An Improved Sequential Energy Flow Analysis Method Based on Multiple Balance Nodes in Gas-electricity Interconnection Systems

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ABSTRACT Gas-electric energy interconnection is one of the main forms of energy interconnection in the future. Energy flow analysis is the basis for its characteristic analysis and optimization operation. It is not in line with the actual situation that prescribed output of the gas turbine and neglected dual constraint of the gas-electric in the sequential energy flow analysis. In addition, considering the role of multi-balance nodes and the computational requirements of the sequential algorithm, this paper proposes an improved sequential energy flow analysis method based on multi-balance nodes in gas-electricity interconnection systems. In this paper, the gas flow in the gas network with multiple gas sources, electric compressors and gas compressors is analyzed in detail, and the sequential algorithm is combined with the multi-balance nodes equation in the form of injected current to analyze the gas-electric interconnect system. Then, by programming the gas-electric interconnection example, comparing with the results of unified algorithm and traditional sequential algorithm, it is verified that the multi-balance nodes algorithm is correct and effective.

INDEX TERMS Energy flow analysis; Gas-electric interconnected system; Multi-balance nodes; Multi-gas sources

I. INTRODUCTION
Since Rifkin's book "The Third Industrial Revolution" [1] made the energy internet an important part of the third industrial revolution, the energy internet has gradually become a research hotspot and frontier in the current energy field [2-5]. In the current social energy system, power supply and gas supply systems have obvious load demand phenomena, and gas-electricity interconnection is one of the most basic forms of energy interconnection. With the deepening of the coupling degree between the electric grid and the gas network, it is increasingly important to analyze the influence of the gas network on the stability and safety of the electric grid, and it is also a factor that must be considered when constructing the gas-electric interconnected system. The most basic work of optimization, stability and safety analysis of gas-electric energy interconnected systems is energy flow analysis.

In recent years, the research on algorithms and applications of energy flow analysis has been deepened. The methods of energy flow analysis are mainly divided into unified algorithms and sequential algorithms [6]. The reference [7] is based on the energy hub theory and uses the sequential algorithms to propose hybrid energy flow algorithm in the different operating mode; the reference [8] uses the sequential algorithm of the gas-electric interconnected system to decouple the grid and the gas network, and the convergence speed is fast and algorithm is easy to analyze, but the research object only stays in the simple gas-electrical interconnection system stage. Reference [9] constructs a model of gas-electric energy interconnection system under unified energy flow. On this basis, the reference [10] addresses the cumbersome problem of gas network modeling with compressors and considers grid-connected and island operation of power systems. And the method improves the unified power flow algorithm; the reference [11] considers the influence of natural gas temperature, and describes a general unified framework to implement the energy flow analysis method. The unified algorithm is relatively intuitive and easy to understand, but, there is often a problem that the Jacobian matrix is
irreversible and the convergence is difficult to guarantee; Reference [12] proposed the concept of distributed balance node, which overcomes the problem of power balance caused by random fluctuation of wind power generation, which is difficult to achieve by single balanced machine, and emphasized the necessity and role of multi-balance node. Further deepening, Professor Wei Zhinong’s team carried out probabilistic energy flow analysis [13]. Professor Jia Hongjie analyzed the influence of different states of natural gas network on energy flow distribution [14]. And the network state estimation [15-16] and static security analysis [17] of the gas-electric interconnect network are also further studied. However, the above research mainly analyzes the simpler gas-electric interconnect system. For systems with multiple gas sources, multiple gas turbines, and multiple compressors, the power is still adjusted by a single balanced machine, which is difficult to ensure correctness.

Although in previous studies, there are systems with multiple gas sources, multiple gas turbines, and multiple compressors coexisting, the output of the gas turbine is always prescribed, and the dual constraints of the gas network and the grid are ignored; Moreover, when only one balance node can be analyzed in the system, it will encounter a lot of limitations. For example, when the system external equivalent and the solution of the ring distribution network will introduce multi-balance nodes [18]. In addition, when the grid interconnection is tight and the load fluctuates drastically, the single balancing machine is difficult to meet the power balance requirement, and in the actual online calculation, the unbalanced power is considered to be absorbed by multiple generators; Considering the role of multi-balance nodes and the simultaneous presence of electric compressors and gas turbines, the applicability of previous energy flow algorithms in the case of multi-coupling variables is limited. Based on the traditional sequential algorithm and considering the complex phenomena existing in the actual gas-electric interconnected system, this paper proposes an improved sequential energy flow analysis method based on multi-balance nodes in gas-electricity interconnection systems.

This paper focuses on the energy flow method of the multi-balanced node for gas-electric interconnected system under multi-coupling variables conditions. In the power flow solution, multiple gas turbines are used together as the balance nodes, considering two types of coupling nodes (gas turbine, electric compressor) and the multi-balance node flow algorithm based on injection current form is adopted. In the calculation of gas network, the coupling relationship between gas compressor and gas network needs to be considered, and inferring the specific solution method under multi-gas sources. Then, the grid and the gas network are formed into a gas-electric interconnection system through the coupling elements, and the energy flow analysis is performed by iteratively.

