Two-stage collaborative global optimization design model of the CHPG microgrid

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Abstract. With the continuous developing of technology and reducing of investment costs, renewable energy proportion in the power grid is becoming higher and higher because of the clean and environmental characteristics, which may need more larger-capacity energy storage devices, increasing the cost. A two-stage collaborative global optimization design model of the combined-heat-power-and-gas (abbreviated as CHPG) microgrid is proposed in this paper, to minimize the cost by using virtual storage without extending the existing storage system. P2G technology is used as virtual multi-energy storage in CHPG, which can coordinate the operation of electric energy network and natural gas network at the same time. Demand response is also one kind of good virtual storage, including economic guide for the DGs and heat pumps in demand side and priority scheduling of controllable loads. Two kinds of storage will coordinate to smooth the high-frequency fluctuations and low-frequency fluctuations of renewable energy respectively, and achieve a lower-cost operation scheme simultaneously. Finally, the feasibility and superiority of proposed design model is proved in a simulation of a CHPG microgrid.

1. Introduction

CHPG system including energy storage is one of the most economical multi-energy systems to make full use of renewable energy sources. Energy storage is essential in the systems concluding renewable generation, due to the intermittent nature of renewable energy.

By multi-mode scheduling of energy generation, storage and consumption devices, a microgrid can operation autonomously, such as a group of houses[1]. Thermal storage is considered to dividing the use of electricity and heat apart on terms of time, in order to make full use of renewable energy and minimize the costs of purchasing energy[2-3]. However with the proportion of renewable generation becoming higher and higher, one of the bottleneck for full use of renewable energy is the limited power storage. Virtual energy storage has been proposed to make up for the deficiencies of power storage. Demand response is considered to be one kind of virtual power storage in demand side, to reduce the size of traditional power storage system by cooperating with battery. But some scheduling of demand response, such as smoothing the tie-line power[4-5], has forgotten to take users’ comfort into account.

In addition to demand response, the emerging P2G (Power-to-Gas) technology can be another type of virtual storage. By generating gas through the use of electricity, P2G can utilize the excess power of renewable generation and the generated gas can be used in gas-to-power technologies, which can improve the proportion of renewable generation without increasing the capacity of power storage, and minimize the gas cost [6-7].
In this paper, a new multi-energy system-CHPG micro grid and its two-stage collaborative global optimization design model are proposed. P2G and demand response are used as virtual storage to reduce the operating cost and keep security of CHPG without affecting users’ comfort, by a method of frequency division to smooth fluctuations caused by the intermittent nature of renewable energy sources.

2. Modeling framework of CHPG microgrid
The structure of CHPG is shown as Figure 1. The electricity demand is satisfied by WTs, PVs and gas turbines; The heat demand is satisfied by heat pumps in demand side and gas turbines in supply side. Power, heat and gas systems are combined by conversion devices, which will offer diverse solutions to fully consume renewable energy. For example, P2G is used to produce gas by low-price power, in order to reduce the energy cost.

![Figure 1. Structure of the CHPG microgrid.](image)

2.1. Modeling of devices in the CHPG microgrid
The model of wind turbine, PV, gas turbine and battery are the same as[1-3].

2.1.1. Heat Pump. The model of a heat pump is shown as equation (1).
\[
Q_{HP,i}(t) = \eta_{HP,i}P_{HP,i}(t)
\]
where \( \eta_{HP,i} \), \( P_{HP,i}(t) \), and \( Q_{HP,i}(t) \) are the efficiency, consumed power, and generated thermal power of the \( HP_i \).

2.1.2. P2G. A typical P2G plant consists of two processes, the electrolysis and the methanation. The model of the two processes are proposed in [8] and [9] perspective. Therefore, the model of the whole P2G process can be described as equation (2).
\[
V_{CH4}(t) = \eta_{P2G}P_{P2G}(t)
\]
where \( \eta_{P2G} \), \( P_{P2G}(t) \), and \( V_{CH4}(t) \) are the efficiency, consumed power and flow rate of generated gas of P2G plant.

