Research on Wind Power Accommodation of Integrated Energy System Considering Power-to-gas Operational Cost

Shuai Dong¹, Shijie Xu², Jun Liang¹
¹School of Electrical Engineering, Shandong University, Jingshi Road 17923, Jinan, China;
²State Grid Changyi Electric Power Company, Changyi, China
E-mail: dongshuai9412@163.com

Abstract. It is effective to use Power-to-gas (P2G) technology to improve wind power accommodation of the integrated energy system. While there are several ongoing discussions on optimal scheduling of P2G, few studies have taken its operational cost into account. To bridge this gap, this paper takes P2G operational cost into the day-ahead scheduling model of the integrated energy system, and then analyses the influence of these costs on the wind power accommodation and operational economics of the system. A four-node energy hub system is used to verify the proposed model and the effects of the raw material costs of P2G are analysed. The results demonstrate the relatively high P2G operational costs will restrict the wind power accommodation and increase the total operation costs of the integrated energy system. Only when it falls to a certain lower value, the operation of P2G can be economically viable.

1. Introduction

Currently, the amount of wind curtailment is still very large in China. The introduction of the integrated energy system provides a new solution to wind power accommodation [1]. As one of the key technology of the integrated energy system, power-to-gas (P2G) can transform excessive wind power into natural gas which can be stored on a large scale. Hence, it can effectively improve the accommodation of wind power and promote coordination of power and gas system deeply. Therefore, there has been widespread discussion of P2G technology and its optimal operation.

However, although P2G has a good effect on improving wind power accommodation, its operational cost will not have a sharp reduction in the foreseeable future. Thus, the consideration of P2G operational cost is particularly critical.

The present research about P2G operational costs are mainly focused on the field of optimal allocation of P2G and its economic evaluation [2-5]. In [2], the cost-benefit analysis method is used to determine the optimal capacity of P2G. In [3-4], a comprehensive technical and economic analysis of P2G technology has been conducted. Reference [5] analyzes the cost characteristics and operational economics of P2G in different scenarios. The above studies show that, on one hand, due to the relatively high cost of P2G, the operational cost must be properly investigated in the application. On the other hand, except for electricity cost, the raw material costs of P2G will affect its economic as well, so there is a need to consider P2G operational cost comprehensively. However, in the area of optimal scheduling of integrated energy system including P2G [6-9], few studies have taken P2G operational cost into account.
Based on this, this paper analyzes the effect of P2G operational cost on wind power accommodation in day-ahead scheduling of integrated energy system. It is structured as follows: In Section 2, a comprehensive and reasonable analysis of the P2G operational costs is given, and the energy hub including P2G is modeled. In Section 3, a day-ahead scheduling model of the integrated energy system considering P2G operational cost is proposed. In Section 4, a four-node energy hub system is used to verify the proposed model and the effects of the raw material costs of P2G are analyzed. The conclusion and contribution of this paper are provided in Section 5.

2. P2G operational cost and energy hub model

P2G technology contains two main processes, which are electrolysis and methanation, as shown in Fig. 1. The operational costs of P2G mainly include the consumptions of electricity and raw materials. The former is proportional to the electric power consumption, and the latter includes the cost of water and carbon dioxide, while the cost of water can be negligible compared with that of electricity. However, the expenses for carbon dioxide vary a lot depending on its sources (such as carbon capture technology, biogas, etc.), which range from 10 $/t to 1000 $/t [8].

![Fig. 1. Principle of P2G technology](image)

Energy hub with multiple energy sources can improve operational flexibility of P2G further, as shown in Fig. 2. The system cannot effectively utilize available wind energy when it’s under high wind generation levels while low load levels. However, P2G can convert excessive wind power into natural gas. The produced gas is provided to combined heat and power generation (CHP), furnace or stored in the gas storage facility.

