeability wind power generation and P2G

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Abstract

As an important form of the future energy utilization, the operation of the combined electricity-gas energy systems is also threatened by high-level penetration intermittent renewable energy. The application of power to gas (P2G) technology has deepened the coupling between the concerned power system and natural gas system, and hence bidirectional energy flow between the power system and natural gas system can be implemented. P2G technology provides an alternative solution for the optimal operation of the combined electricity-gas energy systems to accommodate intermittent renewable energy, particularly wind power. Under this new environment, the unit commitment optimization of high permeability wind power and P2G are addressed, where the objective is to minimize the total operating cost of combined electricity-gas energy systems. Firstly, the P2G technology, the application and supportive policies are introduced. Secondly, considering the characteristics of P2G devices and the combined system, a two-level economic dispatch model of the combined system with security constraints is proposed. Thirdly, based on Karush Kuhn Tucker (KKT) optimality condition, the two-level optimization model is transformed into a mixed integer linear programming. Finally, the case study shows that the proposed unit commitment model is effective and accurate in optimizing the combined energy systems with high penetration level wind power.

Key words: Power to gas(P2G); wind power high permeability; electricity and natural gas combined system; two-level optimization model of unit commitment; KKT

I. INTRODUCTION

With the increasing energy demand and environmental concerns, the traditional economic development model for the traditionally centralized fossil energy utilization as the core is gradually changing. However, the third industrial revolution with the Energy Internet as the core is emerging discussed in Refs. 1–5. In Ref. 1, the author discusses the basic concept and research framework of the Energy Internet. As seen, the energy internet uses the power system as the core and renewable energy as the primary energy. It is a complex multi-network system closely coupled with other systems such as natural gas network and transportation network, etc.

Within the framework of the energy internet, renewable energy will gradually replace traditional fossil fuels to act as the play the main energy supply. However, the volatility and intermittency of renewable energy, such as wind power, restrict its application. This situation has led to a large volume of wind energy waste such as in Refs. 6–9. In recent years, the gradually maturing technology of P2G provides with a new way to store and utilize the large amount of renewable energy.

Through P2G equipment, excess renewable energy can be converted into artificial natural gas, which has similar characteristics of the ordinary natural gas. Thus, the artificial natural gas can be injected into natural gas networks for transporting and storing. Natural gas is generally stored in abandoned oil and gas fields, aquifers or salt caverns. During the peak periods of electric load, natural gas can be converted into electric energy through the gas to power (G2P) process, forming an electric-gas-electric circulation system as illustrated in Ref. 10. The coupling between the power system and the natural gas system can further deepen. On the basis of this, the capability of the system to accommodate renewable energy generation can be obviously enhanced by coordinating the operation of the power system and natural gas network.

Certainly, not all sites are suitable for constructing and operating P2G facilities. Some commercial P2G demonstration projects have been built in Germany such as in Refs. 11-12. The authors suggest a 1 km buffer around a wind farm to indicate an area that is suitable for the operation of P2G facilities. With regard to a further development of renewable energy in this region, this factor is only a supplement but not a strict requirement for P2G. Some areas not suitable for constructing P2G are listed in Ref. 13. These are areas with a steep slope, flood protection areas, water expanse, existing buildings,
infrastructure and forests. Inspired by Ref. 14, P2G is also suitable for tidal energy and can be built in rural areas such as inner land or offshore sites.

Different countries have different policies, which are very important for the development of emerging technologies such as Ref. 15. Europe sees P2G technology as a key to energy transformation. In order to promote technological innovation, stimulate the potential market and healthy development, Western countries have implemented a series of policy incentives such as Ref. 13. As a result, at least 20 P2G research projects have been carried out in Germany. The Deutsche Energie-Agentur (dena) has set up a dedicated information tracking platform, which can provide relevant project information. dena and China also have started collaborating on P2G such as Ref. 16. At present, the China’s policies on P2G technology are few and still in the exploratory stage. However, these policies are expected to promoting the development of P2G technologies, reducing technical costs and deepening the reform of the electricity market. P2G technology is expected to play an important role in optimizing unit commitment and participating in ancillary service markets.

A. Relevant studies

The emerging P2G technology strengthens the coupling between the power system and the natural gas system but also challenges their coordinated operation. The traditional power system and natural gas system are coupled only by G2P, which makes the energy flow in one direction between them. Some studies have explored this type of system. For example, in Ref. 17, evolutionary strategies are used to solve the optimal scheduling problem of combined electricity-gas energy systems. In Ref. 18, considering electric-gas load correlation, the probabilistic optimal power flow model of electric-gas combined system is constructed. In Ref. 19, the combined electricity-gas energy network operation strategy considering uncertain wind power prediction is proposed.

With the gradual maturity and commercial application of P2G technology, the bidirectional coupling of combined electricity-gas energy systems is becoming possible. Thus, the flexibility of system operation increases. In Ref. 13, the development potential of P2G technology in Germany is described. In Ref. 20, the impact of P2G technology on combined electricity-gas energy systems is analyzed by using two-stage optimal power flow method. However, the collaborative planning and operation of combined electricity-gas energy systems including P2G equipment are still in the exploration stage.

