Research on Optimized Synergistic Operation of Electricity-Gas Interconnected Integrated Energy System Based on Benefit Game

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Abstract: In order to realize the simultaneous coordination of economy and low-carbon of the electricity-gas interconnected integrated energy system composed of the coupled electricity and natural gas grids, this paper proposes a low-carbon and economic optimization method for the electricity-gas interconnected integrated energy system based on the game of interests. Firstly, the energy hub is used to model the main energy stations in a unified way, the upper and lower level energy flow equivalence decomposition, the same level energy flow mutual aid and the same level coupled energy flow pricing game model are introduced, the coordinated operation method based on the relaxation energy flow (SEF) and the market game solving method are proposed, and finally, the market equilibrium state obtained by the above mentioned market game method is verified by the simulation results to have a better economic benefit.

Keywords: electricity-gas interconnected integrated energy system; game of interest; upper and lowerlevel energy flow equivalence decomposition; peer energy flow mutualization; peer coupled energy flow pricing game

1 Introduction

In the traditional energy system, the natural gas grid only interacts with the grid through gas turbines, but with the gradual maturity of Power to Gas (P2G) technology, two-way flow of energy between the grid and the natural gas grid has become possible [1-3]. Especially in today's rapid development of renewable energy and the pressure of energy saving and emission reduction, P2G technology can be used to make hydrogen from surplus clean power sources (e.g., wind power, photovoltaic power, etc.), and then synthesize methane by absorbing CO_2 into the natural gas grid. In addition to providing a new way for renewable energy consumption, this pathway is of great significance for energy saving and environmental protection. Therefore, both gas turbine and P2G technologies will play an important role in adapting to future power systems containing large-scale, intermittent renewable energy sources. Moreover, based on the slower inertia and longer response time of natural gas in the pipeline network, the natural gas network is expected to become a transmission and distribution carrier for large-scale renewable energy consumption, while mitigating the additional investment in energy storage systems. Integrated electric power and natural gas system (IEGS), which is composed of coupled electric and natural gas grids, will become the

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most critical energy supply and network transmission system for the development of integrated energy system (or energy internet) [4-7]. The grid and natural gas network based on gas turbine and P2G two-way coupling is an important carrier to carry the synergy of production-consumption-storage of IEGS, which will realize the source-load balance resource transmission and distribution of power and natural gas flows. In terms of spatial coverage and service objects, IEGS can be divided into cross-regional electricity-gas coupled network (hereinafter referred to as Integrated electric power and natural gas network (IEGN)) and Electricity-Gas Coupled Energy Center (EGC-Gas). The IEGN consists of inter-regional electric power transmission network and natural gas transmission pipeline network, which mainly serves the centralized and large-scale access to power (including renewable energy) and gas sources to realize the optimal allocation of inter-regional energy resources [7-10,]. EGC-EC, on the other hand, takes IEGN as the upper level energy support, and mainly realizes multi-energy consumption and distributed energy consumption in the local area. EGC-EC can be regarded as the energy load node of IEGN in the broad sense, or a "virtual energy station", which realizes the coupling and optimization of multi-energy flow distribution and transmits it to the next level energy system. The coupling of multiple energy flows is optimized for distribution and transmission to the next level of energy system. Multiple EGC-ECs are independent of each other and interconnected through IEGN.

2 Cooperative Operation Model of Electricity-Gas Interconnection System Based on Benefit Game

The coupling of multiple energy flows in IEGS can be decomposed into multiple electric-gas energy coupling centers (EGC-ECs) and their upper-level electric-gas coupling energy networks (IEGNs) according to the upper and lower energy levels, and considering the power grid, natural gas network, and EGC-ECs as the main bodies of relatively independent operation, the framework of the IEGS synergistic operation and the benefit game proposed in this paper includes three major aspects of the decomposition of the upper and lower energy flows, mutual assistance of the same-level energy flows, and the pricing game of the same-level coupled energy flows. mutual aid, and the pricing game of peer-coupled energy flows.

