Optimal Energy Management for the Integrated Power and Gas Systems via Real-time Pricing

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***Abstract*— This work proposed a bi-level formulation for energy management in the integrated power and natural gas system via real-time price signals. The upper-level problem minimizes the operational cost, in which dynamic electricity price and dynamic gas tariff are proposed. The lower level problem is the arbitrage model of gas-fired plants and P2Gs stations, in which the transient gas flow is introduced. This bi-level model is relaxed to a mixed-integer quadratic programming problem using the Karush-Kuhn-Tucker optimality conditions. Results show that the dynamic price and tariff can make gas-fired units and P2Gs plants follow the system operator's preferences such as wind power accommodation, mitigation of unsupplied load and relieving the network congestion.**

***Index Terms*—integrated energy system, bi-level programming, equilibrium constraints.**

I. INTRODUCTION

Coordinated operation of the integrated energy system to improve the comprehensive utilization of energy has drawn broad interests [1], [2], especially the integrated power and natural gas system [3]. There is a great potential for energy storage in gas pipes due to the compressibility of energy transmission media. In the meantime, the gas-fired unit can act quickly to respond the volatility of renewable energy like wind power and photovoltaic [4]. The flexibility of power system is enhanced with the commitment of gas-fired unit. On the other hand, the development of power-to-gas (P2G) can convert electrical power to gas fuel more efficiently, such as hydrogen or natural gas converted from hydrogen produced by means of water electrolysis. P2G enables bi-directional energy conversion between power and gas system [5], [6]. The integrated power and gas system can significantly improve the flexibility of power system [7].

Models of integrated power and gas system are established based on a steady-state gas flow model [8], [9]. However, the failure to consider the difference between the gas and power system results in model inaccuracy. The transient gas flow is an extremely complicated process [10], [11]. A linear formulation for transient gas flow has been proposed in our previous work [12]. However, In most of the existing work, gas-fired plants and P2G stations are dispatched directly by system operators. The objective of their operation is improving the general welfare instead of their profit, which does not conform to reality. The identity as arbitrager connecting two different system is ignored: whether gas-fired unit/P2G decide to operate and how much they generate depend on the real-time electricity price and gas price.

Considering the arbitrage characteristic, it is practicable to control the operation of gas-fired plants and P2G stations to achieve energy management between power and gas system via price signals [13], [14]. In the power system, dynamic tariff/subsidy method is proposed to reflect the congestion cost [15]. The effectiveness of DT to dispatch the distributed load like electric vehicles has been demonstrated in [16], [17].

This paper proposes a bi-level formulation for the energy management of integrated power and gas system via real-time pricing. The main contribution of this paper is as follows:

- Considering the arbitrage characteristic of gas-fired units and P2Gs, a bi-level formulation that results in a mathematical program with equilibrium constraints is proposed for the energy management of integrated power and gas system.
- Dynamic electricity price (DEP) and dynamic gas tariff (DGT) are proposed to optimally operate the gas-fired units and P2G stations via real-time price signals. Through proper pricing mechanisms, their operation will align with the system operator's preference.
- A linear model is introduced to describe the transient gas flow. The relevance of gas state variables and gas controlled variables is described as matrix $\mathbf{S_G}$ form like power flow relational matrix $\mathbf{S_E}$.

II. PROBLEM FORMULATION

A. *Transient Gas Flow and its Matrix Representation*

The energy flow in the natural gas pipelines is different from the load flow in power system due to the compressibility of the energy transmission media. The gas flow follows the basic principle of fluid dynamics and can be mathematically formulated using the momentum equation and the material-balance equation. By differencing the partial differential equations [12], it can be modeled as following linear equations:

$$\begin{aligned}&\frac{1}{c^2}\left(p_{j,t+1}+p_{i,t+1}-p_{j,t}-p_{i,t}\right)\\&+\frac{\Delta t}{L_{ij}A_{ij}}\left[M_{Eij,t+1}-M_{Fij,t+1}+M_{Eij,t}-M_{Fij,t}\right]=0\end{aligned} \tag{1}$$

$$\begin{aligned}&\frac{1}{A_{ij}}\left[M_{Eij,t+1}+M_{Fij,t+1}-M_{Eij,t}-M_{Fij,t}\right]\\&+\frac{\Delta t}{L_{ij}}\left(p_{j,t+1}-p_{i,t+1}+p_{j,t}-p_{i,t}\right)\\&+\frac{\lambda\omega_{ij}\Delta t}{4d_{ij}A_{ij}}\left[M_{Eij,t+1}+M_{Fij,t+1}+M_{Eij,t}+M_{Fij,t}\right]=0\end{aligned} \tag{2}$$