In recent years, in the framework of developing energy internet, the research on the operation strategies for specific energy systems has been gradually extended to the coordinated operation and optimization of multi-energy systems. Although there are some references on the coordinated operation of electric-gas systems such as Refs. 21-25, the modelling methods still lack extensibility. In the source-network-load framework of the energy systems, the coupling between electricity and natural gas energy systems mainly exists in "source" and "load". For example, the power system and natural gas system are coupled together by P2G and G2P, and P2G equipment is a load to the power system but a source for the natural gas system. In the view of the coupling between "source" and "load", the energy hub (EH) modelling method which can model different energy systems, is proposed in Refs. 26-31.

B. The objective of this study

In this context, the problem of unit commitment optimization of high-penetration wind power and P2G is investigated. Considering the coupling characteristics of the multi-energy systems under source-network-load architecture and the linepack (LP) constraints reflecting the storage capacity of the pipeline, the EH method is used to model the coupled part of the multi-energy system (G2P, P2G, LP), which is universal and extensible. The diagram is shown in Fig. 1. The EH can convert the excess wind power to natural gas via P2G, and the energy can be fed back to the grid via G2P devices if necessary. This achieves the two-way coupling of the natural gas and power system. It benefits the optimization of the gas-power combination system unit combination scheme and improves the economy of the combined system operation.

In order to achieve the optimal allocation of the gas-power combination system, a double-layer optimization model is built to use the lowest operation cost of electricity and gas combined system as its objective. The upper layer optimizes power system operation and the lower layer optimizes the gas system. Under the KKT optimization condition, the two-layer optimization model can be converted into a mixed integer linear programming model to obtain the unit combination alternative options. Considering the fluctuation of wind power output, the Monte Carlo method is used to generate multiple scenarios of wind power output. These scenarios are used to check whether the unit combination alternative options can accommodate changes in wind power generation and finally obtain the optimization schemes to meet all wind power output scenarios.
The figure is given in Fig. 2.

Fig. 2. strategy of unit combination of electricity and natural gas combined system optimal operation

II. SYSTEM DESCRIPTION AND MATHEMATICAL MODEL

Fig. 1 is the schematic diagram of a typical combined electricity and natural gas system. The blue part is EH which consists of P2G, G2P and LP with storage capability. The working principle is summarized as: When the wind power is excessive, EH works at P2G state which converts the excessive wind power into natural gas stored in LP. When the wind power output is sufficient and load peaks, the EH works in G2P state which uses the natural gas stored in LP to generate electrical power.

The P2G process of the EH can be achieved by alkaline electrolysis or proton exchange membrane (PEM). The EH has rapid response capability in response to energy fluctuation. Compared with traditional generation, the G2P devices have faster start-up speed and better climbing speed. In Refs. 32-33, authors studied the optimal capacity configuration of P2G and G2P from an economic point of view. Such a combination of facilities has been proved to be able to provide energy balance and regional maintenance for lines.

Considering the wind turbine and EH based combined electricity and gas system, it is essential to optimize the two system with safety constraints. This section builds the double layer economic dispatching unit combination model shown in Fig. 2. The detailed process is described as follows.

A. Upper layer model--Power System Economic Dispatching Operation Model

1) Target function

\[
\min \left\{ \sum_{i=1}^{NGT} \left( \gamma_i F_i(P_i) I_{P,i} + \eta_i a_i \right) \times (P_i - P_i) + S_i \right\}
\]

The target function of unit combination optimization problem considering high permeability and EH is shown in formula (1). The formula (1) include the fuel and start cost of generator, the spare capacity cost of generator, operation and abandoned wind power cost of wind turbine, fuel cost of EH and CO2 emission reduction benefits.

In the formula, \( i, j \) and \( j \) is the index of time, gas generator and EH. \( NT, NGT \) and \( NEH \) is the total number of time, gas generator and EH. \( \gamma \) is fuel cost which unit is $/m^3$. \( P \) is power which unit is MW. \( F(P) \) is fuel consumption function. \( \eta \) is the unit spare capacity cost which unit is $/m^3$. \( S \) is start and stop cost of generator which unit is $. \( c \) is wind turbine operation cost which unit is $/MW$. \( \pi \) is the abandon wind power cost which unit is $/MW$. \( f_{CO2} \) is the CO2 emission reduction benefits which unit is $. \( I \) is the unit operation state.

Gas units can be divided into condensing, pumping and backpressure unit. The condensing unit is only used for power generation, backpressure and exhaust gas units can be used for power generation and heating.

The fuel consumption function of condensing and backpressure unit is shown in equation (2):

\[
F_i(P_i) = a_i P_i^2 + b_i P_i + c_i
\]

The fuel consumption function of pumping unit is shown in equation (3):

\[
F_i(P, h_i) = A P_i^2 + B P_i + C_i P_i + D_i P_i^2 + E_i P_i + F_i
\]

In the equation, \( P \) is the electric power of pumping unit which unit is MW. \( P \) is the heating power of pumping unit which unit is MW.