2.2. Modeling of the power characteristics of the CHPG microgrid
The power balance and voltage constraint are described as equation (3) and equation (4) respectively.
\[
\sum P_{PV,i}(t) + \sum P_{WT,j}(t) + \sum P_{GT,i}(t) + P_{grid}(t) + P_{DG}(t) + P_{ES}^{d}(t) = P_{load}(t) + P_{P2G}(t) + \sum P_{HP,i}^{d}(t) + P_{ES}^{e}(t)
\]

The variables on the left of equation (3) is the power of all the PV devices, all the WT devices, all the GT devices, the tie-line power, produced power of demand response, and the discharge power of
battery respectively. $P_{load}(t)$ and $P_{ES}(t)$ is the consumed power of uncontrollable load and the charging power of battery respectively.

2.3. Modeling of demand response in the CHPG microgrid

2.3.1. Economic guide for demand response. Demand response will change the characteristic of the load in the CHPG microgrid, making the flow of power bi-directional. By guiding demand response to smooth the peak-valley difference, the cost of purchasing power or gas will be saved. A peak-valley price mechanism for demand response is proposed, during 8:00 a.m to 20:00 p.m, the price is at peak.

2.3.2. Priority scheduling of controllable load—heat pumps (HPs). The fundamental requirement for any priority scheduling is not to reduce the user’s comfort. Users’ heat pumps will be forced to shut down when the room temperature $T_r$ reaches $T_{max}$ (the maximum temperature that users can bear), and will be forced to increase power when $T_r$ reaches $T_{min}$ (the minimum temperature that users can bear).

As long as the room temperature is maintained within $(T_{min} - T_{max})$, adjustment of HPs’ power will not affect the users’ comfort. $T_{S}^{i}$ is proposed to judge the adjustability of the heat pump:

$$T_{S}^{i} = \frac{T_r^{i} - T_{min}^{i}}{T_{max}^{i} - T_{min}^{i}}$$

(4)

$T_{S}^{i}$ close to 1 or 0 means that the room temperature is close to $T_{max}^{i}$ or $T_{min}^{i}$, and the adjustment of HP may be forced to stop during the scheduling because of the reduce of users’ comfort.

In order to compose a group of HPs with strong adjustability quickly, an efficient method for selection is proposed:

1. When $T_{S}^{low} \leq T_{S}^{i} \leq T_{S}^{high}$, the power of the HP can vary within a larger range without reducing users’ comfort, so the HP is good to control;
2. When $T_{S}^{low} \leq T_{S}^{i} \leq T_{S}^{high}$, or $T_{S}^{i} \leq T_{S}^{low}$, the operation status is prone to change;
3. When $T_{S}^{i} = T_{S}^{high}$, the HP can maintain the maximum operating status during the next $\Delta t$ without reducing users’ comfort. When $T_{S}^{i} = T_{S}^{low}$, the HP can shut down during the next $\Delta t$ without reducing users’ comfort. The adjustability of the HP group can be described as equation (5):

$$C_{HP}^{i} = \frac{I(T_{S}^{high} \geq T_{S}^{i} \geq T_{S}^{low})}{N}$$

(5)

where $I(T_{S}^{high} \geq T_{S}^{i} \geq T_{S}^{low})$ and $N$ is the number of strong adjustable HPs and the total number of controllable HPs respectively.

3. Two-stage collaborative global optimization design model

In order to make full use of renewable energy, WTs and PVs are under the MPPT control strategy, which will affect the stability of CHPG and larger-capacity storage is demanded. The proposed two-stage collaborative global optimization can make full use of P2G and demand response, to relieve the pressure of battery to smooth fluctuations of renewable energy and minimize the operation cost. The proposed optimization method is shown as Figure 2.

3.1. Modeling of stability optimization for the CHPG microgrid

The intermittent nature of renewable energy is the key factor affecting the stability of CHPG, which leads to the overcharge/excessive discharge of battery and large fluctuations of tie-line power, and will
reduce the service life of battery and bring the security risks to other grids. Therefore, an intelligent energy storage/utilizing scheme is needed to take advantage of demand response devices and P2G.

