Two-Layer Optimization Scheduling Model of Integrated Electricity and Natural Gas Energy System Considering the Feasibility of Gas-Fired Units’ Reserve

XUETING ZHOU1,2, YU-QING BAO1,2, (Member, IEEE), TONGZHOU JI1, AND QI WANG1,2

1School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing 210046, China
2Engineering Laboratory of Gas-Electricity Integrated Energy of Jiangsu Province, Nanjing Normal University, Nanjing 210046, China

Corresponding author: Yu-Qing Bao (baoyuqing@njnu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 51707099, and in part by the Postgraduate Innovation Cultivating Project in Jiangsu Province under Grant SJCX19_0198.

ABSTRACT The reserve scheduling is important for integrated energy systems to cope with sudden disturbances such as fluctuations of renewable energy. The existing reserve scheduling approaches for integrated energy systems need iterations of calculation to guarantee the feasibility of the gas-fired units’ reserve, leading to problem of high computational burden. In this paper, a two-layer optimization model is proposed to set the boundary of the gas-fired units’ power and reserve, so that the scheduling result can meet the gas network constraints. The proposed two-layer optimization framework can avoid repeated loop iterations, resulting in low computational complexity. Testing results verify the effectiveness of the proposed method.

INDEX TERMS Gas-power integration, integrated energy system, two-layer optimization.

NOMENCLATURE

| Symbol | Definition |
|--------|------------|
| t      | Index of time periods |
| i      | Index of non-gas-fired units |
| g      | Index of gas-fired generating units |
| w      | Index of natural gas suppliers |
| d      | Index of electric loads |
| l      | Index of electric power transmission lines |
| e      | Index of gas storage tanks |
| s      | Index of boundaries |
| m, n   | Index of gas network nodes |
| j, k   | Index of power system bus nodes |
| η      | Confidence value |
| A_{i,l}/B_{g,l}/C_{d,l} | Element of non-gas-fired units/gas-fired units/elecric load incidence matrix |
| P_{G}  | Price of natural gas |
| P_{Rg} | Price of gas-fired units’ reserve |
| P_{Rc} | Price of non-gas-fired units’ reserve |
| a_{i}/b_{i}/c_{i} | Unit cost coefficients of non-gas-fired unit i |
| a_{g}/b_{g}/c_{g} | Unit cost coefficients of gas-fired unit g |
| K_{s,g,t} | Coefficient of gas-fired unit g under boundary s at time t |
| Q_{N,w,t} | Gas delivery amount of the supplier w at time t |
| Q_{Df,m,t} | Natural gas consumed by Node m at time t |
| Q_{Da,g,t} | Natural gas consumed by gas-fired unit g at time t |
| Q_{L,g,t} | Natural gas network cutting load |
| $Q_{N,w,t}$ | Gas delivery amount of the supplier w at time t |
| $P_{D,d,t}$ | Electric load of load bus d at time t |
| $E(P_{D,d,t})$ | Load forecasting value |
| $P_{E,s,t}$ | Maximum value of the sum of the gas-fired units’ output and reserve of boundary s at time t |
| $P_{G,i,t}$ | Power generation of non-gas-fired unit i at time t |
| $P_{G,g,t}$ | Power generation of gas-fired unit g at time t |
| $P_{R,i,t}$ | Reserve capacity provided by non-gas-fired unit i at time t |
The integrated electricity and natural-gas energy system (IEGS) is becoming closer. The connection between electric power systems and other energy systems (e.g., natural gas, heat, cooling) is becoming closer. With the development of multi-energy systems, the connection between electric power systems and other energy systems is becoming closer. With the development of society and increasing consumption of energy, fossil energy shortages and environmental pollution cannot be ignored. Natural gas is becoming rapidly the optimal choice for new generating units in electricity grid [1]. With the development of multi-energy systems, the connection between electric power systems and other energy systems (e.g., natural gas, heat, cooling) is becoming closer. The integrated electricity and natural-gas energy system (IEGS) receives more and more attention, since it can improve the energy efficiency and help accommodating renewable energies [2], [3].

At present, some scholars have conducted research on IEGS. In references [4]–[7], the planning of IEGS is analyzed. References [8], [9] focus on the electricity markets and natural gas markets of IEGS. The long-term integrated planning of interdependent natural gas and electric transmission systems is analyzed in [10]. References [11]–[13] focus on the economic dispatch problem of IEGS. Reference [14] points out that gas storage tanks can be used as alternatives to natural gas suppliers to provide natural gas to the network and ensure sufficient natural gas load supply. References [5]–[7], [15]–[20] propose different piecewise linear approximation methods to solve the non-convex and nonlinear IEGS optimization problem. These methods mainly include the following types, metaheuristic algorithm [5], [6], second-order cone (SOC) relaxation [15], [16], and piecewise linear approximation [7], [17]–[20] etc. References [18], [21] present the study of the coordinated scheduling strategy, in which, the models of the electricity network and gas network are developed in detail, and the operation constraints of the networks are fully considered. Considering the uncertainties of load and wind power, a robust day-ahead scheduling model for the optimal coordinated operation of integrated energy systems is established in [22], [23]. Reference [24] proposes a robust security-constrained unit commitment model to enhance the operational reliability of integrated electricity-natural gas system (IEGS) against possible transmission line outages. Reference [25] proposes a novel optimal scheduling model based on chance-constrained programming to seek the minimum generation cost for a small-scale integrated energy system.