2.1 Equivalent decomposition of upper and lower energy flows

The upper and lower energy flow equivalence decomposition can first obtain the generalized energy load demand of EGC-EC. At this time, IEGN is the upper level equivalent energy of EGC-EC. Then, it uploads the electricity and gas energy load demand to the IEGN, and the IEGN achieves its own optimized operation while satisfying the generalized equivalent load demand of the EGC-EC. In this way, the energy flow decomposition modeling of the upper and lower levels can be optimized separately. Definition of specific variables: For an IEGS with D EGC-ECs, for the dth EGC-EC, the generalized demand model can be used to obtain the expected value of electric power PEGC, d,t , the expected value of natural gas flow PEGC, d,t , and the expected value of natural gas flow EGC, d,t , which are needed by the EGC-EC to be supplied by the upper-level IEGN.EGC, d,t as well as the electric power interval [$P_{EGC\_DN, d,t}$, $P_{EGC\_UP, d,t}$], the natural gas flow interval [$f_{EGC\_DN, d,t}$ $f_{EGC\_DN, d,t}$, $f_{EGC\_UP, d,t}$], the gas flow interval [$P_{EGC\_DN, d,t}$ $f_{EGC\_UP, d,t}$].

2.2 peer-to-peer energy flow

Considering the background that the energy flows of coupled devices (gas turbine and P2G) in IEGN can be priced, we focus on the optimal scheduling methods for grid and gas network disaggregation in the case of different pricing of coupled energy flows.

2.3 Sibling-coupled energy flow pricing game

In this paper, the coupled energy flow pricing game mainly considers the possible coupled energy flow pricing rights of power grid and natural gas network under the market environment for their interacting equipment (gas turbine and P2G), and further investigates the synergistic operation and market equilibrium state of the power grid and natural gas network under the game of interests on the basis of the mutual benefit link of the same level energy flow. In this paper, the concept of Slack EnergyFlow (SEF) is proposed as an interface for interactive optimization, and this slack variable can be used to modify the energy flow at the coupled network contact according to the optimal dispatch results of the electricity and gas networks. Define the indicator set: u is the counting variable of generating units, *GT* is the set of gas turbines; c is the counting variable of natural gas sources, TR is the set of P2G devices.

The corresponding SEF for the gas turbine, as shown in Equation 1.

$$P_{\mathrm{Gmax},u,t} = \mathrm{G}_1\left(f^{\mathrm{A}}_{\mathrm{GT},u,t} - f^{\mathrm{S}}_{\mathrm{GT},u,t}\right) \; u \in GT \tag{1}$$

In the formula:$f^{\mathrm{A}}_{\mathrm{GT},u,t}$ is the gas turbine active output, the$f^{\mathrm{S}}_{\mathrm{GT},u,t}$ is the natural gas flow rate, and$f^{\mathrm{S}}_{\mathrm{GT},u,t}$ is the corresponding SEF of the gas turbine, and G 1 (*) denotes the relationship between the active output of the gas turbine and the natural gas consumption.$P_{\mathrm{Gmax},u,t}$ upper limit of the gas turbine in the grid dispatch model.

The SEF corresponding to the P2G device, as shown in Equation 2.

$$P_{\mathrm{TRmax},c,t} = \mathrm{G}_2\left(f^{\mathrm{B}}_{\mathrm{G},c,t}\right) \; c \in TR \tag{2}$$

$$f^{\mathrm{S}}_{\mathrm{G},c,t} = f^{\mathrm{A}}_{\mathrm{G},c,t} - f^{\mathrm{B}}_{\mathrm{G},c,t} \; c \in TR \tag{3}$$

where:$f^{\mathrm{B}}_{\mathrm{G},c,t}$ is the natural gas supply from the P2G source obtained by the natural gas grid for optimal dispatch;$f^{\mathrm{A}}_{\mathrm{G},c,t}$ is the P2G power $P^{\mathrm{A}}_{\mathrm{TR},\,c,t}$ and its corresponding natural gas flow rate that can be obtained by the grid based on its optimal scheduling model, and G_2 (*) is the relationship between the power consumption of P2G equipment and the natural gas flow rate. The sibling coupled energy flow pricing game considers the market pricing game played by the grid and the natural gas network in the market environment with respect to the possible coupled energy flow pricing power of their interacting equipment (gas turbine and P2G). It is characterized by the optimization formulation of the variables C_{TR} and C_{GT} . Where C_{TR} is the pricing strategy of the grid company and C_{GT} is the pricing strategy of the gas grid company. The game reaches market equilibrium when both companies are unable to adjust their pricing strategies to obtain greater benefits under the other's established pricing strategy.