2) EH model and its constraint condition

Gas and electricity combined system two-way coupled is achieved by EH which provides a channel for two-way flow of combined system energy. The fuel consumption is shown in equation (4). In this equation, the consumption electricity power function \( P_e \) of EH is shown in equation (10).

\[
F_j(P_e) = F_{P2G,j}(P_e) F_{P2G,j} + F_{G2P,j}(P_e) F_{G2P,j}
\]

TABLE I

<table>
<thead>
<tr>
<th>Three operation modes of EH</th>
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<td>Operation mode</td>
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<td>Standby mode</td>
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<td>Standby mode</td>
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TABLE I shows the three operation modes of EH, as detailed below:
(1) G2P mode and its constraints
When EH is working in G2P mode, the output constraint of G2P is shown in formula (5). The output upper limit \( P_{G2P,j,max} \) is related to the available capacity of LP and is shown in equation (6). The LP of time \( t \) \( L_j(t) \) and its upper limit \( L_j(t) \) is shown in equation (12) and (18).

\[
P_{G2P,j,max} = \min \left( P_{\text{forecast},\text{wind},t} - P_{\text{wind},j}, P_{G2P,j,max} \right)
\]

The working style of G2P is same as backpressure unit, the fuel consumption function is refer to equation (2).

(2) P2G mode and its constraint
When EH is working in P2G mode, it can consume the excessive wind power in power system effectively. The chemical process is describe as \( 2H_2O \rightarrow 2H_2 + O_2 \). \( CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \). Compare with \( H_2 \), the natural gas injected into gas network is more safety. Therefore, all H2 in this paper is used to generate gas. The power consumption in P2G is all from the excessive wind power in power system, the power consumption constraint is shown in formula (7). The P2G power consumption constraint \( P_{G2P,j,max} \) is related to the its access location which is shown in TABLE II.

\[
P_{G2P,j,max} = \min \left( \frac{HHV \left( L_j(t) - L_j(t) \right)}{\eta}, P_{G2P,j,max} \right)
\]

The inequality constrains of LP storage capability in EH is shown in formula (13)-(15). The formula (13) and (14) is the available capacity constraints of LP in pipeline and region, the calculation process is shown in equation (16)- (19); formula (15) promised a LP energy storage recycle period is over, the final gas storage state is similar to gas storage state of start time.

\[
L_j(t_0) = \frac{ZV}{P_{NTP}} \frac{2}{3} \left( \frac{\Pi_k + \Pi_m}{\Pi_k + \Pi_m} \right)
\]

\[
L_{j+1} = L_j + \frac{F_{P2G,j}(P_j) \Delta t - F_{G2P,j}(P_j) \Delta t - D_j}{\eta_j}
\]

The inequality constrains of LP storage capability in EH is shown in formula (13)-(15). The formula (13) and (14) is the available capacity constraints of LP in pipeline and region. According to the reduction of \( CO_2 \) in atmosphere, the \( CO_2 \) emission reduction is shown below:

\[
CER = \frac{\text{molecular mass of } CO_2}{\text{molecular mass of } CH_4} \times \frac{1}{HHV_{CH_4}}
\]

In this equation, \( HHV_{CH_4} \) is the high calorific value of solid methane which use 0.0153MWh/kg; \( CO_2 \) molecular mass is 44; \( CH_4 \) molecular mass is 16. According to equation (9), P2G can consume 180kg \( CO_2 \) when it consume 1MWh power.

When EH is working in P2G mode, the output can still be seen as minus gas load. Therefore, combined the P2G and G2P mode analysis of EH, the expression of \( P_j \) which was mentioned in equation (4) is shown in equation (10).

\[
P_j = \eta_{G2P,j} P_{G2P,j} - P_{P2G,j} \left( \eta_{P2G,j} P_{P2G,j} \right)
\]

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The upper limit and lower limit of storage capacity that can be used to consume excessive wind power or maintain region tie line balance is shown in equation (20) and (21). When EH is working at P2G mode, the natural gas amount stored in LP can be seen as a kind of spare capacity or peaking capacity. This can supply the EH feedback grid when it working at G2P mode. When wind power is excessive or the region tie line switching power increasing, if EH is working in G2P mode, it need meet the G2P minimum output constraint; if EH is working in P2G mode, it need meet the P2G maximum output constraint. The expression of constraint that EH decrease power output \( d_i \) is shown in formula (22).

\[
0 \leq d_i \leq P_{G2P_j} - P_{G2P_j,\text{min}} - I_{P2G_j} P_{P2G_j,\text{max}}
\]

Similarly, when the wind power production capacity is insufficient or the regional tie line switching power increasing, the expression of constraint that EH increase power output is shown in formula (23).

\[
0 \leq u_i \leq I_{G2P_j} P_{G2P_j,\text{max}} - I_{P2G_j} P_{P2G_j,\text{min}} - P_{G2P_j}
\]

B. Lower layer model-- Economical Operation Model of Gas System

1) Target function

The goal of gas system economical operation is to make the whole gas system have lowest gas consumption according to the different price of gas from gas resource. The target function is shown below:

\[
\min f(S_j) = \sum_{t=1}^{NT} \sum_{j=1}^{NS} \text{Price}_{i,j,gas} * S_{ji}
\]

In this equation, \( S_{ji} \) is the amount of natural gas supplied from gas resource. \( \text{Price}_{i,j,gas} \) is the price of gas. NS is the number of gas resource.