Aiming at the problem that the existing scheduling model of IEGS does not fully consider the feasibility of gas-fired units’ reserve, references [26], [27] propose robust economic scheduling and reserve configuration model considering wind power uncertainty and gas network operation constraints. The model is configured to verify the feasibility of gas-fired units’ reserve, and the grid scheduling and reserve results are repeatedly modified until the output and reserve of gas-fired units meet the gas network constraints. However, repeated loop iterations will increase the amount of unnecessary calculations, and it is also prone to situations where the number of iterations is too large and the system has no solution.

In order to avoid repeated loop iterative calculation process, this paper sets the boundary of the gas-fired units’ output and reserve through the two-layer optimization to make the gas-fired units’ output and reserve meet the gas network constraints. By this way, the computational efficiency can be improved, and therefore reduce the calculation time.

Compared with existing methods, the key contributions of this paper are threefold.

I. INTRODUCTION

With the development of society and increasing consumption of energy, fossil energy shortages and environmental pollution cannot be ignored. Natural gas is becoming rapidly the optimal choice for new generating units in electricity grid [1]. With the development of multi-energy systems, the connection between electric power systems and other energy systems (e.g., natural gas, heat, cooling) is becoming closer. The integrated electricity and natural-gas energy system (IEGS)

\[ P_{R,g,t} \] Reserve capacity provided by gas-fired unit \( g \) at time \( t \)

\[ P_{f,l,t} \] Power flow of transmission line \( l \) at time \( t \)

\[ P_{G,i}^{\min} / P_{G,i}^{\max} \] Minimum/maximum capacity of non-gas-fired unit \( i \)

\[ P_{G,g}^{\min} / P_{G,g}^{\max} \] Minimum/maximum capacity of gas-fired unit \( g \)

\[ RU_i / RD_i \] Ramp up/Ramp down rate of non-gas-fired unit \( i \) at time \( t \)

\[ RU_g / RD_g \] Ramp up/Ramp down rate of gas-fired unit \( g \) at time \( t \)

\[ x_{i,t} / y_{i,t} \] Binary start-up/shutdown variable of non-gas-fired unit \( i \) at time \( t \)

\[ x_g / y_g, t \] Binary start-up/shutdown variable of gas-fired unit \( g \) at time \( t \)

\[ u_{i,t} \] Binary commitment variable of non-gas-fired unit \( i \) at time \( t \)

\[ u_g, t \] Binary commitment variable of gas-fired unit \( g \) at time \( t \)

\[ P_{f,l,\max} \] Electricity power flow maximum capacity of transmission line \( l \) at time \( t \)

\[ S_{e,\min} / S_{e,\max} \] Minimum/maximum storage capacity of the gas storage tank \( e \)

\[ Q_{in}^{\min} / Q_{out}^{\max} \] Gas injection/output flow of the gas storage tank \( e \) at time \( t \)

\[ Q_{in}^{\max} / Q_{out}^{\min} \] Maximum gas injection/output flow of the gas storage tank \( e \) at time \( t \)

\[ q_{N,w}^{\min} / q_{N,w}^{\max} \] Minimum/maximum gas delivery amount of the supplier \( w \)

\[ \pi_m / \pi_n \] Gas nodal pressure of node \( m/n \)

\[ \pi_{\min} / \pi_{\max} \] Minimum/maximum nodal pressure

\[ \sigma_{nm,p} \] Segment value and binary indicator variable for one-dimensional piecewise linearization

\[ k_{np} \] Coefficients of one-dimensional piecewise linear function

\[ Q_{mn} \] Gas flow from node \( m \) to node \( n \)

\[ C_{mn} \] Weymouth equation coefficient

\[ N_l \] Number of time periods

\[ N_w \] Number of gas suppliers

\[ N_i \] Number of non-gas-fired units

\[ N_g \] Number of gas-fired units

\[ N_d \] Number of load buses

\[ CN_m \] Set of nodes connected to node \( m \)
(1) The proposed two-layer scheduling model of integrated energy systems can guarantee that the gas-fired units’ reserve meets the gas network operating constraints.

(2) The proposed method avoids the repeated loop iterative calculation, and therefore results in lower computational complexity and shorter calculation time.

(3) The proposed method is unlimited to the scale of system. The larger the system, the more processing time the proposed method saves.

The rest of this paper is organized as following. In section II, the IEGS optimization scheduling model without considering the feasibility of the gas-fired units’ reserve is briefly introduced. In section III, the two-layer optimization scheduling model of IEGS considering the feasibility of the gas-fired units’ reserve is proposed. Testing results are provided in Section IV. Conclusions are summarized in Section V.

II. THE IEGS OPTIMIZATION SCHEDULING MODEL WITHOUT CONSIDERING THE FEASIBILITY OF THE GAS-FIRED UNITS’ RESERVE

The IEGS model includes the power system and the natural gas system and needs to establish the objective function and constraints on both the integrated electricity and natural gas energy system.

