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The coordinated operation of electricity, gas and district heating systems

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Abstract

This paper focuses on the coordinated operation of the electricity, gas and district heating systems in urban areas where multi-energy systems belong to a single entity. The energy conversions among these three systems are scheduled simultaneously so that the demands of the three systems could be met at the least operation cost and maximum social welfare. A nonlinear optimization problem is formulated considering the detailed network constraints in the integrated system. A case study is carried out to show the effectiveness and feasibility of the proposed approach.

Keywords: Power system, natural gas system, district heating system, coordinated operation.

Nomenclature

Indices:

CFP	coal-fired power unit
GC	gas compressor
GS	gas storage
GW	gas well
HS	heat storage

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H, P, G	heat, power, gas
LP	linepack
WF	wind farm
Parameters:	
B	susceptance of the transmission line, p.u.
c	operational cost, $/MWh
D	gas demand, power demand, heat demand, MW
m	water flow rate, $\mathrm{m^3/h}$
Z	the resistance coefficient of the pipeline, $\mathrm{kPa^2/(MW)^2}$
λ	energy consumption coefficient
η	energy conversion efficiency
K	heat exchange coefficient
Ξ	Set of decision variables
Variables:	
P,H,Q	power flow, heat flow, gas flow, MW
δ,p,τ	the angle of voltage, gas pressure, water temperature
W	wind power, MW
S	gas flow rate, MW

1. Introduction

In recent years, research investigations have demonstrated that the integration of energy systems can balance the energy production and consumption in a broader scope, and hence improve the efficiency and sustainability of the energy utilization [1]. Therefore, the investigations of multi-energy systems (MES) are currently receiving increasing attention.

Since electricity and natural gas are two of the common options for bulk energy transmission, extensive studies have been carried out to investigate the coordinated operation of the gas and power system. [2] develops a steady-state model for the integrated gas and power systems, while [3] develops a dynamic energy flow model which considers the different response times of the gas and power systems. [4] proposes a coordinated scheduling strategy to optimize conflicting benefits of the electricity and gas networks. [5] proposes a bi-level dispatch model to minimize the total operation costs of both natural gas and electricity systems.

Several works have also been conducted in the coordination of electrical system and heating system, due to the extensive use of CHP units, heat pumps and electric boilers. [6] proposes an optimization model to coordinate the electrical and heating systems to accommodate the renewable sources. [7] proposes a combined heat and power dispatch model to operate the electric power system and district heating system. [8] develops a transmission constrained unit commitment model on the combined electricity and district heating networks. These studies suggest that the coordinated operation can enhance the flexibility of the power system and accommodate high penetration level of renewable energy generation.

Although the coordination of the gas and power systems and the coordination of electrical and heating system have been studied well, there is few work on the joint operation of electricity, gas, and district heating systems. [9] presents a steady state power flow model for combined optimization of electricity, gas, and district heating systems based on the concept of energy hubs. However, it ignores the detailed network constraints of the electricity, gas and district heating system.

This paper focuses on the coordination of electricity, gas, and district heating systems with network constraints considered. The major contribution is providing an optimization problem for joint operation of electricity, gas, and district heating systems. The objective is to minimize the operational costs of the integrated systems while maximises the renewable energy consumed.

The remainder of the paper is organized as follows. Section 2 presents a model to describe the optimization problem for joint operation of the electricity, gas and heating systems. Section 3 analyzes a case study. Finally, Section 4 gives conclusions.

2. Optimization Model

In this section, an optimal cooperation model is formulated to represent the scheduling of the integrated electricity, gas and heating system. This problem is formulated below.

$$\begin{aligned}\min_{\Xi}\sum_{t=1}^{n^{\mathrm{T}}}\Bigg\{&\sum_{j=1}^{n^{\mathrm{CHP}}}\left(c_j^{\mathrm{CHP,P}}P_{j,t}^{\mathrm{CHP}}+c_j^{\mathrm{CHP,H}}H_{j,t}^{\mathrm{CHP}}\right)+\sum_{i=1}^{n^{\mathrm{CFP}}}c_i^{\mathrm{CFP}}P_{i,t}^{\mathrm{CFP}}+\sum_{f=1}^{n^{\mathrm{WF}}}c_f^{\mathrm{WF}}W_{f,t}^{\mathrm{S}}+\sum_{w=1}^{n^{\mathrm{GW}}}c_w^{\mathrm{GW}}Q_{w,t}^{\mathrm{GW}}\\&+\sum_{k=1}^{n^{\mathrm{P2G}}}\left(c_k^{\mathrm{P2G,Q}}Q_{k,t}^{\mathrm{P2G}}+c_k^{\mathrm{P2G,H}}H_{k,t}^{\mathrm{P2G}}\right)+\sum_{s=1}^{n^{\mathrm{GS}}}\left(c_s^{\mathrm{GS,in}}Q_{s,t}^{\mathrm{GS,in}}+c_s^{\mathrm{GS,out}}Q_{s,t}^{\mathrm{GS,out}}\right)+\sum_{h=1}^{n^{\mathrm{HS}}}\left(c_h^{\mathrm{HS,in}}H_{h,t}^{\mathrm{HS,in}}+c_h^{\mathrm{HS,out}}H_{h,t}^{\mathrm{HS,out}}\right)\Bigg\}\end{aligned} \tag{1}$$