Demand response and P2G both have a quick reaction speed, and the impact of control on the other energy systems is minimal. Therefore, a method of frequency division to smooth fluctuation is proposed, as shown in Figure 3.

![Figure 2. Diagram of the proposed method for CHPG microgrid.](image1)

![Figure 3. Method of frequency division to smooth fluctuation.](image2)

The high-frequency fluctuations are intermittent and fast-changing, but the low-frequency fluctuations are smooth and slow-changing. Demand response and P2G are used to smooth the high frequency fluctuations, in order to avoid overcharge/excessive discharge of battery and large fluctuations of tie-line power.

Given the energy balance constraint as equation (3), the model of Figure 4 can be described as equation (6) and equation (7).

\[
P_{\text{new}}^{H}(t) = P_{\text{F2G}}(t) + \sum P_{\text{new}}^{\text{con}}(t) - P(t) \tag{6}
\]

\[
P_{\text{new}}^{L}(t) = P_{\text{load}}(t) - \sum P_{\text{grid}}(t) - P_{\text{F2G}}(t) - P_{\text{ES}}^{E}(t) \tag{7}
\]

where \( \sum P_{\text{new}}^{\text{con}}(t) \) is the total power of all the controlled HP with strong adjustability. \( P_{\text{new}}^{H}(t) \) and \( P_{\text{new}}^{L}(t) \) are the high-frequency fluctuations and low-frequency fluctuations of all the renewable energy generators respectively.

Butterworth low-pass filter is used to divide fluctuations in this paper, modeled by equation (8):

\[
[n,W_{n}] = \text{buttord} \left( W_{p}, W_{s}, R_{p}, R_{s} \right) \tag{8}
\]

where \( n \cdot W_{n}, W_{p}, W_{s}, R_{p}, \) and \( R_{s} \) is the lowest order, cutoff frequency, passband corner frequency, stopband corner frequency, passband ripple, and stopband attenuation respectively. \( W_{p} < W_{s} \)
$W_n$ is changing with the status of demand response during the scheduling, to make full use of virtual storage to smooth as large range as possible of the fluctuations.

$W_p$ can be determined by equation (9).

\[
\begin{align*}
W_p &= W_p^{nom}, C_{HP}^L \leq C_{HP}^t \leq C_{HP}^H \\
W_p &= W_p^{nom} - \Delta W_p^H, C_{HP}^t > C_{HP}^H \\
W_p &= W_p^{nom} + \Delta W_p^L, C_{HP}^t < C_{HP}^L
\end{align*}
\]

(9)

where $W_p^{nom}$ is the rated passband corner frequency.

When $C_{HP}^t > C_{HP}^H$, the adjustability of HPs is stronger to smooth a larger range of fluctuations, so the passband corner frequency is reduced by $\Delta W_p^H$ to gain a larger range of high-frequency fluctuations.

When $C_{HP}^t < C_{HP}^L$, the adjustability of HPs is too weaker to smooth the rated range of fluctuation, so the passband corner frequency is increased by $\Delta W_p^L$ to reduce the range of high-frequency fluctuations.

The operation of tie line and any battery is restricted by equation (10) and equation (11), respectively.

\[
0 \leq P_{grid}(t) \leq P_{grid}^{m}(t)
\]

(10)

\[
\begin{align*}
-\gamma_p Cap &\leq P_{ES}(t) \leq \gamma_p Cap, SOC^t \leq SOC(t) \leq SOC^H \\
0 &\leq P_{ES}(t) \leq 0, SOC(t) \leq SOC^L \\
0 &\leq P_{ES}(t) \leq \gamma_p Cap, SOC(t) \geq SOC^H
\end{align*}
\]

(11)

where $P_{grid}^{m}(t)$ is the maximum permitted exchanged power on tie line; $SOC^t$, $SOC^H$, and $SOC(t)$ is the minimum permitted storage state, the maximum permitted storage state, and the real storage state, respectively. When the state is lower than minimum permitted state, batteries are forced to charge electricity to restore to the safe state.