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where the subscriptions i and j indicate the two ends of the gas pipe. ω denotes the gas flow velocity. c is the acoustic velocity in the natural gas. A, L and d are the cross-sectional area, length, and diameter of the pipe, respectively. λ is the coefficient. p and M with subscriptions denote the gas pressure and gas mass flow rate, respectively, which are the state variables of gas system.

For any node k, the nodal gas flow balance expressed as follows:

$$\sum_{i\in(.)k} M_{Eik,t} - \sum_{j\in k(.)} M_{Fkj,t} = M_{Dk,t} \tag{3}$$

where M_{Dk} is the gas consumption at node k. P2G is an emerging facility to convert electricity into natural gas. In this work, the P2G production injected to the gas grid is considered as negative gas consumption.

In addition to the fluid dynamic equations and nodal flow balance, boundary conditions such as the nodal pressure should be given as part of the gas flow model:

$$p_{i,t} = p_{si,0} \quad \text{if } i \in \text{Source Nodes} \tag{4}$$

Usually, the natural gas is under strict test and measurements before feeding into the pipelines. So the pressure at the source node is constant.

For a gas network with N nodes (including S source nodes) and M branches (when indicating the number of branches, M is without subscriptions), the number of states variables is $T_N \times (N + 2M)$: $T_N \times N$ node pressure variables and $T_N \times 2M$ gas mass flows variables. In the meantime, the number of linearly independent state equations is also $T_N \times (N + 2M)$, including $T_N \times M$ momentum equations, $T_N \times M$ material-balance equations, $T_N \times S$ source nodal pressure equations and $T_N \times (M - S)$ non-source nodal gas flow balance equations. Therefore, the state equations can be described in compact matrix form as follow.

$$\mathbf{J} \times \mathbf{z} = \mathbf{u} \tag{5}$$

where $\mathbf{J}$ is a full-rank state matrix in which network parameters and the coefficients in (1) ~ (4). $\mathbf{z}$ is the state variables vector, consisting of gas pressure and mass flow rate. $\mathbf{u}$ is a vector consisting of the controlled variables and constants. Therefore, the constraints (6) can be described as

$$\underline{\mathbf{z}} \le \mathbf{z} = \mathbf{S_G}\mathbf{u} \le \overline{\mathbf{z}} \tag{6}$$

where $\mathbf{S_G}$ denotes the inverse matrix of $\mathbf{J}$. Partitioning $\mathbf{u}$ into sub-vectors $\mathbf{M^{gas}}$, $\mathbf{M^{p2g}}$ and constant vector $\mathbf{b}$, $\mathbf{S_G}$ is partitioned into $\mathbf{S^{gas}}$, $\mathbf{S^{p2g}}$ and $\mathbf{S^b}$ accordingly. Constraint (6) can be re-written as:

$$\underline{\mathbf{z}} \le \mathbf{S^{gas}}\mathbf{P^{gas}} / \boldsymbol{\eta}^{\mathbf{gas}} + \mathbf{S^{p2g}}\mathbf{P^{p2g}}\boldsymbol{\eta}^{\mathbf{p2g}} + \mathbf{S^b}\mathbf{b} \le \overline{\mathbf{z}} \tag{7}$$

B. *Bi-level Structure of the Model*

In this subsection, the optimal energy management via dynamic pricing in the integrated power and gas system is formulated. The problem is to identify the real-time price for both electric system and gas system. And it can be mathematically stated using the following bi-level model:

$$\min \sum_t \left[\begin{array}{l} \sum_i^{N^g} c_i^g P_{i,t}^g + \sum_i^{N^{gas}} \left(c_{i,t}^{gas} + \lambda_{i,t}^{gas}\right) P_{i,t}^{gas} \\ - \sum_i^{N^{p2g}} \left(c_{i,t}^{p2g} + \lambda_{i,t}^{p2g}\right) P_{i,t}^{p2g} - \sum_i^{N^d} c_{i,t}^d \left(P_{i,t}^d - L_{i,t}^{cur}\right) \\ + \sum_i^{N^w} c_w P_{i,t}^{wcur} + \sum_i^{N^d} c_l L_{i,t}^{cur} \end{array} \right] \tag{8}$$