2) Gas system constraints conditions

A 7 nodes gas system is shown in Fig. 4, the key components include gas resource, pipelines and compressors.

Fig. 4 diagram of seven node natural gas system

(1) Gas resource and gas load

Natural gas is mostly produced in gas wells, and its gas flow constraints are as shown in formula (25)

\[
S_{j,\text{min}} \leq S_{ji} \leq S_{j,\text{max}}
\]

Gas load is divided in residential, commercial and industrial. The unit gas load play a key role in coupling of electricity and gas combined system. Referring to the constraint of gas unit, the
constraint of gas load is shown in formula (26)
\[ D_{\text{gas},j,\min} \leq D_{\text{gas},j,t} \leq D_{\text{gas},j,\max} \]  
(26)

(2) Pipeline flow

Pipeline flow is determined by the pipeline characteristics (e.g. length, diameter and operating temperature, etc.) and the pressure difference between the relevant nodes. The gas in pipeline will always flow form high-pressure node to low pressure node. The constraint of node pressure is shown below

\[ \Pi_{j,\min} \leq \Pi_{j,t} \leq \Pi_{j,\max} \]  
(27)

Using the gas network transient analysis model in Refs. 34-35, which is possible to better analyze the storage characteristics of the gas pipe network - the change of the LP when the EH is operating in different modes and its influence on the devices regulation capacity. Assuming that the pipeline gas flow is one-dimensional such as Refs. 36-37, the gas flows along the pipeline obey the law of conservation of mass and Newton's second law of motion. Pipeline continuous equation and simplified expression of motion equation is shown below:

\[ \frac{\partial Q_{jt}}{\partial x} = - \frac{A}{\rho Z T} \frac{\partial \Pi_{jt}}{\partial t} \]  
(28)

\[ \frac{\partial \Pi_{jt}}{\partial x} = \frac{2 f \rho n O_{n}}{A^2 D} \left[ Q_{jt} \right] \]  
(29)

In these equations, \( \Pi \) is pipeline node pressure. \( A \) is pipeline cross-sectional area. \( Q \) is pipeline gas flow. \( D \) is pipeline diameter. \( f \) is pipeline friction coefficient that is closely related to gas network pressure; \( \rho \) is gas density. \( Z \) is gas compression factor; \( T \) is gas temperature; \( x \) is distance. \( \rho_n \) and \( Q_n \) is the density and flow of gas in standard pressure and temperature.

\( \text{MGS}_{\text{gas}} \) is defined as the transfer matrix that reflects the influence of gas source node \( S \) and gas load node \( D_{\text{gas}} \) on pipeline flow \( Q \). Using the interpolation linearization method to deform equations (28) and (29), the linear function for solving the gas network gas flow is as follows:

\[ Q_{jt} = \sum_{j=1}^{NG} \text{MGS}_{\text{gas},j,t} \cdot \left[ S_{jt} - D_{\text{gas},jt} - F_{2G,j} \left( P_{jt} \right) \right] \]  
(30)

In this equation, \( NG \) is the total number of gas network nodes. According to the matrix \( \text{MGS}_{\text{gas}} \) and data of each gas source nodes, gas load nodes, the pipeline flow of each pipeline in gas network can be calculated.

(3) Compressor equation

Natural gas will lose its pressure when it flow through the pipeline. The compressor can improve the gas transmission efficiency and maintain the pipeline pressure. The compressor can be divided into fixed node pressure type and fixed compression ratio type in Ref. 38, the electricity drive fixed node pressure is selected and seen as an electricity load.

C. Unit combination constraint that considering about wind power output fluctuation

This section combines the typical unit combination constraints listed in Ref. 39, and list the unit combination constraint that considering about wind power output fluctuation.