In the game, the strategy space of the grid company and the natural gas company is x_{ele} ={CTR,t} and x_{gas} ={CGT,t}, respectively, and the set of strategies of the two is x = {x_{ele} ,x_{gas} }, and each element in the set of strategies is the price of natural gas per unit flow rate of the gas turbine or the P2G equipment at a certain point in time. The payoff functions of the two sides of the game are defined in terms of each maximizing the payoff from the other. Where ϕele(x) and ϕgas(x) are the gain functions of the grid company and the gas company, respectively, as shown in Equation 4.

$$\begin{cases}\phi_{\text{ele}}(\boldsymbol{x}) = \sum_{t=1}^{T}\left(C_{\text{TR},t}\sum_{c\in \boldsymbol{TR}} f_{\text{G},c,t}^{\text{A}}\right)\\ \phi_{\text{gas}}(\boldsymbol{x}) = \sum_{t=1}^{T}\left(C_{\text{GT},t}\sum_{u\in \boldsymbol{GT}} f_{\text{GT}u,t}^{\text{A}}\right)\end{cases} \tag{4}$$

3 Analysis of examples

In the example analysis, the power grid adopts the IEEE-118 node network, which contains 54 generator sets (8 gas turbines, 40 coal-fired units and 6 wind farms are set up), and 4 P2G devices are added. Generator sets and P2G equipment, the natural gas network adopts 20-node network, modifying the gas source type and load type of the corresponding node, the parameters of coal-fired units are shown in Table 1, the parameters of gas turbines are shown in Table 2, and the parameters of electricity-to-gas P2G equipment are shown in Table 3, and the values of carbon emissions trading parameters are taken: the carbon emissions allocation amount δ_1 is taken as 0.798t/MWh, and the carbon trading price is taken as 42$/t . The natural gas network adopts a 20-node network, modifying the gas source type and load type of the corresponding nodes, and the network and its connection relationship with the power grid are shown in Fig. 1. The simulation of this example focuses on the synergistic operation and market equilibrium between the grid and the natural gas network, and the energy flow uploaded by the lower-level EGC-EC after separate optimization analysis is considered to have been imputed to the loads of the grid and the natural gas network, and the total load curve is shown in Fig. 2.

Table 1. Parameters of coal-fired power generators.

Bus node	cost parameters ($/MWh)			P_{Gmin}	P_{Gmax}	δ G
	C_{GA}	C_{GB}	C_{GD}	(MW)	(MW)	(t/MWh)
10/12/15/18/19/24/25/110	0	37.68	127.5	9.375	93.75	1.32
26/27/31/32/36/46/49/105	0	52.875	40.5	15	172.5	1.44
54/55/56/59/61/62/65/104	0	55.875	124.5	15	150	1.5
66/69/70/72/73/74/76/100	0	43.755	87	9.375	93.75	1.47
77/80/85/89/90/92/99/103	0	50.025	40.5	15	150	1.5

Table 2. Parameters of gas turbines.

Bus node	P_{Gmin}	P_{Gmax}	LHV	δ G
	(MW)	(MW)	(MJ/m 3)	(t/MWh)
1/4/6/8/111/112/113/116	0	300	53.82	0.6

Table 3. Parameters of power to gas facilities.

Bus node	P2G capacity	η P2G	CO 2 uptake by P2G	LHV
	(MW)		(t/MWh)	(MJ/m 3)
22/35/43/67	187.5	1.05	0.21	53.82

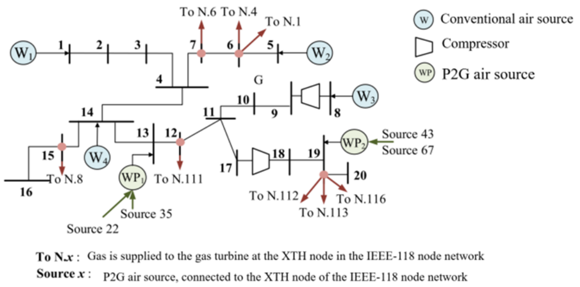

Fig. 1. Structure of modified 20 nodes natural gas system.