A. OBJECTIVE FUNCTION

The objective function of the IEGS model is to minimize the operating cost. Assuming that the natural gas consumed by the gas-fired units is provided by the natural gas system, and the operating cost mainly considers the cost of non-gas-fired unit, natural gas and reserve provided by generators. The objective function is expressed as:

$$\text{min} \sum_{i=1}^{N_t} \left( \sum_{w=1}^{N_w} Q_{N_w,t} \cdot P_{G,w} + \sum_{i=1}^{N_t} P_{R,i,t} \cdot p_{G,i,t} \right)$$

$$+ \sum_{g=1}^{N_g} p_{G,g} \cdot P_{G,g,t} + \sum_{i=1}^{N_t} (a_i + b_i \cdot P_{G,i,t} + c_i \cdot P_{G,i,t}^2)$$

(1)

B. ELECTRIC POWER SYSTEM CONSTRAINTS

1) GENERATING UNIT CONSTRAINTS

The generating unit constraints include startup/shutdown constraints, capacity constraints, ramp rate constraints, reserve capacity constraints, power balance constraints, etc. These constraints can be expressed as follows:

$$x_{i,t} - y_{i,t} = u_{i,t} - u_{i,t-1}$$

$$x_{i,t} + y_{i,t} \leq 1$$

$$x_{g,t} - y_{g,t} = u_{g,t} - u_{g,t-1}$$

$$x_{g,t} + y_{g,t} \leq 1$$

$$u_{i,t} \cdot p_{G,i,t}^\text{min} \leq P_{G,i,t} \leq u_{i,t} \cdot p_{G,i,t}^\text{max}$$

(2)

(3)

(4)

(5)

(6)

2) POWER TRANSMISSION CONSTRAINTS

Constraint (13) shows the power balance at each bus. Constraint (14) represents that the power flow is limited by the transmission line capacity.

$$P_{G,i,t} = A_{i,t} \cdot P_{G,i,t} + B_{i,t} \cdot P_{G,i,t} - C_{d,t} \cdot P_{D,d,t}$$

$$|P_{G,i,t}| \leq P_{G,i,t}^\text{max}$$

(7)

(8)

(9)

(10)

(11)

(12)

3) CHANCE CONSTRAINTS CONSIDERING LOAD UNCERTAINTY

The paper mainly considers that load randomly deviates from forecast values, so the uncertain load of power system is the reserve range of generating units. It can be expressed as:

$$\text{Pr} \left\{ \sum_{i=1}^{N_t} \sum_{g=1}^{N_g} P_{G,i,t} + \sum_{g=1}^{N_g} P_{R,g,t} \sum_{g=1}^{N_g} P_{G,g,t} \geq \sum_{d=1}^{N_d} P_{D,d,t} \right\} \geq \eta$$

(13)

(14)

(15)

Assuming that the error of the load forecast obeys the normal distribution with expectation of 0 and standard deviation of $\delta_D$:

$$\sum_{d=1}^{N_d} P_{D,d,t} \sim E(\sum_{d=1}^{N_d} P_{D,d,t}) + N(0, \delta_D^2)$$

(16)

The constraint (15) can be transformed into:

$$\Phi \left( \frac{\sum_{i=1}^{N_t} \sum_{g=1}^{N_g} P_{G,i,t} + \sum_{g=1}^{N_g} P_{R,g,t} + \sum_{g=1}^{N_g} P_{G,g,t} - E(\sum_{d=1}^{N_d} P_{D,d,t})}{\sqrt{\delta_D^2}} \right) \geq \eta$$

(17)

where $\Phi$ is probability distribution function.

The formula (17) can be transformed into:

$$\sum_{g=1}^{N_g} P_{G,g,t} - E(\sum_{d=1}^{N_d} P_{D,d,t}) \geq \Phi^{-1}(\eta) \cdot \sqrt{\delta_D^2}$$

(18)
C. NATURAL GAS NETWORK CONSTRAINTS

1) NATURAL GAS SUPPLIERS
Natural gas suppliers provide the natural gas through its transmission network. The lower and upper limits of gas suppliers at each period are given as:

\[ Q_{\text{in}}^{\text{min},w,t} \leq Q_{\text{in},w,t} \leq Q_{\text{in}}^{\text{max},w} \quad (19) \]

2) GAS STORAGE TANK
Gas storage tank refers to the equipment which is specially used to store gas. When inadequate gas is provided by the natural gas suppliers, gas storage tank can supply natural gas to the natural gas system instead of natural gas supplier to ensure that the system can supply adequate gas and maintain normal operation. Gas storage tank is constrained to storage capacity limits, the limits of natural gas injection and output.