where $P_{i,t}^g$, $P_{i,t}^{gas}$, $P_{i,t}^{p2g}$, $P_{i,t}^d$ denote the power output/demand of the thermal unit, gas fired unit, P2G, and load. $c_{i,t}^g$, $c_{i,t}^{gas}$, $c_{i,t}^{p2g}$, $c_{i,t}^d$ denote the electricity prices for the thermal unit, gas fired unit, P2G and load. $P_{i,t}^{wcur}$, $L_{i,t}^{cur}$ denote the wind power curtailment and shed load. c_w and c_l are the penalty factor for the wind power curtailment and load shedding.

The optimization is subject to following constraints, including the well-documented DC power flow, nodal power balance, and the operational limits for the generation units.

$$\begin{aligned} \sum_i^{N^g} P_{i,t}^g + \sum_i^{N^{gas}} P_{i,t}^{gas} - \sum_i^{N^{p2g}} P_{i,t}^{p2g} - \sum_i^{N^w} P_{i,t}^{wcur} + \sum_i^{N^d} L_{i,t}^{cur} \\ = \sum_i^{N^d} P_{i,t}^d - \sum_i^{N^w} P_{i,t}^w \end{aligned} \tag{9}$$

$$-C_{nm} \le S_E^{-1} \times \left[\begin{array}{l} P^d - L^{cur} - P^g - P^{gas} \\ + P^{p2g} - P^w + P^{wcur} \end{array} \right] \le C_{nm} \tag{10}$$

$$P_i^{g,\min} \le P_{i,t}^g \le P_i^{g,\max} \tag{11}$$

$$\lambda_{i,t}^{gas} \ge 0,\ \lambda_{i,t}^{p2g} \le 0 \tag{12}$$

$$P_{i,t}^{gas}, P_{i,t}^{p2g} \in \arg\min \sum_t \left[\begin{array}{l} \sum_i^{N^{gas}} -\left(c_{i,t}^{gas} + \lambda_{i,t}^{gas}\right) P_{i,t}^{gas} + e_{i,t}^{gas} M_{i,t}^{gas} + \frac{1}{2} P_{i,t}^{gas} B_{i,t}^{gas} P_{i,t}^{gas} \\ + \sum_i^{N^{p2g}} \left(c_{i,t}^{p2g} + \lambda_{i,t}^{p2g}\right) P_{i,t}^{p2g} - e_{i,t}^{p2g} M_{i,t}^{p2g} + \frac{1}{2} P_{i,t}^{p2g} B_{i,t}^{p2g} P_{i,t}^{p2g} \end{array} \right] \tag{13}$$

$$P_{i,t}^{gas} = \eta_i^{gas} M_{i,t}^{gas} \tag{14}$$

$$0 \le P_{i,t}^{gas} \le P_i^{gas,\max} : \mu_{i,t}^{gas,\min}, \mu_{i,t}^{gas,\max} \tag{15}$$

$$M_{i,t}^{p2g} = \eta_i^{p2g} P_{i,t}^{p2g} \tag{16}$$

$$0 \le P_{i,t}^{p2g} \le P_{i,t}^{p2g,\max} : \mu_{i,t}^{p2g,\min}, \mu_{i,t}^{p2g,\max} \tag{17}$$

$$\underline{\mathbf{z}} \le \left(\begin{array}{l} \mathbf{S^{gas}}\mathbf{P^{gas}} / \boldsymbol{\eta}^{\mathbf{gas}} \\ + \mathbf{S^{p2g}}\mathbf{P^{p2g}}\boldsymbol{\eta}^{\mathbf{p2g}} + \mathbf{S^b}\mathbf{b} \end{array} \right) \le \overline{\mathbf{z}} : \boldsymbol{\pi}^{\mathbf{min}}, \boldsymbol{\pi}^{\mathbf{max}} \tag{18}$$

The upper-level problem (8)-(12) represents the cost minimization in the electrical power system. The costs include thermal unit generation cost, the fuel cost of gas, and penalties on the wind curtailment and load shedding. Reverse revenues on selling electricity to load and P2G units are added to the objective. Constraint (9) enforces the power balance. Constraint (10) enforces that the transmission capacity C_{nm} would not be exceeded. Constraint (11) represents the generation of thermal unit should be within their min/max values $P_i^{gas,\min}/P_i^{gas,\max}$. Constraint (12) represent DEP for gas-fired units $\lambda_{i,t}^{gas}$ is non-negative and the DEP for P2Gs $\lambda_{i,t}^{p2g}$ is negative. $\lambda_{i,t}^{gas}$ and $\lambda_{i,t}^{p2g}$ are the dual variables in the lower level problem.