The power balance of electricity system is shown in equation (31). In this equation, \( P_{em} \) is wind turbine output power. \( Nw \) is the number of wind turbine. \( D_{el} \) is electricity load.

\[ \sum_{i=1}^{NG} P_{d,i,t} + \sum_{j=1}^{NEH} P_{d,j,t} + \sum_{w=1}^{Nw} P_{wt} = D_{el,t} \]  
(31)

Constraints of gas unit and wind turbine power output is shown in formula (32) and (33). In these formulas, \( P_{f,wt} \) represents the wind turbine’s power output forecast:

\[ P_{t,\min} \leq P_{it} \leq P_{t,\max} \]  
(32)

\[ 0 \leq P_{wt} \leq P_{f,wt} \]  
(33)

The constraints of gas unit boot time \( T_{on,i,t} \) and shutdown time \( T_{off,i,t} \) is shown in equation (34) and (35). In these equations, \( X_{on,i,t} \) and \( X_{off,i,t} \) is the already turned on time and already turned off time of gas unit.

\[ \left[ X_{on,i,t} - T_{on,i,t} \right] \geq 0 \]  
(34)

\[ \left[ X_{off,i,t} - T_{off,i,t} \right] \geq 0 \]  
(35)

The gas unit increase output power capability \( u_t \) and decrease output power capability \( d_t \) is shown in formula (36) and (37). In these formula, \( U_{GT,i,t} \) and \( D_{GT,i,t} \) is the limit slope of unit up climbing and down climbing.

\[ u_t = P_{t,\max} - P_{t,\min} \leq \left[ 1 - I_{it} \left( 1 - I_{t(i-1)} \right) \right] U_{GT,i,t} + I_{it} \left( 1 - I_{t(i-1)} \right) P_{t,\max} \]  
(36)

\[ d_t = P_{t,\min} - P_{t,\max} \leq \left[ 1 - I_{it} \left( 1 - I_{t(i-1)} \right) \right] D_{GT,i,t} + I_{it} \left( 1 - I_{t(i-1)} \right) P_{t,\min} \]  
(37)

It is assumed that the wind power output in region is subject to normal distribution \( N(\mu_w, \sigma_w) \). \( \mu_w \) present the forecast of wind turbine output. \( \sigma_w \) present the fluctuation of wind turbine. According to the distribution function, Monte Carlo simulation method is used to generate multiple scenes to simulate the influence of wind turbine output fluctuation on unit combination optimization. The constraint of electricity and gas combined system to wind turbine output fluctuation adjustable ability that is described by electricity and gas combined system output power increase ability \( u_t \) and decrease ability \( d_t \) is shown below:

\[ 0 \leq u_t \leq \sum_{i=1}^{NG} u_t I_{it} + \sum_{j=1}^{NEH} u_t I_{jt} \]  
(38)

\[ 0 \leq d_t \leq \sum_{i=1}^{NG} d_t I_{it} + \sum_{j=1}^{NEH} d_t I_{jt} \]  
(39)

Electricity system line constraint is shown in formula (40).

\[ \text{Limit}_{t,\min} \leq \sum_{i=1}^{NG} \text{MGS}_{el,i} \times (P_{it} + P_{wt} - D_{el,i,t}) \leq \text{Limit}_{t,\max} \]  
(40)
In this formula, MGS_{el} is the transfer matrix that reflects the influence of electricity power resource node S and electrical load node D on line flow; Limit is electricity line transfer capacity constraint.

### III. Solution

The double layer economic dispatching of the combined unit model for the electricity and gas combined system with security constraint has a master-server relationship and strict optimization order. The current method is to transform the double layer optimization model into a mixed integer linear programming model so that it can be solved in KKT optimization conditions.

First, for the lower layer optimization model, the relationship between pipeline flow and node pressure is non-linear. Based on the pipeline flow Q_{jt} from the transfer matrix MGS_{gas}, the pressure of each node in the gas network is calculated by equation (29) through interpolating linearization with known gas source node pressure.

The equation is shown below:

$$\Pi_{jt,n} = \Pi_{jt,m} \cdot \frac{2ZRTF_p \mu_j}{A^2 D\Pi_{jt,av}} \Delta x$$

In this formula, \( \Pi_n \) and \( \Pi_m \) is the pressure of node m and node n. \( \Delta x \) is the pipeline length between m and n.

Second, for linear expression (24)-(30) of lower layer model, these can be transferred to addition constraint and merged to upper layer optimization model in KKT optimization condition such as Refs. 39-41.

The nonlinear constraint condition is linearized by the method in Ref. 42, and the model is transformed into a mixed integer linear programming problem which is shown below:

$$\text{Max} - f(P_{av}) = \sum_{i=1}^{NGT} \left( \gamma_i F_i(P_{av}) \Delta t \right)$$

The newly gas network balance constraint, gas network gas resource constraint and gas network pipeline transmission capacity constraint is shown in formula (43)-(45). In these formula, \( \lambda_{jt} \), \( \omega_{min,jt} \), \( \omega_{max,jt} \), \( \mu_{min,jt} \) and \( \mu_{max,jt} \) are the newly constraint’s non-negative Lagrange multiplier when meet the KKT optimization conditions. Using above Lagrange multiplier modify gas price of different gas resource, which is shown in equation (46). This can make the gas system operation cost be lowest to achieve the economic operation of gas system.