The constraints can be expressed as follows:

\[ S_{S,e,t}^{\text{in}} \leq S_{S,e,t} = S_{S,e,t-1} + Q_{S,e,t}^{\text{in}} - Q_{S,e,t}^{\text{out}} \leq S_{S,e}^{\text{max}} \quad (20) \]
\[ 0 \leq Q_{S,e,t}^{\text{in}} \leq Q_{S,e}^{\text{in}} \quad (21) \]
\[ 0 \leq Q_{S,e,t}^{\text{out}} \leq Q_{S,e}^{\text{out}} \quad (22) \]

3) PIPELINE
The gas flow of natural gas pipeline is influenced by the pressure at both ends of the pipeline, the length and diameter of the pipeline, the working temperature, the roughness of the pipeline, etc. The model of this paper considers the Weymouth pipeline flow equation, which can be expressed as follows:

\[ Q_{mn} = \text{sgn}(\pi_m, \pi_n)C_{mn}\sqrt{|\pi_m^2 - \pi_n^2|} \quad (23) \]
\[ \text{sgn}(\pi_m, \pi_n) = \begin{cases} 1 & \pi_m > \pi_n \\ -1 & \pi_m < \pi_n \end{cases} \quad (24) \]
\[ \pi_m^{\text{min}} \leq \pi_m \leq \pi_m^{\text{max}} \quad (25) \]
\[ \pi_n^{\text{min}} \leq \pi_n \leq \pi_n^{\text{max}} \quad (26) \]

The Weymouth gas flow function (23)(24) is nonlinear and non-convex that cannot be directly solved by many popular optimization techniques. Piecewise linear approximation can be adopted to solve this problem.

It can be noted that the right side of equation (23) is a function of \( \pi_m^2 \) and \( \pi_n^2 \). By introducing variables \( \theta_m = \pi_m^2 \), \( \theta_n = \pi_n^2 \), equation (23) can be replaced by:

\[ Q_{mn} = \text{sgn}(\varphi_{mn})C_{mn}\sqrt{|\varphi_{mn}|} \quad (27) \]
\[ \varphi_{mn} = \theta_m - \theta_n \quad (28) \]

Additionally, nodal pressure limit constraints (25)(26) are replaced by:

\[ (\pi_m^{\text{min}})^2 \leq \theta_m \leq (\pi_m^{\text{max}})^2 \quad (29) \]
\[ (\pi_n^{\text{min}})^2 \leq \theta_n \leq (\pi_n^{\text{max}})^2 \quad (30) \]

Note that constraint (27) is the one-dimensional nonlinear equation, which significantly simplifies the linearization. The upper and lower limitations of \( \varphi_{mn} \) can be determined by:

\[ \varphi_{mn}^{\text{max}} = (\pi_m^{\text{max}})^2 - (\pi_n^{\text{min}})^2 \quad (31) \]
\[ \varphi_{mn}^{\text{min}} = (\pi_m^{\text{min}})^2 - (\pi_n^{\text{max}})^2 \quad (32) \]

The range of \( \varphi_{mn} \) (\([\varphi_{mn}^{\text{min}}, \varphi_{mn}^{\text{max}}]\)) can be divided into \( N_{mn} \) segments. The nonlinear function (27) can be transformed into (33)-(36).

\[ \varphi_{mn} = \varphi_{mn0} + \sum_{p=1}^{N_{mn}} \sigma_{mn,p} \quad (33) \]
\[ Q_{mn} = Q_{mn0} + \sum_{p=1}^{N_{mn}} K_p^{mn} \sigma_{mn,p} \quad (34) \]
\[ z_{mn,p+1} \cdot (\varphi_{mn,p} - \varphi_{mn,p}) \leq \sigma_{mn,p} \quad (35) \]
\[ \sigma_{mn,p} \leq z_{mn,p} \cdot (\varphi_{mn,p} - \varphi_{mn,p}) \quad (36) \]

4) FLOW CONSERVATION
The steady-state natural gas injection at each node is equal to the flow extracted from the node. The flow conservation equation (37) ensures the nodal balance at the natural gas transmission system.

\[ (Q_{S,e,t}^{\text{in}} - Q_{S,e,t}^{\text{out}}) + \sum_{n \in C_{mn}} Q_{mn,t} + Q_{N,w,t} - Q_{Df,m,t} - Q_{Daf,g,t} = 0 \quad (37) \]

D. NATURAL GAS NETWORK AND POWER SYSTEM COUPLING RELATIONSHIP
The IEGS is formed by the coupling of natural gas network and power system. This paper mainly considers the coupling of gas-fired units. Gas-fired units consume natural gas to generate electricity. Their natural gas input can be regarded as the load of the natural gas network, and their energy output is the source of the power system. The coupling relationship can be expressed as:

\[ Q_{Daf,g,t} = a_g + b_g \cdot P_{G,g,t} + c_g \cdot P_{G,g,t}^2 \quad (38) \]

However, the coupling relationship between the natural gas system and the power system given by equation (38) only ensures that the gas-fired units’ output meets the gas network operating constraints, and does not consider the problem that whether the reserve capacity of the gas-fired units meets gas network operation constraints. In order to make the gas-fired units’ reserve meets the gas network operating constraints, it is necessary to propose the IEGS optimization scheduling model considering the feasibility of the gas-fired units’ reserve.

III. TWO-LAYER OPTIMIZATION SCHEDULING MODEL OF IEGS CONSIDERING THE FEASIBILITY OF GAS-FIRED UNITS’ RESERVE
To guarantee the feasibility of the gas-fired units’ reserve, two-layer optimization model of the IEGS sets the gas-fired
units’ output and reserve boundary through the first layer optimization, and then adds the boundary constraints to the second layer optimization constraints to optimize the scheduling model.