![Fig.2. An energy hub including P2G](image)

The energy hub can be expressed as follows:

$$
\begin{align}
L_{\text{in}} &= \frac{1 - v_1 + v_2 \eta_{\text{chp,}}}{\eta_{\text{chp,}} (v_2 \eta_{\text{chp,}} + (1 - v_2) \eta_{\text{gh,}})} \left( \frac{E_{\text{in}}}{G_{\text{out}}} \right) \left( \frac{v_2 \eta_{\text{chp,}}}{v_2 \eta_{\text{chp,}} + (1 - v_2) \eta_{\text{gh,}}} \right) \left( Q_{\text{in}} - Q_{\text{out}} \right) \\
H_{\text{in}} &= \frac{1 - v_1 + v_2 \eta_{\text{chp,}}}{\eta_{\text{chp,}} (v_2 \eta_{\text{chp,}} + (1 - v_2) \eta_{\text{gh,}})} \left( \frac{E_{\text{in}}}{G_{\text{out}}} \right) \left( \frac{v_2 \eta_{\text{chp,}}}{v_2 \eta_{\text{chp,}} + (1 - v_2) \eta_{\text{gh,}}} \right) \left( Q_{\text{in}} - Q_{\text{out}} \right)
\end{align}
$$

Where $m$ and $t$ are indices of hours and energy hubs, respectively; $L_{\text{in}}$ and $H_{\text{in}}$ are the electricity loads and heat load; $E_{\text{in}}$ and $G_{\text{out}}$ are the power input and gas flow input; $Q_{\text{in}}$ and $Q_{\text{out}}$ are gas inflow and outflow of storage facility; $v_1$ and $v_2$ are dispatch factors; $\eta_{\text{chp,}}$, $\eta_{\text{chp,}}$, $\eta_{\text{chp,}}$, $\eta_{\text{gh,}}$ are conversion efficiency of P2G, gas-electric and gas-heat of CHP, and furnace, respectively.

3. Day-ahead scheduling model of integrated energy system

3.1. Objective function

This paper assumes that the integrated energy system is scheduled by a unified dispatcher. The objective function $F_g$ can be written as the sum of power generation costs, gas supply costs, gas
storage costs, and raw material costs of P2G, while the P2G electricity cost is included in the cost of thermal power or wind power generation.

\[
\min F_g = \sum_{t=1}^{T} \left[ \sum_{i=1}^{N_u} a_i (P_{i,t}^{pu})^2 + b_i P_{i,t}^{pu} + c_i \right] + \sum_{j=1}^{N_w} C_{p,j,cf} P_{j,t}^{pf} + \sum_{k=1}^{N_w} C_{p,k,cf} P_{k,t}^{pf} + \sum_{m=1}^{N_m} C_{p,m} Q_{m,t}^{pm} + \sum_{m=1}^{N_m} C_{p,m} G_{m,t}^{pg} \right]
\]

(2)

Where \( P_{i,t}^{pu} \) is the active power generation of unit \( i \); \( P_{j,t}^{pf} \) is the dispatched wind power of wind farm \( j \); \( G_{k,t}^{pf} \) is the gas supply of well \( k \); \( Q_{m,t}^{pm} \) is the gas outflow of gas storage \( m \); \( G_{m,t}^{pg} \) is gas rates of P2G \( m \); \( a_i \), \( b_i \), \( c_i \), \( C_{p,j,cf} \), \( C_{p,k,cf} \), \( C_{p,m} \) are all cost coefficients, and \( C_{p,m} \) is the raw material costs coefficient of P2G \( m \); \( N_u \), \( N_w \), \( N_p \), \( N_g \), \( N_{P2G} \) are the total numbers of thermal units, wind farms, wells, gas storages and P2G.

3.2 Constraints

3.2.1 Energy Hub constraints. CHP, furnace and P2G are constrained by their unit capacity, expressed as (3)–(6):

\[
0 \leq P_{m,j}^{chp} \leq P_{m,j}^{chp,\text{max}}
\]

(3)

\[
0 \leq H_{m,j}^{chp} \leq H_{m,j}^{chp,\text{max}}
\]

(4)

\[
0 \leq H_{m,j}^{gb} \leq H_{m,j}^{gb,\text{max}}
\]

(5)

\[
0 \leq G_{m,j}^{P2G} \leq G_{m,j}^{P2G,\text{max}}
\]

(6)

Where \( P_{m,j}^{chp,\text{max}} \), \( H_{m,j}^{chp,\text{max}} \), \( H_{m,j}^{gb,\text{max}} \), \( G_{m,j}^{P2G,\text{max}} \) are the maximum units capacity.