The objective function (1) minimizes the total system operation cost, which consists of several terms: the operation cost of CHP units to produce electricity and heat, the operation cost of coal-fired power (CFP) units and wind farms (WF) to produce electricity, the cost of gas supply from gas wells (GW), the operation cost of P2G units to produce gas and heat, the operational cost of gas output and gas input of the gas storage, the operational cost of heat output and heat input in the heat storage.

The optimization is subjected to electric power constraints, natural gas constraints, district heating constraints and energy conversion limits.

1) Electric power constraints:

$$\begin{aligned}&\sum_{j\in\Omega_n^{\mathrm{CHP}}}P_{j,t}^{\mathrm{CHP}}+\sum_{i\in\Omega_n^{\mathrm{CPG}}}P_{i,t}^{\mathrm{CFP}}+\sum_{f\in\Omega_n^{\mathrm{WF}}}\left(W_{f,t}-W_{f,t}^{\mathrm{spill}}\right)-\sum_{k\in\Omega_n^{\mathrm{P2G}}}D_{k,t}^{\mathrm{P2G}}-\sum_{d\in\Omega_n^{\mathrm{ED}}}D_{d,t}^{\mathrm{ED}}=\sum_{m\in\Lambda_n}B_{nm}\left(\delta_{n,t}-\delta_{m,t}\right),\\&\qquad\forall m,n\in\Lambda^{\mathrm{EPS}},\forall t\in T\end{aligned} \tag{2}$$

DC power flow model is used in the network constraint. The electric power constraints consist of the nodal power balance equations (2). The constraints also include the generator capacities, the ramping limits, and the power transmission capacities, which are not listed here due to page limits.

2) Natural gas constraints:

$$\begin{aligned}&\sum_{w\in\Omega_n^{\mathrm{GW}}}Q_{w,t}^{\mathrm{GW}}+\sum_{s\in\Omega_n^{\mathrm{GS}}}\left(Q_{s,t}^{\mathrm{GS,out}}-Q_{s,t}^{\mathrm{GS,in}}\right)+\sum_{k\in\Omega_n^{\mathrm{P2G}}}Q_{k,t}^{\mathrm{P2G}}+\sum_{l\in\Omega_n^{\mathrm{LP}}}\left(Q_{l,t}^{\mathrm{LP,out}}-Q_{l,t}^{\mathrm{LP,in}}\right)-\sum_{d\in\Omega_n^{\mathrm{GD}}}D_{d,t}^{\mathrm{GD}}-\sum_{g\in\Omega_n^{\mathrm{GC}}}D_{g,t}^{\mathrm{GC}}\\&-\sum_{j\in\Omega_n^{\mathrm{CHP}}}D_{j,t}^{\mathrm{CHP}}=\sum_{m\in\Lambda_n}S_{nm,t},\quad\forall m,n\in\Lambda^{\mathrm{NGS}},\forall t\in T\end{aligned} \tag{3}$$

$$p_{n,t}^2-p_{m,t}^2=Z_{nm}\left(S_{nm,t}\right)^2,\quad\forall n,m\in\Lambda^{\mathrm{NGS}},\forall t\in T \tag{4}$$

Equations (3)-(4) state the steady-state model of the natural gas system. In addition, the natural gas constraints also include the gas production capacities of the GW and P2G units, the operational constraints of the gas storage and gas linepack, which are not listed here due to page limits. Finally, the model of the compressor is adapted from [2].