A. THE METHOD OF VERIFYING THE FEASIBILITY OF THE GAS-FIRED UNITS’ RESERVE

1) OBJECTIVE FUNCTION

The objective function of verifying the feasibility of gas-fired units’ reserve is to minimize the natural gas network cutting load, which is a slack variable. When the value of natural gas network cutting load is greater than 0, it indicates that the gas-fired units’ output and reserve do not meet the constraints of the gas network operation.

\[
\text{min} \sum_{t=1}^{N_t} \sum_{g=1}^{N_g} Q_{L,g,t} \tag{39}
\]

2) CONSTRAINTS

The constraints of the gas network constraints subproblem are the same as equations (19)-(38). The gas network operation constraints subproblem is to verify whether the gas-fired units’ output and reserve meet the gas network operation constraints, so in the gas network operation constraints subproblem, the constraint (37) becomes (40), and the constraint (38) becomes (41).

\[
Q_{\text{Duf},g,t} = a_g + b_g \cdot (P_{G,g,t} + P_{R,g,t}) + c_g \cdot (P_{G,g,t} + P_{R,g,t})^2 \tag{41}
\]

B. TWO-LAYER OPTIMIZATION METHOD

1) THE UPPER OPTIMIZATION

The objective of the upper optimization is to get different maximum boundaries of the sum of the gas-fired units’ output and reserve. It is expressed as following:

\[
P_{E,s,t} = \max_{g=1}^{N_g} \sum_{g=1}^{N_g} K_{s,g,t}(P_{G,g,t} + P_{R,g,t}) \tag{42}
\]

The maximum boundaries of the sum of the gas-fired units’ output and reserve should meet the natural gas system constraints, so the constraints of the upper optimization are the natural gas system constraints which are the same as (19)-(37), (41).

2) THE LOWER OPTIMIZATION

The lower layer optimization is the optimization scheduling problem of the traditional IEGS, which is similar with the model of Section II. The objective function is the same as (1) in Section II.

Different from the model of Section II is the constraint obtained by the upper layer optimization. Through upper layer optimization, we get the maximum boundaries of the sum of the gas-fired units’ output and reserve, which is express as (42). It is necessary to add the maximum boundaries in the constraints and it is expressed as (43). So the constraint of the lower layer optimization is (2)-(38) in Section II and the constraint (43) obtained by the upper layer optimization.

\[
\sum_{g=1}^{N_g} K_{s,g,t}(P_{G,g,t} + P_{R,g,t}) \leq P_{E,s,t} \tag{43}
\]

C. COMPARISON BETWEEN TWO-LAYER OPTIMIZATION METHOD AND EXISTING METHODS

In order to make the gas-fired units’ output and reserve meet the gas network operating constraints, the method in references [26], [27] is to continuously reduce the maximum power \(P_{G,g}^{\text{max}}\) of gas-fired units, so that the grid dispatching and reserve results can be repeated modified until the gas-fired units’ output and reserve boundary through the first layer optimization, and then adds the boundary constraints to the second layer optimization constraints to optimize the scheduling model.

FIGURE 1. Flow chart of two models. (a) loop iterative method (existing method); (b) two-layer optimization method.
units’ output and reserve meet the gas network operating constraints.

Figure 1 shows the flow chart of the two models. The red solid line in Figure 1(b) is the boundary of the gas-fired units’ output and reserve. Comparing the flow chart of the loop iterative method in references [26], [27], it can be seen that the two-layer optimization method reduce calculating amount by setting the maximum boundaries of the sum of the gas-fired units’ output and reserve, because it avoids repeated loop iteration process.

IV. TESTING RESULTS

In this paper, the 6-bus-6-Node IEGS and the 118-bus-10-Node IEGS are adopted to test the effectiveness of the proposed model.

A. 6-BUS-6-NODE IEGS

The 6-bus power system depicted in Figure 2 has three generators (including one non-gas-fired unit and two natural gas-fired units), seven transmission lines, and three loads. The 6-Node natural gas system is given in Figure 3, which has 2 natural gas suppliers, 5 pipelines, 1 gas storage tank, and 5 natural gas loads. Natural-gas-fired units 2 and 3 are connected to the Nodes 1 and 3. The gas storage tank is connected to the Node 2. The parameters of power system and natural gas system refer to references [18], [27]. The parameters of three generators G1, G2 and G3, the natural gas suppliers W1 and W2 and the gas storage tank S are shown in Table 1 and Table 2. The confidence value \( \eta \) is 0.95.

In order to investigate the influence and differences of different integrated energy system optimization scheduling models considering the feasibility of gas-fired units’ reserve, three different cases are put forward for comparative analysis.