Gas storage constraints include storage balance (7), storage capacity limit (8), as well as minimum and maximum injection and withdraw rates (9)–(10). Besides, in order to reserve a certain amount of margin for the next scheduling period, the gas storage after one period is restored to initial state, which means the amount of inflows during one period is equal to the outflows (11):

\[
S_{m,j} = S_{m,j-1} + Q_{m,j}^{in} \Delta t - Q_{m,j}^{out} \Delta t
\]

(7)

\[
S_{m,min} \leq S_{m,j} \leq S_{m,max}
\]

(8)

\[
0 \leq Q_{m,j}^{in} \leq Q_{m,j}^{in,\text{max}}
\]

(9)

\[
0 \leq Q_{m,j}^{out} \leq Q_{m,j}^{out,\text{max}}
\]

(10)

\[
\sum_{t=1}^{T} Q_{m,j}^{in} = \sum_{t=1}^{T} Q_{m,j}^{out}
\]

(11)

Where \( S_{m,j} \) is the storage volume of gas storage facility \( m \), \( S_{m,min} \) and \( S_{m,max} \) are minimum and maximum capacities; \( Q_{m,j}^{in} \) and \( Q_{m,j}^{out} \) are gas inflow and outflow, \( Q_{m,j}^{in,\text{max}} \) and \( Q_{m,j}^{out,\text{max}} \) are maximum flow rates.

3.2.2 Electric power system constraints. Operation constraints for an electric power system include power balance equations (12)(13), generation capacities (14) (15), wind power availability (16), and voltage and line flow limits (17) (18), as follows:

\[
P_{i,j} - P_{i,j'} - U_{i,j} \sum_{j''} U_{i,j''} (G_{j'y} \cos \theta_{j,y} + B_{j'y} \sin \theta_{j,y}) = 0
\]

(12)
\begin{equation}
Q_{i,j} - Q_{i,j} - U_{i,j} \sum_{j' \neq i} U_{i,j'} (G_{i,j} \sin \theta_{i,j} - B_{i,j} \cos \theta_{i,j}) = 0 \tag{13}
\end{equation}

\begin{align}
P_{i,t}^{\text{min}} & \leq P_{i,t}^{\text{in}} \leq P_{i,t}^{\text{max}} \tag{14} \\
Q_{i,t}^{\text{min}} & \leq Q_{i,t}^{\text{in}} \leq Q_{i,t}^{\text{max}} \tag{15} \\
0 & \leq P_{i,t}^{\text{drf}} \leq P_{i,t}^{\text{max}} \tag{16} \\
U_{i,t}^{\text{min}} & \leq U_{i,t} \leq U_{i,t}^{\text{max}} \tag{17} \\
|P_{i,t}^{\text{drf}}| & \leq P_{i,t}^{\text{max}} \tag{18}
\end{align}

Where $P_{i,t}^{\text{in}}, Q_{i,t}^{\text{in}}$ is the active and reactive power generation of the unit $i$; $P_{i,t}^{\text{in}}, Q_{i,t}^{\text{in}}$ is the active and reactive power input of the energy hub at bus $i$; $U_{i,t}$ is the voltage magnitude of bus $i$; $\theta_{i,j}$ is the difference of voltage angle between bus $i$ and bus $j$; $G_{i,j}, B_{i,j}$ are the conductance and susceptance between bus $i$ and bus $j$, respectively; $P_{i,t}^{\text{drf}}$ is predicted wind power, $P_{i,t}^{\text{dlf}}$ is power line flow.