$$\sum_{i=1}^{NS} S_{it} + \sum_{k=1}^{NEH} P_{P2G, jk} = \sum_{j=1}^{NG} D_{gas, j} \cdot \lambda_{jt}$$

$$S_{j, min} \leq S_{j, max} : \omega_{min,jt} \leq \omega_{max,jt}$$

$$L_x(t) \leq \sum_{j=1}^{NG} MGS_{gas, j} \left[ S_{jt} - GL_{jt} - F_{P2G,j} \left( P_{jt} \right) \right]$$

$$\leq L_x(t) : \mu_{min,jt} \leq \mu_{max,jt}$$

$$\text{Price}_{jt, gas} = \text{Price}_{j(t-1), gas} + \lambda_{jt} + \omega_{min,jt} - \omega_{max,jt} + \sum_{j=1}^{NG} MGS_{gas, j} \left( \mu_{min,jt} - \mu_{max,jt} \right)$$

Third, after solving the double layer optimization model, the node pressure of the gas network is calculated to check the feasibility of solutions. If the solution is infeasible, the data will be corrected to solve the model again; if the solution is feasible, a unit combined option is achieved. The Monte Carlo method is used to generate multiple scenarios to simulate wind power output fluctuation which is then used to check whether the unit combination options can accommodate wind power output fluctuation. If it is not satisfied, the data will be corrected to solve the model again; if it is satisfied, the final unit combination optimization solution is achieved.

### IV. Case Study

#### A. Electricity and gas combined system case description

Fig. 5 show a 6 nodes electricity system case, include 1 gas unit G1 which is supply basic load, 2 electricity load peaking regulation unit G2 and G3, 1 wind turbine and 1 EH unit which all access node 4.

![Diagram of six node electric power system](image)

### TABLE III

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<th>G2P access location</th>
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</tbody>
</table>

This section combine the 24hours’operation of 7 nodes gas system in Fig. 4 and 6 nodes electricity system in Fig. 5, build 3 scenes to research the optimization of unit combination. The access location is shown in TABLE III.
Table IV: GENERATOR PARAMETER TABLE

<table>
<thead>
<tr>
<th>Name</th>
<th>Gas unit 1</th>
<th>Gas unit 2</th>
<th>Gas unit 3</th>
<th>G2P</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.0113</td>
<td>0.0283</td>
<td>0.1415</td>
<td>0.184</td>
</tr>
<tr>
<td>b</td>
<td>382.33</td>
<td>923.43</td>
<td>500.91</td>
<td>554.68</td>
</tr>
<tr>
<td>c</td>
<td>5007.7</td>
<td>3678.2</td>
<td>3888.7</td>
<td>4001.6</td>
</tr>
</tbody>
</table>

Table V: POWER SYSTEM BRANCH PARAMETERS

<table>
<thead>
<tr>
<th>Name</th>
<th>Start node</th>
<th>End node</th>
<th>Resist ance (p.u.)</th>
<th>React ance (p.u.)</th>
<th>Limit capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line1</td>
<td>1</td>
<td>2</td>
<td>0.005</td>
<td>0.17</td>
<td>200</td>
</tr>
<tr>
<td>Line2</td>
<td>1</td>
<td>4</td>
<td>0.003</td>
<td>0.258</td>
<td>100</td>
</tr>
</tbody>
</table>

Table VI: TRANSFORMER PARAMETERS

<table>
<thead>
<tr>
<th>Name</th>
<th>Start node</th>
<th>End node</th>
<th>Minimum transfer ratio</th>
<th>Maximum transfer ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer1</td>
<td>2</td>
<td>3</td>
<td>1.0204</td>
<td>1.0753</td>
</tr>
<tr>
<td>Transformer2</td>
<td>4</td>
<td>5</td>
<td>1.0204</td>
<td>1.0753</td>
</tr>
</tbody>
</table>

Table VII: PRESSURE DATA OF GAS SYSTEM NODE

<table>
<thead>
<tr>
<th>Node number</th>
<th>Node pressure lower limit (Mpa)</th>
<th>Node pressure upper limit (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.72</td>
<td>1.03</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>1.17</td>
</tr>
<tr>
<td>3</td>
<td>1.03</td>
<td>1.34</td>
</tr>
<tr>
<td>4</td>
<td>0.48</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>1.03</td>
<td>1.38</td>
</tr>
<tr>
<td>6</td>
<td>1.10</td>
<td>1.65</td>
</tr>
<tr>
<td>7</td>
<td>0.69</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Table VIII: COMPRESSOR PARAMETERS

<table>
<thead>
<tr>
<th>Name</th>
<th>Access node</th>
<th>Minimum supply volume (km³)</th>
<th>Maximum supply volume (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pressure</td>
<td>Gas resource1 (constant current source)</td>
<td>7 150.1</td>
<td>150.1</td>
</tr>
<tr>
<td>High pressure</td>
<td>Gas resource1 (constant current source)</td>
<td>7 150.1</td>
<td>150.1</td>
</tr>
</tbody>
</table>
Gas resource 2 (constant voltage source)  

<table>
<thead>
<tr>
<th>Name</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>b(m³/MWh)</td>
<td>353.75</td>
<td></td>
</tr>
<tr>
<td>c(m³/h)</td>
<td>3990.3</td>
<td></td>
</tr>
<tr>
<td>γ(S/ m³)</td>
<td>0.0121</td>
<td></td>
</tr>
<tr>
<td>P_{max}(MW)</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>P_{min}(MW)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Climbing speed(MW)</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

TABLE X
P2G parameters

Combined with the pipe parameters in Refs. 43-45, it can be calculated that the upper and lower limits of the LP for maintaining the regional pipe security and gas flow are 250km³ and 100km³. Among them, 150 km³ of the capacity is used to achieve the storage capacity of LP in EH, the initial state of LP region is 141.6km³.