---

**TABLE 1. Parameters of the generating units.**

| Units  | Unit type | Electricity system bus number | Natural gas system node number | Maximum output power (MW) | Minimum output power (MW) |
|--------|-----------|--------------------------------|--------------------------------|---------------------------|---------------------------|
| G1     | Non-gas   | 1                              | 1                              | 220                       | 100                       |
| G2     | Gas-fired | 2                              | 1                              | 80                        | 10                        |
| G3     | Gas-fired | 6                              | 3                              | 20                        | 2                         |

**TABLE 2. Parameters of natural gas suppliers and gas storage tank.**

| Type    | Natural gas system node number | Maximum capacity (kcf) | Minimum capacity (kcf) | Maximum gas injection flow (kcf/h) | Maximum Gas output flow (kcf/h) |
|---------|--------------------------------|------------------------|------------------------|-----------------------------------|---------------------------------|
| W1      | 4                              | 5000                   | /                      | /                                 | /                               |
| W2      | 6                              | 6000                   | 1500                   | /                                 | /                               |
| S       | 2                              | 200                    | 0                      | 100                               | 12                              |

Case 1: Integrated energy system optimization scheduling model without considering the feasibility of gas-fired units’ reserve;

Case 2: Integrated energy system loop iteration scheduling model considering the feasibility of gas-fired units’ reserve [26], [27];

Case 3: Two-layer optimization scheduling model of integrated energy systems considering the feasibility of gas-fired units’ reserve.

Reserve capacity provided by non-gas-fired units, reserve capacity provided by generators, natural gas network cutting load, the reserve feasibility and processing time are listed in Table 3. Generators scheduling results and the sum of the gas-fired units’ output and reserve of different cases are shown in Figure 4 and Figure 5, respectively.

Among them, the shaded part in Figure 6 indicates the feasible range of the gas-fired units’ output and reserve determined by the three boundaries of the sum of gas-fired units’ output and reserve after the first layer optimization of Case 3. The maximum sum of two gas-fired units’ output and reserve is 117.67 MW, the maximum sum of the first gas-fired unit’ output and reserve is 45.58 MW, and the maximum sum of the second gas-fired unit’ output and reserve is 72.09 MW.

It can be seen from Table 3, Figure 4, and Figure 5 that the reserve capacity provided by the two gas-fired units in Case 1 is higher than that of Case 2 and Case 3, resulting in higher gas-fired units’ output and higher reserve than Case 2 and Case 3. Natural gas network cutting load \( Q_L \) is obviously greater than 0 in Case 1, indicating that gas-fired units’ output and reserve do not meet the gas network operating constraints in Case 1, and natural gas network cutting load \( Q_L \) is approximately equal to 0 in Case 2 and Case 3, indicating that gas-fired units’ output and reserve meet the gas network operating constraints in Case 2 and Case 3. From the comparison of Case 1, Case 2 and Case 3, it can be seen that the gas-fired units’ reserve of two kinds of integrated energy system models considering the feasibility of gas-fired units’ reserve is less than that of integrated energy system models considering the feasibility of gas-fired units’ reserve.

---
Comparing Case 2 and Case 3, the sum of the gas-fired units’ output and reserve of two kinds of IEGS scheduling model considering the gas network operating constraints are similar, and both the gas-fired units’ output and reserve meet the gas network operating constraints, which proves the effectiveness of the two-layer optimization method. In Case 2, the power grid dispatching and reserve results are modified twice in two iterations of calculation to make the gas-fired units’ output and reserve capacity meet the gas network operating constraints. In Case 3, the boundary of the sum of the gas-fired units’ output and reserve is set at the beginning, which can avoid iterative process and save time. Meanwhile, the total cost in Case 1, Case 2 and Case 3 are almost the same, but Case 3 obviously makes the best performing.
B. 118-BUS-10-NODE IEGS

The 10-Node natural gas system is shown in Figure 7, which includes 3 natural gas suppliers, 10 pipelines, 2 gas storage tanks, and 12 natural gas loads. The modified IEEE 118-bus power system depicted in Figure 8 has 54 generators (including 46 non-gas-fired units and 8 natural gas-fired units), 186 transmission lines, and 91 loads. Natural gas-fired units G1, G2, G3, G4, G5, G6, G7, G8 are connected to the natural gas system Nodes 4, 7, 7, 5, 5, 8, 10, 10, respectively. The relevant parameters of the power system and the natural gas system are referred to the reference [18]. The simulation is also carried out considering three cases in Section IV, Subsection A. The sum of gas-fired units’ power and reserve of different cases of 118-bus-10-Node IEGS are shown in Table 4 and the scheduling results of different cases of 118-bus-10-Node IEGS are shown in Table 5.

It is more obvious from Table 4 and Table 5 that the total reserve capacity provided by the gas-fired units in the Case 1 is higher than that in Case 2 and Case 3, resulting in higher gas-fired units’ output and higher reserve than Case 2 and Case 3. And the gas-fired units’ output and reserve capacity in Case 1 do not meet the gas network operating constraint. Meanwhile, in Case 2, there is a small amount of