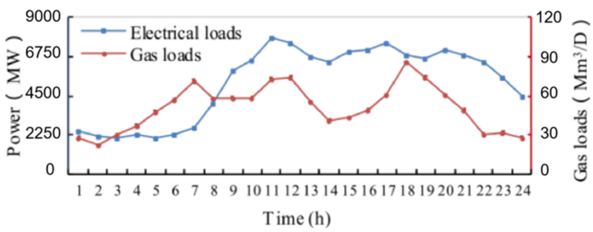

Fig. 2. Data of electrical loads and gas loads.

Table 4. Optimal power output of gas turbines and the corresponding revenue ϕgas (x) under different CGT in the 11 th hour.

C_{GT} ($/m3)	C_{HG} (*) ($)	Gas turbine optimal power output (MW)	ϕgas (x) ($)
0.45	57.42PG	2400	132,000.00
0.51	68.43PG	2321.55	144,709.95
0.57	79.425PG	1871.55	130,384.65

From Table 4, it can be seen that as C_{GT} keeps rising, the optimal generation output of gas turbine decreases when the marginal cost of gas turbine exceeds the marginal cost of generation of a certain coal-fired generating unit. Moreover, during the rising process of C_{GT} , $\phi gas_{(x)}$ first increases (when the optimal power output of gas turbine is not decreased) and then decreases (when the optimal power output of gas turbine is decreased). The optimization scheme that maximizes $\phi_{gas(x)}$ at this moment is: C_{GT} is 0.51$/MW, and the total output of gas turbine is 2321.55MW.

The market equilibrium state studied in this paper reflects the unit capacity arrangement under price fluctuation from another perspective. The comparative analysis of the benefits of constant gas price strategy and market equilibrium state is carried out according to Equation 4, and the specific scenarios of constant gas price strategy are shown in Table 5, and the results of the comparative analysis of the benefits under different scenarios are given in Table 6.

Table 5. Scenario-setting of fixed-price mode.

Scenario	Scene Description	C_{GT} (\$/m3)	C_{HG} (*) (\$)
scenario 1	high price	0.495	0.51
scenario 2	low prices	0.435	0.45

Table 6. Benefit comparison among different scenarios.

Scenario	ϕ_{ele} (\$)	ϕ_{gas} (\$)
scenario 1	36661.5	785236.5
scenario 2	134959.5	1718793
market equilibrium	140046	1800531

Based on the data results in Table 6, it can be seen that the pricing strategy in the market equilibrium is undoubtedly optimal if we only look at the benefits gained from the coupled energy flow transactions of the two major companies, electricity and gas. If the price of gas is raised (Scenario 1), the amount of electricity generated by gas turbines and the amount of gas purchased from P2G sources will decrease accordingly. This will not only make both sides of the game less profitable, but also be detrimental to emission reduction and wind energy consumption. In contrast, when the gas price is low (Scenario 2) the carbon benefits are comparable to the equilibrium state. This is because low gas prices encourage gas turbines to generate more electricity and reduce carbon emissions. However, under the market equilibrium mechanism, the lower price will reduce the benefits of both sides of the game, and the use of the market mechanism can maximize the benefits of both sides of the game.

4. Conclusions

In this paper, a framework of cooperative operation and benefit game for electrical interconnection systems is proposed, including decomposition of upload and download energy flow equivalence, peer energy flow mutualization and peer coupling energy flow pricing game. After obtaining the uploaded energy flow of EGC-EC under the decomposition of cooperative operation framework, focusing on the cooperative operation of power grid and natural gas network and the market game problem, we propose a solution method for the market game of peer-coupled energy flow based on the cooperative operation method of slack energy flow (SEF), and investigate the cooperative benefits of the market equilibrium state with bi-directionally-coupled power grid and natural gas network through simulation and analysis.

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