3.2. Modeling of economic optimization for the CHPG microgrid

The economic optimization is executed under the stability optimization, as stability is the fundamental support for the operation of CHPG. The result of economic optimization is also the final result of stability optimization.

In order to minimize the operating cost, which consists of gas cost, tie-line cost, and demand-response cost, the objective function is described as equation (12).

\[
\begin{align*}
\min F = \frac{1}{T} \left[ \sum_{j=1}^{N} \left( f_{gas}(t) P + f_{GT}(t) P_{grid}(t) \right) \sum_{j=1}^{N} F_{GT,j}(t) - V_{P2G}(t) / 29.31 \right] \Delta t \\
\text{s.t.} & \quad g_i(t) = 0 \\
& \quad h_i(t) \leq 0
\end{align*}
\]

(12)

where $f_{gas}(t)$ and $F_{GT,j}(t)$ is the price of purchasing gas and the purchase gas power of GT, respectively.

P2G can smooth the fluctuation in CHPG, and reduce the gas cost, shown in equation (12). $g_i(t) = 0$ represents the equality constraints in CHPG, consisting of the energy balances of multi-
energy systems and the frequency division model. 

\[ h_j(t) \leq 0 \] represents the inequality constraints in CHPG, consisting of the constraints of all the devices, the constraint of tie-line power, and the constraints of node voltage.

4. Simulation

In order to verify the optimization design model proposed above, the simulation verification is done under a CHPG, whose parameters is shown in Table 1. The scheduling period is 24 hours and the gap is 1h. \( \Delta W_{up}^{n} = 0.1, \Delta W_{up}^{n} = 0.02, \Delta W_{up}^{L} = 0.01. \)

\[
f(t) = \begin{cases} 
0.075, & 8 \leq t \leq 20 \\
0.05, & \text{other}
\end{cases} 
\] (13)

\[
f_j(t) = \begin{cases} 
0.07, & 8 \leq t \leq 22 \\
0.05, & \text{other}
\end{cases} 
\] (14)

\( f_j(t) \) is the same as \( f(t) \), as shown in equation(13). \( f_j(t) \) is shown as equation(14).

where \( f(t) \), \( f_j(t) \), and \( f_k(t) \) is the price for uncontrollable load, for DG & controllable load, and for tie-line power at the time \( t \), respectively. The unit is $/(kWh).

And the power prediction of WT, PV, and load is shown in Figure 4.

Simulation results of devices power prediction are shown in Table 2. At 13:00, when the power load is at peak, the total power of HPs is reduced to smooth the peak-valley difference. The proportion of DGs is increasing at the same time, to reduce the power purchasing from tie line.

The operating cost is decreasing along with the increasing of the P2G power, shown in Figure 5, because P2G is generating gas by lower-price electric power. Simultaneously, the operating cost is decreasing along with the decreasing of HP power, shown in Figure 6, because the total power of HP is reduced at the time when load power is at peak to reducing the purchasing cost from tie-line power and demand response.

Table 1. Device parameters and values of the CHPG microgrid.

| Name                      | Parameter       | Value                  |
|---------------------------|-----------------|------------------------|
| Wind Turbine              | Quantity        | 2                      |
|                           | \( P_{WT,n}^{nom} \) (kW) | 150                    |
|                           | Quantity        | 2                      |
|                           | \( P_{GT,n}^{nom} \) (kW) | 200                    |
|                           | \( \eta_{GT,n} \) | 0.9                    |
| Gas Turbine               | Quantity        | 1                      |
|                           | Cap/kWh         | 400                    |
| Battery & thermal storage | \( W_{min}, W_{max} \) (kWh) | 40, 180                |
|                           | \( \delta_c, \delta_p, \delta \) | 0.95, 0.95, 0.04       |
|                           | \( \gamma_c, \gamma_p \) | 0.2, 0.4               |
| Tie Line                  | \( P_{P2G}^{nom} \) (kW) | 600                    |
| PV                        | Quantity        | 2                      |
|                           | \( P_{PV,n}^{nom} \) (kW) | 75                     |
| P2G                       | Quantity        | 1                      |
|                           | \( P_{P2G}^{nom} \) (kW) | 400                    |
| Battery & thermal storage | \( \eta_{HP,n} \) | 3                      |
| Heat Pump                 | \( T_{min}, T_{max} \) | 20, 30                 |
|                           | \( T_{HP,n}, T_{HP,c} \) | 0.4, 0.8               |
|                           | \( C_{HP,n}, C_{HP,c} \) | 0.4, 0.8               |