As for the P2G and gas-fired power plants, they are assumed to be rational to maximize their own profit, represented by the lower level problem (13)-(18). P2G plants purchase electricity while at the same time sells gas. And the gas-fired plants do the opposite. The cost of gas-fired units consists of two parts. One is gas consumption multiplied by gas price $e_{i,t}^{gas}$. The other part is quadratic cost with price sensitivity coefficient $B_{i,t}^{gas}$. The cost and profit for P2Gs are similar to the gas-fired plants. Constraint (14) represents the relationship of gas-fired units between the produced power and the consumed gas by efficiency η_i^{gas}. Constraint (16) represents the relationship of P2Gs between the produced gas and the consumed power by efficiency η_i^{p2g}. Constraint (15) and (17) represent operation limits of gas and P2G units. Constraint (18) represents the state variables limits of natural gas system. Dual variables are indicated by the corresponding equations. Notably, $\boldsymbol{\pi}^{\mathbf{min}}$ and $\boldsymbol{\pi}^{\mathbf{max}}$, multiplied by $\mathbf{S^{gas}}$ and $\mathbf{S^{p2g}}$, can denote DGT for gas-fired units and P2Gs to represent congestion cost [16].

C. Equilibrium constraints

Since the lower level problem is continuous and convex, it can be replaced by Karush-Kuhn-Tucker (KKT) conditions as follow [18]:

$$\begin{aligned}\frac{\partial L_{low}}{\partial P_{i,t}^{gas}} &= -\left(c_{i,t}^{gas}+\lambda_{i,t}^{gas}\right)+e_{i,t}^{gas}/\eta_i^{gas}+P_{i,t}^{gas}B_{i,t}^{gas}-\mu_{i,t}^{gas,\min} \\ &+\mu_{i,t}^{gas,\max}+\sum_{r=1}^{N+2M}S_{r,i,t}^{gas}\left(\pi_r^{\max}-\pi_r^{\min}\right)/\eta_i^{gas}=0\end{aligned} \tag{19}$$

$$\begin{aligned}\frac{\partial L_{low}}{\partial P_{i,t}^{p2g}} &= c_{i,t}^{p2g}+\lambda_{i,t}^{p2g}-e_{i,t}^{p2g}\eta_i^{p2g}+P_{i,t}^{p2g}B_{i,t}^{p2g}-\mu_{i,t}^{p2g,\min} \\ &+\mu_{i,t}^{p2g.\max}+\sum_{r=1}^{N+2M}S_{r,i,t}^{p2g}\left(\pi_r^{\max}-\pi_r^{\min}\right)\eta_i^{p2g}=0\end{aligned} \tag{20}$$

$$0\le P_{i,t}^{gas}\perp\mu_{i,t}^{gas,\min}\ge 0 \tag{21}$$

$$0\le P_i^{gas,\max}-P_{i,t}^{gas}\perp\mu_{i,t}^{gas,\max}\ge 0 \tag{22}$$

$$0\le P_{i,t}^{p2g}\perp\mu_{i,t}^{p2g,\min}\ge 0 \tag{23}$$

$$0\le P_i^{p2g,\max}-P_{i,t}^{p2g}\perp\mu_{i,t}^{p2g,\max}\ge 0 \tag{24}$$

$$\mathbf{0}\le\begin{pmatrix}\mathbf{S^{gas}P^{gas}/\eta^{gas}}\\ \mathbf{+S^{p2g}P^{p2g}\eta^{p2g}+S^{b}b-\underline{z}}\end{pmatrix}\perp\boldsymbol{\pi}^{\mathbf{min}}\ge\mathbf{0} \tag{25}$$

$$\mathbf{0}\le\begin{pmatrix}\mathbf{\overline{z}-S^{gas}P^{gas}/\eta^{gas}}\\ \mathbf{-S^{p2g}P^{p2g}\eta^{p2g}+S^{b}b}\end{pmatrix}\perp\boldsymbol{\pi}^{\mathbf{min}}\ge\mathbf{0} \tag{26}$$