P2G conversion efficiency is about 75% to 82%, G2P conversion efficiency is about 40%, considering the conversion efficiency of P2G and G2P is about 32% such as Ref. 45. The curve of 24 hour electricity load (partition coefficient of load 1, load 2, load 3 is 0.2, 0.35 and 0.45), wind turbine power and non-electricity gas load (partition coefficient of load 1 and load 2) is shown in Fig. 6.

On the basis of the above scenario and data, the discussion about validity and accuracy of the double layer economic dispatching unit combination model of electricity and gas combined system security constraint is detailed show below.

B. Unit commitment and operation results in different scenarios

Unit combinations and their power generation contrast of Scene1 and scene2 is shown in Fig. 7. In scene 1, G2 start to operation to fill the wind power decrease in 19th-21st hour. Consider the need that gas unit provide spare capacity for total electricity load, G3 start to operate in 18th hour. The operation period of G2 and G3 is 4 hours and 12 hours, G1 as the unit supply basic load is still in operation mode.

In scene 2, the EH working in P2G mode from 18th hour to 19th hour play the role of spare capacity to avoid the operation of G3. EH working in G2P mode from 20th hour to 21st hour play the role of increase additional system climbing capacity to avoid the operation of G2 that the fuel cost is high, this can also decrease the electricity generated by G3.

The total operation cost of electricity and gas combined system, natural gas consumption, wind power consumption ratio and gas generate by P2G of scene 1, scene 2 and scene 3 is shown in TABLE XI. It can be found that the total operation cost of scene 2 and scene 3 have a significant decrease than scene 1.

C. Role of P2G and G2P in EH

In scene 2, the EH work in G2P mode from 20th hour to 22nd hour which is shown in Fig. 7. EH work in 1st-5th, 7th, 19th and 20th, which is shown in Fig. 8.
The process of P2G generates gas and injects them into gas network make the region of LP increase from the initial 141.6 km$^3$ to 215.3 km$^3$. Then 73.7 km$^3$ of LP capacity is used in G2P and gas unit to generate electricity that feed back to grid. In the end of the day, area of LP is back to 141.6 km$^3$, the change of LP is shown in Fig. 9.

In scene 3, for the change of EH access location, the change of LP in pipeline that is related to the EH access location is shown in figure 10. The data of 1st to 12th hour is from pipeline 5-3 that the LP $\in$ [30,70], the data of 13th to 24th hour is from pipeline 2-1 that LP $\in$ [15,40]. It can be found that when EH work in P2G mode, the excessive wind power can be transferred to gas stored in pipeline 5-3, and the fuel need of G3 at the end of pipeline 5-3 is not too high. In 3rd and 5th hour, the LP of pipeline 5-3 reaches the upper limit 70km$^3$. This make the EH work from P2G mode to standby mode to achieve the upper limit constraint of gas pipeline LP. When the EH work in G2P mode, the gas stored in pipeline 2-1 is used to generate electricity that feed back grid and the G1 in the end of pipeline 2-1 have high fuel demand. In the 11th and 12th hour, the LP of pipeline 2-1 reaches the lower limit 30km$^3$. This make the EH work from G2P mode to standby mode to achieve the lower limit constraint of gas pipeline LP.

Comparing with scene 2, the abandoned wind power and operation cost have a little increase. Therefore, the access location of EH is critical to the unit combination optimization of electricity and gas combined system. It is recommended that the P2G devices in EH can be connected to the heavy gas load node, G2P devices can be connected to the light gas load node to consume the wind power and support grid more efficient.
excessive wind power reduction is limited. It can be found that the relative position between EH and wind turbine will also influence the unit combination and its power output. It is recommended that the P2G devices can be connected near the wind turbine installation location to consume wind power more effective.

E. Unit combination considering wind turbine power output fluctuation

Considering about the fluctuation range of wind turbine power output is [-10%, +10%] of the prediction, the Monte Carlo simulation method is used to generate 3000 wind turbine power output fluctuation scenes. Then the clustering method in Ref. 46, which is used to summarize these scenes into 10 typical scenes to check whether the unit combination option can meet the demand of wind turbine power output.