3) District heating constraints:

$$\sum_{j\in\Omega_n^{\mathrm{CHP}}} H_{j,t}^{\mathrm{CHP}} + \sum_{k\in\Omega_n^{\mathrm{P2G}}} H_{k,t}^{\mathrm{P2G}} + \sum_{h\in\Omega_n^{\mathrm{HS}}} \left(H_{h,t}^{\mathrm{HS,out}} - H_{h,t}^{\mathrm{HS,in}}\right) - \sum_{d\in\Omega_n^{\mathrm{HD}}} H_{d,t}^{\mathrm{HD}} = c\cdot m_{n,t}\cdot\left(\tau_{n,t}^{\mathrm{out}} - \tau_{n,t}^{\mathrm{in}}\right), \quad \forall n\in\Lambda^{\mathrm{DHS}}, \forall t\in T \tag{5}$$

$$\tau_{mn,t}^{\mathrm{out}} - \tau_{mn,t}^{\mathrm{am}} = \lambda_{mn,t}\left(\tau_{mn,t}^{\mathrm{in}} - \tau_{mn,t}^{\mathrm{am}}\right), \forall m,n\in\Lambda^{\mathrm{DHS}}, \forall t\in T \tag{6}$$

$$\tau_{n,t}\sum_{m\in\Lambda_n} m_{mn,t} = \sum_{m\in\Lambda_n}\left(m_{mn,t}\cdot\tau_{mn,t}^{\mathrm{out}}\right), \forall m,n\in\Lambda^{\mathrm{DHS}}, \forall t\in T \tag{7}$$

Equations (5)-(7) represent the model of the district heating network, which consist of the nodal heat balance equation, the temperature drop equations, and the nodal mixed temperature equation. It also consists of production capacities of the CHP and P2G units, the operational constraints of the heat storage and the heat transmission capacities.

4) Energy conversion among subsystems:

$$H_{j,t}^{\mathrm{CHP}} = P_{j,t}^{\mathrm{CHP}}\cdot\left(1-\eta_j^{\mathrm{E}} - \eta_j^{\mathrm{L}}\right)/\eta_j^{\mathrm{E}}\times K^{\mathrm{E}}, \quad \forall j\in\Omega^{\mathrm{CHP}}, \forall t\in T \tag{8}$$

$$D_{j,t}^{\mathrm{CHP}} = P_{j,t}^{\mathrm{CHP}}/\eta_j^{\mathrm{E}}, \quad \forall j\in\Omega^{\mathrm{CHP}}, \forall t\in T \tag{9}$$

$$H_{k,t}^{\mathrm{P2G}} = \eta_k^{\mathrm{P2G,H}}\left(D_{k,t}^{\mathrm{P2G}} - Q_{k,t}^{\mathrm{P2G}}\right), \quad \forall k\in\Omega^{\mathrm{P2G}}, \forall t\in T \tag{10}$$

$$Q_{k,t}^{\mathrm{P2G,Q}} \le \eta_k^{\mathrm{P2G}} D_{k,t}^{\mathrm{P2G}}, \quad \forall k\in\Omega^{\mathrm{P2G}}, \forall t\in T \tag{11}$$

Finally, the interfaces among the electricity, natural gas and district heating systems are constrained by the energy conversion relationships of the CHP (8)-(9) and P2G units (10)-(11).

3. Case study

3.1. System description

Fig. 1 shows a test system considered in this work. This test system includes a 4-bus electricity system, a 3-node heating system and a 4-node gas network. The electricity system is composed of a CHP unit, a CFP unit, and a wind farm. The gas network includes a gas source, a gas storage and a gas compressor. The heating system includes heat storage and three nodes. There are two links: CHP and P2G units. The coordinated operation model presented above is solved by using IPOPT [10] under GAMS [11]. The laptop used has an Intel(R) Core (TM) i7 CPU clocking at 2.70 GHz and 8 GB of RAM. The iteration number is 45; the computational time is 1.2 seconds.

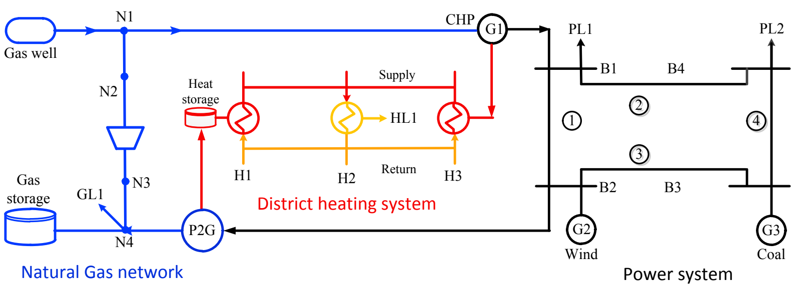

Fig. 1. The structure of an integrated electricity, natural gas and district heating system.

3.2. Network operational parameters

Just as the voltage stability, which plays a major role in the electrical power system, the gas pressure and water temperature are critical factors for the security operation of natural gas system and district heating system, respectively.