1) Linearization of (21)-(26):

The big-M method is used to linearize constraint (21) to

$$0\le P_{i,t}^{gas}\le y_{i,t}^{gas,\min}M \tag{27}$$

$$0\le\mu_{i,t}^{gas,\min}\le\left(1-y_{i,t}^{gas,\min}\right)M \tag{28}$$

where M is a large enough constant. $y_{i,t}^{gas,\min}$ denotes whether the $P_{i,t}^{gas}$ is equal to zeros. Constraints (22)-(26) can be linearized by the big M method too.

2) Linearization of objective function

In order to linearize the non-linear parts of the objective function (except quadratics), we use the KKT conditions to obtain a new form:

$$\begin{aligned}&\sum_t\left[\sum_i^{N^{gas}}\left(c_{i,t}^{gas}+\lambda_{i,t}^{gas}\right)P_{i,t}^{gas}-\sum_i^{N^{p2g}}\left(c_{i,t}^{p2g}+\lambda_{i,t}^{p2g}\right)P_{i,t}^{p2g}\right]\\
&=\sum_t\sum_i^{N^{gas}}\begin{pmatrix}e_{i,t}^{gas}P_{i,t}^{gas}/\eta_i^{gas}+P_{i,t}^{gas}B_{i,t}^{gas}P_{i,t}^{gas}\\ -\mu_{i,t}^{gas,\max}P_{i,t}^{gas,\max}\end{pmatrix}\\
&+\sum_t\sum_i^{N^{p2g}}\begin{pmatrix}-e_{i,t}^{p2g}P_{i,t}^{p2g}\eta_i^{p2g}+P_{i,t}^{p2g}B_{i,t}^{p2g}P_{i,t}^{p2g}\\ -\mu_{i,t}^{p2g,\max}P_{i,t}^{p2g,\max}\end{pmatrix}\\
&+\sum_r\left[\left(\overline{z}_r-S_r^b b_r\right)\pi_r^{\max}-\left(S_r^b b_r-\underline{z}_r\right)\pi_r^{\min}\right]=X\end{aligned} \tag{29}$$

Considering the linearization in (29), the final mix-integer quadratic programming problem equivalent to problem (8)-(18), is as follows:

$$\min\ \sum_t\left[\begin{aligned}&\sum_i^{N^g}c_i^g P_{i,t}^g-\sum_i^{N^d}c_{i,t}^d\left(P_{i,t}^d-L_{i,t}^{cur}\right)\\ &+\sum_i^{N^w}c_w P_{i,t}^{wcur}+\sum_i^{N^d}c_l L_{i,t}^{cur}\end{aligned}\right]+X \tag{30}$$

subject to constraints (9)-(12), (19)-(20) and linear form of (21)-(26) like (27)-(28).

D. Arbitrage Model of Gas Fired Units & P2Gs

In real arbitrage behavior, gas-fired units and P2Gs will not consider gas state variables limits. Therefore, DGT is proposed to reflect the gas state variables off-limit. Generations make their own optimal behavior with the predicted price, DEP and DGT. The gas-fired units and P2Gs can arbitrage as follows:

$$\min\sum_t\left[\begin{aligned}&\sum_i^{N^{gas}}\begin{aligned}&-\left(c_{i,t}^{gas}+\lambda_{i,t}^{gas}\right)P_{i,t}^{gas}+\frac{1}{2}P_{i,t}^{gas}B_{i,t}^{gas}P_{i,t}^{gas}\\ &+\left(e_{i,t}^{gas}+\sum_r S_{r,i,t}^{gas}\left(\pi_r^{\max}-\pi_r^{\min}\right)\right)M_{i,t}^{gas}\end{aligned}\\
&+\sum_i^{N^{p2g}}\begin{aligned}&\left(c_{i,t}^{p2g}+\lambda_{i,t}^{p2g}\right)P_{i,t}^{p2g}+\frac{1}{2}P_{i,t}^{p2g}B_{i,t}^{p2g}P_{i,t}^{p2g}\\ &-\left(e_{i,t}^{p2g}-\sum_r S_{r,i,t}^{p2g}\left(\pi_r^{\max}-\pi_r^{\min}\right)\right)M_{i,t}^{p2g}\end{aligned}\end{aligned}\right] \tag{31}$$

subject to constraints (14)-(17).