According to the unit installed capacity and load level, the unit installed capacity higher than 130MW is belong to high permeability, the unit installed capacity lower than 80MW is belong to low permeability. Considering about the wind power low permeability level and its output fluctuation, the final unit combination option of scene 1 and scene 2 is shown in TABLE XII and TABLE XIII. The EH in scene 2 only operate in 2nd and 3rd hour, the excessive wind power reduction do not have significant improved for the access of EH. Due to the access of EH improve the operation cost of electricity and gas combined system, the total operation cost of scene 1 and scene 2 is \(7.397 \times 10^6\) and \(7.696 \times 10^5\) $.

TABLE XII

1~24 HOUR FINAL UNIT COMBINATION SCHEME OF SCENE1

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 1st -12th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>0 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 13th -24th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

TABLE XIII

1~24 HOUR FINAL UNIT COMBINATION SCHEME OF SCENE2

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 1st -12th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>0 0 0 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2P</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>P2G</td>
<td>0 1 1 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 13th -24th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2P</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>P2G</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

Considering about the wind power high permeability level and its output fluctuation, the final unit combination option of scene 1 and scene 2 is shown in TABLE XIV and TABLE XV. The operation time of EH in scene 2 have a significant increase, this can consume excessive wind power efficiently. The total cost of scene 1 and scene 2 is \(6.262 \times 10^6\) and \(6.155 \times 10^5\) $. Therefore, under high permeability level wind turbine, the access of EH have benefits on the optimization of electricity and gas combined system unit combined option and operation cost of combined system.

TABLE XIV

1~24 HOUR FINAL UNIT COMBINATION SCHEME OF SCENE1

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 1st -12th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2P</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>P2G</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

TABLE XV

1~24 HOUR FINAL UNIT COMBINATION SCHEME OF SCENE2

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 1st -12th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2P</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>P2G</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Operation state of 13th -24th hour (1-Operate; 0-Stop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G3</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>G2P</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>P2G</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>
F. The effectiveness of electricity and gas combined system double layer economical dispatching unit combination model

The double layer optimization model which use economical operation of electricity and gas combined system as target can simultaneously achieve the lowest cost of power network and gas network operation. To prove the effectiveness and accuracy of double layer optimization model, the model is compared with multi-objective single layer optimization model.

Single layer optimization model is shown below:

\[ \text{Min } \text{Equation}(1) + \text{Equation}(24) \]

\[ \text{st.}\text{Equation}(5),(7),(13) \sim (15)\text{and} (22) \sim (23) \]

\[ \text{Equation}(25) \sim (27) \]

\[ \text{Equation}(32) \sim (40) \]

TABLE XVI

<table>
<thead>
<tr>
<th>Name</th>
<th>Double layer model</th>
<th>single layer multi-objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation cost of combined system/10^6 $</td>
<td>0.6155</td>
<td>0.6244</td>
</tr>
<tr>
<td>Natural gas consumption /km³</td>
<td>3957.3</td>
<td>4129.5</td>
</tr>
<tr>
<td>wind power consumption ratio %</td>
<td>87.5</td>
<td>84.5</td>
</tr>
<tr>
<td>gas generated by P2G /km³</td>
<td>73.75</td>
<td>69.71</td>
</tr>
</tbody>
</table>

TABLE XVI show the result of comparison between double layer optimization model and multi-objective single layer optimization model. It can be found that using double layer optimization model is better to decrease the operation cost of electricity and gas combined system and consume the excessive wind power. It can also generate more natural gas through P2G process to decrease the amount of natural gas bought from gas network.

V. CONCLUSION

This paper presents a double-layer electricity and gas combined system unit combination optimization model considering high penetration of wind power and EH (consist of P2G, G2P and LP). It converts the double layer optimization model to a mixed integer linear programming model to solve under the KKT optimization conditions. The Monte Carlo simulation is used to generate wind power output fluctuation scenarios to check the feasibility of the solutions. Then the optimal unit combination option is achieved. The contributions and conclusions of this paper are shown as follows:

1. Building the mathematical model of combined electricity and gas system with EH and introducing the security constraints and coupling constraints of two the networks.
2. Adding the natural gas network optimization into the combined electricity and gas system unit combination problem, and converting it into a double layer model, which is the economic dispatch of the electricity and natural gas. Compared with the multi-objective single layer optimization model, the double layer model has better optimization capability.
3. EH achieves bidirectional coupling of electricity and gas combined system. This can decrease the reduction of excessive wind power significantly, stabilize the fluctuation of wind power output and gain carbon emission benefits. This can also fully play the storage role of gas network pipeline, especially under high permeability wind power conditions.
4. The access location of the EH is critical to the optimization of the unit combination of the electricity and gas combined system. It is recommended that the P2G devices of EH is connect with heavy gas load node or near the installed location of a wind turbine, G2P devices of EH is connected with light gas load node to consume the wind power and support grid more efficiently.

REFERENCES


35. I. Cameron, Using an Excel Based Model for Steady State and Transient Simulation, Pipeline Simulation Interest Group (PSIG), 31st annual meeting, 20-22 October 1999.