---

**TABLE 4.** The sum of gas-fired units’ power and reserve of different cases of 118-bus-10-Node IEGS.

| Case 1 | First iteration | ... | The fifth iteration | Case 3 |
|--------|----------------|-----|-------------------|-------|
| $P_{G1}^0$ - $P_{G1}$ (MW) | 1384.2 | 1132.5 | ... | 1062.2 | 1134.2 |
| $P_{G2}^0$ - $P_{G2}$ (MW) | 1057.2 | 853.3 | ... | 838.7 | 528.4 |
| $P_{G3}^0$ - $P_{G3}$ (MW) | 904.9 | 710.4 | ... | 600.1 | 130.2 |
| $P_{G4}^0$ - $P_{G4}$ (MW) | 308.8 | 227.6 | ... | 253.6 | 559.7 |
| $P_{G5}^0$ - $P_{G5}$ (MW) | 280.8 | 427.4 | ... | 413.6 | 8 |
| $P_{G6}^0$ - $P_{G6}$ (MW) | 1168.3 | 961.4 | ... | 912.6 | 1159.4 |
| $P_{G7}^0$ - $P_{G7}$ (MW) | 2111.9 | 2256.2 | ... | 1201.2 | 1634.9 |
| $P_{G8}^0$ - $P_{G8}$ (MW) | 926.3 | 1419.9 | ... | 1180.8 | 335.2 |

**TABLE 5.** Scheduling results of different cases of 118-bus-10-Node IEGS.

| Case 1 | First iteration | ... | The fifth iteration | Case 3 |
|--------|----------------|-----|-------------------|-------|
| Total reserve capacity provided by non-gas-fired unit (MW) | 2193.7 | 5120.7 | ... | 5805.4 | 6063.6 |
| Total reserve capacity provided by natural gas-fired units (MW) | 3869.9 | 942.9 | ... | 258.2 | 0 |
| Natural gas network cutting load (kcf) | 156570.2 | 39798.1 | ... | 8000.5 | 0 |
| Reserve feasibility | Not feasible | Not feasible | ... | Not feasible | Feasible |
| Processing time(s) | 5.05 | 174.35 | ... | 7.67 |
| Total cost($) | 4379000 | 4374900 | ... | 4376854 | 4378300 |
natural gas network cutting load through five iterations. The natural gas network cutting load in Case 3 is approximately equal to 0 through two-layer optimization, which greatly saves calculation time. The total cost in Case 1, Case 2 and Case 3 are similar, but Case 3 obviously makes the best performing, which indicates the advantages and effectiveness of the two-layer optimization scheduling model compared with existing models.

From Table 3 and Table 5, we can see that the proposed method is unlimited to the scale of system. Compared with existing methods, the larger the system, the more processing time the proposed method saves.

V. CONCLUSION

Aiming at the feasibility of gas-fired units’ reserve of the IEGS scheduling, the two-layer optimization scheduling model of integrated energy system considering the feasibility of gas-fired units’ reserve is proposed. The simulation results verify the effectiveness of the proposed method. Compared with existing methods, the main contributions of this paper are as follows:

- The proposed two-layer scheduling model of integrated energy systems can guarantee the feasibility of gas-fired units’ reserve.
- The proposed method avoids the repeated loop iterative calculation, and therefore results in lower computational complexity and shorter calculation time.
- The proposed method is unlimited to the scale of system. The larger the system, the more processing time the proposed method saves.

The future work may be applying the proposed method to a more complex electricity-gas-heat integrated energy system that considers additional heat network constraints.

REFERENCES

[1] (2011). EIA, Annual Energy Review. [Online]. Available: http://www.eia.doc.gov/emeu/aer/
[2] B. Odetayo, J. MacCormack, W. D. Rosehart, and H. Zareipour, “A chance constrained programming approach to integrated planning of distributed power generation and natural gas network,” Electr. Power Syst. Res., vol. 151, pp. 197–207, Oct. 2017.
[3] S. Chen, Z. Wei, G. Sun, D. Wang, Y. Zhang, and Z. Ma, “Stochastic look-ahead dispatch for coupled electricity and natural-gas networks,” Electr. Power Syst. Res., vol. 164, pp. 159–166, Nov. 2018.
[4] C. Shao, M. Shahidehpour, X. Wang, X. Wang, and B. Wang, “Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience,” IEEE Trans. Power Syst., vol. 32, no. 6, pp. 4418–4429, Nov. 2017.
[5] Y. Hu, Z. Bie, T. Ding, and Y. Lin, “An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning,” Appl. Energy, vol. 167, pp. 280–293, Apr. 2016.
[6] J. Qu, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng, and D. J. Hill, “Low carbon oriented expansion planning of integrated gas and power systems,” IEEE Trans. Power Syst., vol. 30, no. 2, pp. 1035–1046, Mar. 2015.
[7] C. M. Cortaze-Posada and P. Sanchez-Martín, “Integrated power and natural gas model for energy adequacy in short-term operation,” IEEE Trans. Power Syst., vol. 30, no. 6, pp. 3347–3355, Nov. 2015.
[8] C. O’Malley, S. Delikaraoglou, and G. Hug, “Improving electricity and natural gas systems coordination using swing option contracts,” in Proc. IEEE Milan PowerTech, Jun. 2019, pp. 1–6.
[9] G. Byeon and H. P. Van, “Unit commitment with gas network awareness,” IEEE Trans. Power Syst., vol. 30, no. 2, pp. 1035–1046, Sep. 2015.

S. Hecq, Y. Bouffioux, P. Douliere, and D. Saintes, “The integrated planning of the natural gas and electricity systems under market conditions,” in Proc. IEEE PowerTech, Porto, Portugal, Sep. 2001, pp. 1–5.