III. Case Study

A. System Description

In this section, the Graver 6-bus system and the 12-node natural gas system are used as the test case, which is shown in Fig. 1 and Fig. 2. Two P2Gs and one gas turbine are installed to connect to the power and natural gas system. An hourly scheduling problem is considered in this work.

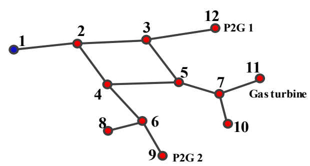

Fig. 1. The natural gas system.

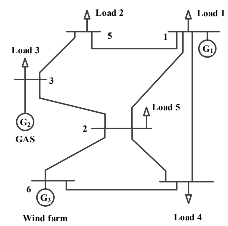

Fig. 2. The electrical power system.

Practical operational data from Energinet.dk, the transmission system operator for gas and electricity in Denmark is used in this work. Fig. 3 shows the electricity price in a day. According to Denmark natural gas market, the typical natural gas price is 0.1389 $/kg (500$/h as gas consumption is 1kg/s) in the case study. Only comparative prices, instead of the values, influence the operational results.

Firstly, the test system is operated with the given gas and electricity prices, i.e. the real-time price cannot be changed according to the variations of the generation and demand in gas and power systems. Fig. 4 shows the wind power curtailment. And Fig. 5 shows the electricity load shedding. The wind curtailment and load shedding result from the unwillingness of the gas-fired plants and P2G stations to operate in proper time periods. Consequently, the gas pressure crosses the limit at the period t=12~15h at node 9. It can be seen that without properly designed pricing mechanisms, the gas-fired unit and P2Gs fail to help the system operating efficiently.

B. Result of Bi-level Model

Then the dynamic pricing mechanism is introduced. DEP and DGT can be obtained from bi-level optimization considering the energy management with real-time price signals. Fig. 6 shows the adjusted electricity price and critical action electricity price for P2Gs. The adjusted electricity price is given from the system operators to achieve the most economical operation of the whole system, while the critical action price is calculated from the P2G plant owner's viewpoint. If and only if the paid price is lower than the critical action price, the P2G plant owner starts to purchase electricity to produce gas. In the period *t*=1~9h, the price for P2Gs to purchase electricity is tuned lower. Fig. 7 shows those prices for the gas-fired unit including original electricity price. It can be seen from Fig. 6 that the low adjusted price happens in the periods when there is much wind. This demonstrates the effectiveness of the pricing mechanism.

As for the gas-fired units, the adjusted electricity price is higher than the critical price in the period *t*=6~8, 10~12 and 20~24h. In the period *t*=20~24h, only the DEP takes effect to make the electricity price higher, which will make gas-fired unit operate for the electricity shortage. In addition to providing electricity, the gas-fired plants are obliged to gas pressure regulations. So in the period t=6~8 and 10~12h, both the DGT and DEP take effect, which guides gas-fired unit arbitrage operation to reduce the gas pressure. The over-limit gas pressure is mitigated by negative DGT and positive DEP, which turns on the gas-fired units to keep the pressure within the operational limits while at the same time runs the P2G to accommodate the wind power.