Fig. 2 demonstrates the comparison of the simulation results with P2G and without P2G. Fig. 2 (a) shows the water temperature at the inlet and outlet of node 2, which is a load node. The reference temperature is fixed to 100 ℃. As there are heat losses generated during the process of heat transmission, the water temperatures at the inlet of node 2 are lower than the reference node. Besides, there is a lot of heat exchange happen at the load node. Thus the water temperature at the outlet of node 2 will be further declined. The level of temperature drop at load node mainly depends on the amount of heat load. It shows that the temperature drop is larger during the night hours when there is higher heat demand. Finally, due to heat supply from P2G unit, the inlet and outlet temperatures of integrated system with P2G are higher than that without P2G. A higher outlet temperature helps to guarantee safety operation of heating network. Fig. 2 (b) shows the variability of nodal gas pressure. The reference pressure is fixed to 1 bar. It shows that the variability of nodal gas pressure can be dampened by assembling P2G in the multi-energy systems. Further, the nodal gas pressure varies in a narrow range, which indicates that the gas system can play a stabilizing role in multi-energy systems as there is gas linepack in the operational process. It is illustrated that both the district heating system and the natural gas system can provide flexibility to accommodate the fluctuation of the electrical power system.

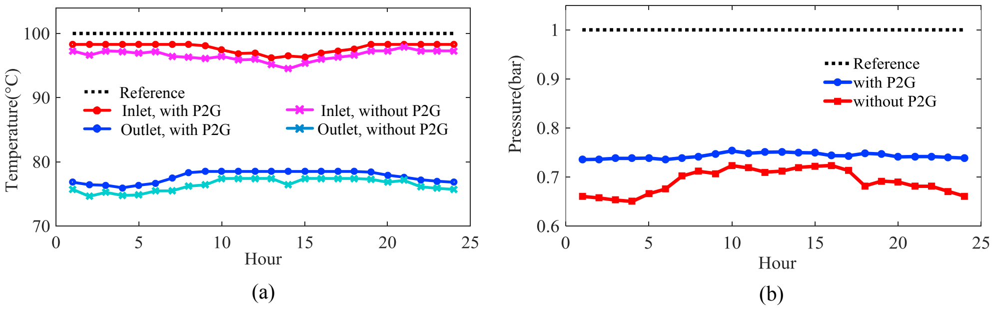

Fig. 2. Network operational parameters: (a) node 2 at the district heating system, (b) node 4 at the natural gas system.

3.3. Scheduling of the energy sources

This subsection analyzes the scheduling strategy throughout a 24-hour time horizon. Fig. 3 (a) illustrates the optimal schedule of the electrical system. The total electricity consumption is composed of the power load and the electricity consumption at the P2G unit. In this case, there is a high wind power output, but only a small amount of surplus wind power is curtailed in the night. Most of the excess electricity is converted into gas and heat by the P2G unit, which helps to reduce the wind curtailment. Fig. 3 (b) illustrates the optimal schedule of the gas system. The total gas consumption includes both the gas demand and the gas consumption at CHP unit. The difference between gas production and consumption is balanced by linepack storage, which provides the flexibility to gas networks. Fig. 3 (c) illustrates the optimal schedule of district heating system. The total heat consumption includes the heat load and the heat loss. The heat loss comes from the heat dissipation of the high-temperature water. There is about 12.4% of heat loss in this study.

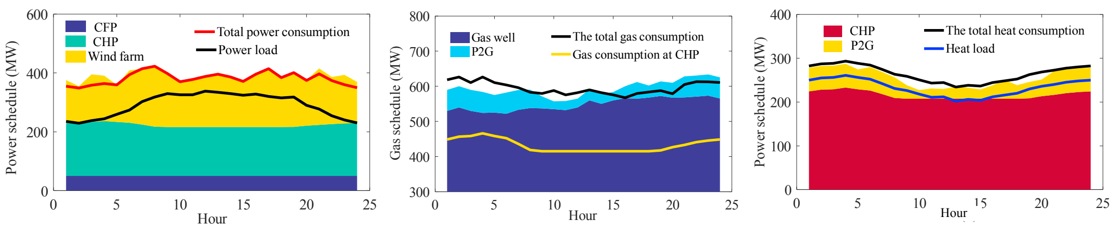

Fig. 3. Optimal schedule of sources: (a) the electrical system, (b) the natural gas system, (c) the district heating system.

4. Conclusion

This paper proposes a coordinated optimization model for the joint operation of the electricity, gas and district heating systems of an urban area. A nonlinear programming is formulated by considering the network constraints in the integrated systems. This model is solved using IPOPT under GAMS. Simulation results demonstrate the effectiveness of the proposed approach. The required computational time is acceptable with operational requirements. It shows that most of the surplus wind power can be converted into gas and heat by the P2G unit, which helps to reduce wind curtailment. Further, both the district heating system and the natural gas system can provide flexibility to accommodate the fluctuation of the electrical power system.

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