M. Geidl and G. Andersson, “Optimal power flow of multiple energy carriers,” IEEE Trans. Power Syst., vol. 22, no. 1, pp. 145–155, Feb. 2007.

C. Uno, J. W. M. Lima, and A. C. Z. de Souza, “Modeling the integrated natural gas and electricity optimal power flow,” in Proc. IEEE Power Eng. Soc. Gen. Meeting, Jun. 2007, pp. 1–7.

S. An, Q. Li, and T. W. Gedra, “Natural gas and electricity optimal power flow,” in Proc. IEEE PES Transmiss. Distrib. Conf. Expo., Sep. 2003, pp. 138–143.

Z. Wei, S. Zhang, G. Sun, H. Zang, S. Chen, and S. Chen, “Power-to-gas considered peak load shifting research for integrated electricity and natural-gas energy systems,” in (Chinese), Proc. CSEE, vol. 37, no. 16, pp. 4601–4609, 2017.

F. Liu, Z. Bie, and X. Wang, “Day-ahead dispatch of integrated electricity and natural gas system considering reserve scheduling and renewable uncertainties,” IEEE Trans. Sustain. Energy, vol. 10, no. 2, pp. 646–658, Apr. 2019.

C. Wang, W. Wei, J. Wang, L. Bai, Y. Liang, and T. Bi, “Convex optimization based distributed optimal gas-power flow calculation,” IEEE Trans. Sustain. Energy, vol. 9, no. 3, pp. 1145–1156, Jul. 2018.

C. He, L. Wu, T. Liu, and M. Shahidehpour, “Robust co-optimization scheduling of electricity and natural gas systems via ADMM,” IEEE Trans. Sustain. Energy, vol. 8, no. 2, pp. 658–670, Apr. 2017.

X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, “Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks,” IEEE Trans. Power Syst., vol. 31, no. 1, pp. 592–601, Jan. 2016.

C. Shao, X. Wang, M. Shahidehpour, X. Wang, and B. Wang, “An MILP-based optimal power flow in multicarrier energy systems,” IEEE Trans. Sustain. Energy, vol. 8, no. 1, pp. 239–248, Jan. 2017.

Y.-Q. Bao, M. Wu, X. Zhou, and X. Tang, “Piecewise linear approximation of gas flow function for the optimization of integrated electricity and natural gas system,” IEEE Access, vol. 7, pp. 91819–91826, 2019.

J. H. Zheng, Q. H. Wu, and Z. X. Jing, “Coordinated scheduling strategy to optimize conflicting benefits for daily operation of integrated electricity and gas networks,” Appl. Energy, vol. 192, pp. 370–381, Apr. 2017.

C. He, T. Liu, L. Wu, and M. Shahidehpour, “Robust coordination of independent electricity and natural gas systems in day-ahead scheduling for facilitating volatile renewable generations via power-to-gas technology,” J. Mod. Power Syst. Clean Energy, vol. 5, no. 3, pp. 375–388, Apr. 2017.

C. Wang, R. Gao, W. Wei, M. Shafie-khah, T. Bi, and J. P. S. Catalao, “Risk-based distributionally robust optimal gas-power flow with water-source distance,” IEEE Trans. Power Syst., vol. 34, no. 3, pp. 2190–2204, May 2019.

Y. B. He and M. Shahidehpour, “Robust constrained operation of integrated electricity-natural gas system considering distributed natural gas storage,” IEEE Trans. Sustain. Energy, vol. 9, no. 3, pp. 1061–1071, Jul. 2018.

Y. Li, C. Wang, G. Li, J. Wang, D. Zhao, and C. Chen, “Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings,” Energy Convers. Manage., vol. 207, Mar. 2020, Art. no. 112526.

L. Yi, S. Zhouce, and Z. Lei, “Robust economic dispatch and reserve configuration considering wind uncertainty and gas network constraints,” (in Chinese), Trans. China Electrotech. Soc., vol. 33, no. 11, pp. 58–69, 2018.

Y. Zhang, J. Le, F. Zheng, Y. Zhang, and K. Liu, “Two-stage distributionally robust coordinated scheduling for gas-electricity integrated energy system considering wind power uncertainty and reserve capacity configuration,” Renew. Energy, vol. 135, pp. 122–135, May 2019.

XUETING ZHOU was born in Jian, China, in 1996. She received the B.S. degree from Nanjing Normal University (NJNU), Nanjing, China, in June 2017, where she is currently pursuing the M.S. degree. Her current research interest includes power system operation and scheduling.
YU-QING BAO (Member, IEEE) was born in Zhenjiang, China, in 1987. He received the Ph.D. degree from Southeast University (SEU), Nanjing, China, in March 2016. He is currently an Associate Professor with Nanjing Normal University (NJNU). His current research interests include power system operation and scheduling, power demand side management, and frequency control of the power systems.

TONGZHOU JI was born in Yancheng, China, in 1962. He is currently a Senior Experimentalist with Nanjing Normal University (NJNU). His current research interests include automated detection and intelligent control.

QI WANG received the Ph.D. degree from the Harbin Institute of Technology, Harbin, China, in 2008. She is currently an Associate Professor with Nanjing Normal University (NJNU). Her current research interest includes power systems and automation.

* * *