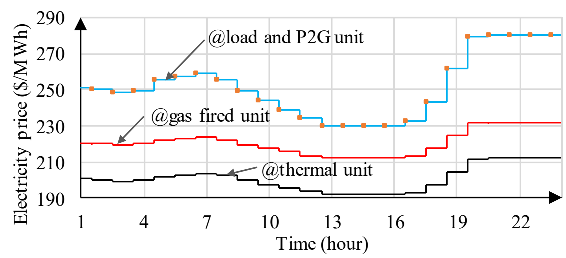

Fig. 3. The electricity prices

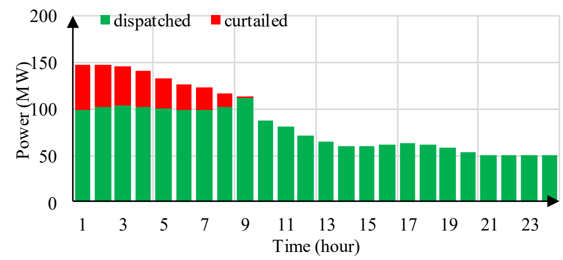

Fig. 4. The wind power curtailment

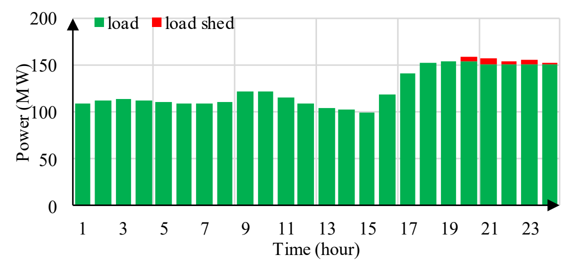

Fig. 5. The electricity load shed

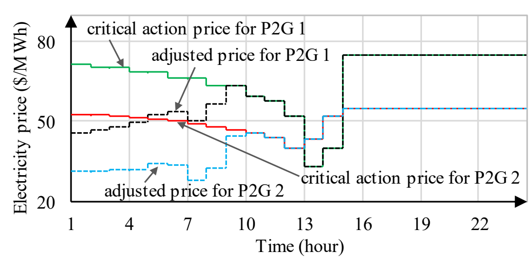

Fig. 6. The electricity price relevance for P2Gs

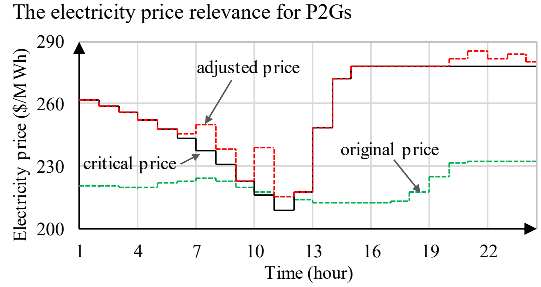

Fig. 7. The electricity price relevance for gas-fired unit

Fig. 8 and Fig. 9 show the arbitrage operation of P2Gs and gas-fired unit. Due to efficient pricing mechanisms, both wind power curtailment and load shed come down to zero.

Fig. 10 shows the gas pressure at node 9. In the period t=1~10h, the gas pressure is higher than before one due to the arbitrage operation. But gas pressure is lower than limit all the time especially in the period t=12~15h. The real-time pricing mechanism for P2G and the gas-fired unit controls the gas pressure within limits successfully.

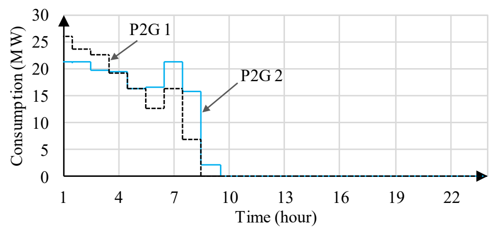

Fig. 8 The arbitrage operation of P2Gs.

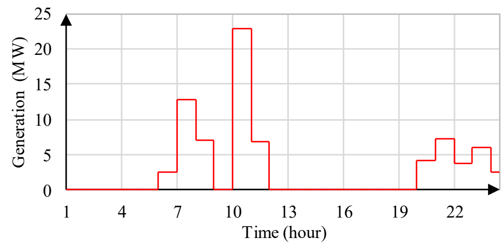

Fig. 9 The arbitrage operation of gas fired unit

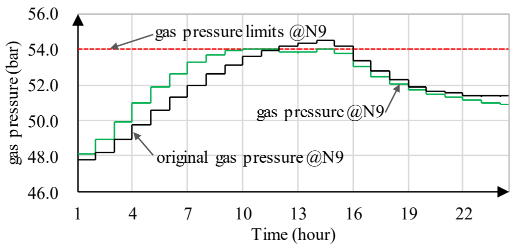

Fig. 10 The gas pressure at node 9.

IV. Conclusion

In this paper, a bi-level model for energy management of the integrated power and gas system via dynamic pricing is proposed. Two price signals, DEP and DGT, are proposed to guide the operation of the gas-fired plants and P2G stations according to the upper-level system operator's preference. Simulation results demonstrate that the DEP and DGT can successfully mobilize the arbitrage operation of the gas-fired unit and P2Gs to accommodate wind power, satisfy load shortage and relieve gas state variables off-limit. Future work focuses on the robust optimizations considering the stochastic character of the wind power.

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