The relationship between cost and P2G is shown in Figure 5 and the relationship between cost and
Demand response is shown in Figure 6. During the whole period, the storage state of battery and the fluctuation of tie-line power are within the security range, shown in Figure 7 and Table 2 respectively.

### Table 2. Simulation results of devices power.

| h | $P_{GT}$ (kW) | $P_{real}$ (kW) | $P_{SS}$ (kW) | $P_{P2G}$ (kW) | $P_{grid}$ (kW) | $P_{P2G}$ (kW) | $P_{SS}$ (kW) | $P_{P2G}$ (kW) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100.78 | 90.03 | 46.44 | 220.12 | 300.24 | 97.00 | 29.27 | 186.46 | 117.60 |
| 2 | 263.11 | 35.65 | 203.96 | 307.21 | -11.01 | -30.89 | 106.50 | 248.48 |
| 3 | 152.33 | 113.81 | 224.69 | 238.05 | 89.87 | 2.30 | 101.22 | 228.73 |
| 4 | 277.37 | 144.35 | 231.62 | 357.01 | -13.71 | -51.56 | 169.48 | 222.07 |
| 5 | 359.77 | 45.99 | 238.11 | 159.86 | 109.49 | 45.52 | 132.75 | 264.01 |
| 6 | 242.37 | 32.80 | 239.84 | 168.63 | 156.94 | 17.57 | 73.34 | 274.79 |
| 7 | 197.80 | 32.67 | 220.93 | 319.25 | 109.12 | -35.34 | 129.96 | 244.21 |
| 8 | 166.05 | 208.02 | 205.19 | 197.11 | 150.63 | -14.76 | 77.77 | 208.14 |
| 9 | 195.94 | 64.32 | 263.37 | 245.45 | 139.88 | -72.63 | 131.32 | 192.80 |
| 10 | 351.71 | 219.42 | 226.95 | 159.77 | 149.97 | 61.39 | 85.82 | 193.42 |
| 11 | 343.77 | 292.79 | 341.15 | 317.16 | 95.17 | 8.34 | 300 | 144.11 |
| 12 | 354.47 | 178.92 | 332.81 | 142.10 | 193.30 | 17.28 | 237.52 | 331.24 |

![Figure 4. Power prediction curves.](image)

![Figure 5. Relationship between cost and P2G.](image)

![Figure 6. the Relationship between cost and demand response.](image)
5. Conclusions
1. A new multi-energy microgrid, CHPG, is proposed, which consists of renewable generation, demand response, energy storage and P2G. Demand response in this paper, consists of economic guide for DGs, and priority scheduling of controllable HPs without affecting users’ comfort. Demand response cooperated with P2G is also used as virtual storage, which can relieve the pressure for battery, and improve the economic and stable state of CHPG.

2. A frequency division method to smooth fluctuation is proposed, considering the difference of reaction ability between battery and virtual storage. Virtual storage is allocated to smooth the high-frequency fluctuations to save the smoothing time and keep the security of battery and micro grid.

3. A two-stage collaborative global optimization design model is proposed. Economic optimization is based on stability optimization, and the economic optimization result is the final optimal scheme of stability optimization. The simulation has verified that the proposed optimization design model can minimize the operating cost by scheduling virtual storage and demand response, and keep the security.

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