3.2.3 Natural gas system constraints. Operation constraints for a natural gas system include gas flow balance equations (19), well flow capacities (20), pressure limits (21), and line flow limits (22)-(24), as follows.

\begin{align}
G_{i,t}^{\text{sp}} - G_{i,t}^{\text{gas}} - \sum_{j \neq i} f_{i,j,t} & = 0 \tag{19} \\
0 & \leq G_{i,t}^{\text{sp}} \leq G_{i,t}^{\text{max}} \tag{20} \\
o_{i,t}^{\text{min}} & \leq o_{i,t} \leq o_{i,t}^{\text{max}} \tag{21} \\
f_{i,j,t} & = \text{sgn}(o_{i,t}, o_{j,t}) \cdot C_{i,j} \sqrt{o_{i,t}^2 - o_{i,t}^2} \tag{22} \\
\text{sgn}(o_{i,t}, o_{j,t}) & = \begin{cases} 1, & o_{i,t} \geq o_{j,t} \\ -1, & o_{i,t} < o_{j,t} \end{cases} \tag{23} \\
f_{j,t}^{\text{min}} & \leq f_{i,t} \leq f_{j,t}^{\text{max}} \tag{24}
\end{align}

Where $G_{i,t}^{\text{sp}}$ is the gas supply of well $i$, $G_{i,t}^{\text{gas}}$ is the gas flow input of the energy hub at bus $i$, $f_{i,j,t}$ is the gas pipeline flow, $o_{i,t}$ is the pressure of bus $i$, $C_{i,j}$ is the pipeline constant related to the temperature, length and gas compositions.

Besides, the higher heating values (HHV) is used to convert volumetric quantity of gas into energy content, expressed as (25).

\begin{equation}
P_{\text{gas}} = H_{\text{GV}} G_{\text{gas}} \tag{25}
\end{equation}

Where $H_{\text{GV}}$ is set at 39MJ/m$^3$.

4. Case studies

4.1. System description
A 4-node energy hub system is given in Fig.3. H1~H4 are the four energy hubs. H4 is shown in Figure 2, and there is no P2G and gas storage in H1–H3. Thermal power unit G1, G2 and wind farm WT are installed at H1, H2, H4, respectively. Gas supplier S is integrated in H1. Assuming that the loads are evenly distributed among the four energy hubs.

All detailed system parameters are given in [10]. The gas flow and the heat load are all calculated as the power. Taking the power base value of 100MVA, all power values are expressed as the per unit (pu). Besides, taking the cost base value of 4 $/MWh, all costs are expressed as the monetary unit (mu). The wind generation cost is set at 3mu and the raw material costs of P2G is set at 1mu.

The dispatched wind energy is the sum of dispatched wind power during the scheduling period, as follows.

\[ F_w = \sum_{j=1}^{N_w} \sum_{t=1}^{T} P_{w,t}^j \]  

(26)

4.2. The effect of raw material costs of P2G

Assuming that wind generation cost is a fixed value, in order to analyze the effect of P2G operational cost on the wind power accommodation, different raw material costs of P2G are set for optimization respectively. The change of \( F_w \) and \( F_g \) are shown in Fig. 4. And the total outputs of each device during the dispatch period under different raw material costs of P2G are shown in the Table 1.
It can be observed from the Fig. 4, with the increase in the raw material costs of P2G, the dispatched wind power energy \( F_w \) reduces and the total costs \( F_g \) increases gradually at the optimal economic operation point.

And as shown in Table I, P2G outputs gradually reduce, so the dispatched wind energy decrease. At the same time, gas storage outputs also reduce, therefore, CHP outputs reduce and thermal unit outputs increase. Accordingly, the change in outputs leads to the change in costs.

In addition, there is no significant change in gas well outputs, which mainly lies in that the cost of gas produced by P2G is similar or even higher than the cost of gas from well directly, so that the change of P2G outputs does not affect the gas outputs obviously.

In conclusion, the higher operational cost of P2G will restrict the wind power accommodation and increase the total operation costs of the integrated energy system. Only when it falls to a certain lower value, the operation of the P2G can be economically viable.

5. Conclusion
This study analyzes the influence of P2G operational cost on the wind power accommodation in the integrated energy system. The main contributions and conclusions are as follows.

1) Give a comprehensive and reasonable analysis of the P2G operational cost.
2) P2G operational cost will restrict the wind power accommodation and increase the total operation costs of the integrated energy system.
3) Provide reference about when P2G can be economically viable for its large-scale application.

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