This paper is divided into six parts. The section I is the introduction part of the article; the section II introduces the modeling of gas network, including various modes such as multi-gas source, electric compressor, gas compressor, and carries out specific modeling analysis of key component compressors; The section III is mainly about the introduction of multi-balance node algorithm based on injection current form in power grid. The section IV integrates the energy flow algorithm of gas-electric interconnection system proposed in this paper based on the previous parts, emphasizing coupling and loop iteration relationship. The section V uses a gas-electrical interconnection to illustrate the correctness of the algorithm and the importance of analyzing multi-balance nodes; the section VI is a summary.

II. ENERGY FLOW ANALYSIS OF GAS NETWORK

The energy flow analysis of natural gas is mainly to solve the node pressure and pipeline flow. Using the multiple equations of the natural gas network, the energy flow distribution of the gas network containing electric compressor, gas compressor and multiple gas sources is gradually considered.

A. STEADY-STATE EQUATIONS AND NODAL EQUATIONS FOR NATURAL GAS PIPELINES

The steady-state equation for natural gas is a description of the relationship between pipe pressure, temperature, and pipe flow [19-21]. Usually, the operating pressure of the gas network is relatively high, the steady-state equations for this pressure class are Panhandle‘A’ formula and Weymouth formula [8]. The relationship between node pressure and pipe flow in this paper is based on the Panhandle ‘A’ formula, which is reduced to the (1).

\[ f_{ij} = \sum_{K} \left( \frac{S_{ij}(p_i^2 - p_j^2)}{K_{ij}} \right)^{1/2} \]

(1)

Where:
\( i, j \) index of natural gas system nodes;
\( m \) flow index;
\( f_{ij} \) flow of pipeline \((i, j)\) \((\text{m}^3/\text{h})\);
\( p_i \) pressure at \( i \) node \((\text{bar})\);
\( K_{ij} \) index of characterizing pipelines and natural gas fluids;
\( S_{ij} \) index of direction for natural gas flow;

Similar to the three types of nodes of the power grid in the stability analysis. 1) PQ, the injection power \( P \) and \( Q \) of this kind of node are known, and the voltage \( U \) and phase angle \( \theta \) of the node are to be determined. 2) PV, such nodes \( P \) and \( V \) are known, and \( Q \) and \( \theta \) are unknown. 3) \( V\theta \) (balance node), used to balance the network loss in the system. The gas network also divides the nodes into two
types: prescribed pressure nodes and prescribed flow nodes. The prescribed pressure nodes mainly include gas source nodes and compressor node whose outlet pressure is known, and the prescribed flow node refers to known nodes of the load flow. The node classification of the system is shown in the Table 1.

<table>
<thead>
<tr>
<th>System</th>
<th>Node classification</th>
<th>Node type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Systems</td>
<td>$V\theta$</td>
<td>Generator node</td>
</tr>
<tr>
<td></td>
<td>PQ</td>
<td>Load node</td>
</tr>
<tr>
<td></td>
<td>PV</td>
<td>Generator node</td>
</tr>
</tbody>
</table>

Natural gas system

Known pressure node

Gas source node

Compressor node

Load node

In the $n$-node gas network with single gas source, only ($n$-1) equations can be listed according to the known load flow, the node equation for removing the gas source node is [20]:

$$L_i = A_i f$$

Where:

$A_i$ node-branch association matrix, remove the line where the gas source node is located. For the node $i$, take the direction outflow from node $i$ as positive.

$L_i$ load flow matrix, remove the gas source node, take the natural gas consumption as positive.

$f$ branch flow matrix, if the gas flow from the node $i$ to the node $j$, take $f_{ij}$ as positive.

The branches of the gas network are classified according to the tree branch and the string branch, and the node equation can be expressed as:

$$L_i = -[A_t: A_s] \begin{bmatrix} f_t \\ f_s \end{bmatrix} = -A_t f_t - A_s f_s$$

Where the matrix $A_t$ is divided into a tree branch association matrix $A_t$ and a string branch association matrix $A_s$; the column vector $f$ is divided into tree branch flow $f_t$ and string branch flow $f_s$. (The lower corner $t$ represents the tree branch; the lower corner $s$ represents the string branch.)

According to the different types of nodes in the gas network, the node pressure is classified:

$$\Pi = \begin{bmatrix} \Pi_{load} \\ \vdots \\ \Pi_{source} \end{bmatrix}$$

$$\Pi(i) = p_i^2$$

Where:

$\Pi$ is column vector for square of node pressure; $\Pi_{load}$ and $\Pi_{source}$ are corresponding to the pressure square of the load node and the gas source node respectively.

At this point, the (1) can be written as the expression of the subtraction of pressure squared $\Delta \Pi_y$ and $f_y$, $\Phi(\cdot)$ is the function:

$$\Phi(f_y) = \Delta \Pi_y$$

B. GAS NETWORK ANALYSIS WITH COMPRESSOR

Since the natural gas pipeline has resistance such as friction, the pressure will gradually decrease as the gas flows. In order to ensure the normal supply of natural gas, it is necessary to set the compressor to increase the pressure in the pipeline. Compressors are usually divided into electric compressors and natural gas compressors. The pipeline model of the compressor is shown in the Fig 1 and Fig 2.

In the gas-electric interconnected system, the power consumed by electric compressors is usually supplied by the grid, equivalent to electrical load, as in (8); natural gas compressor boost pressure by consuming natural gas, equivalent to gas load, as in the (9) [8].

$$HP_{com} = \frac{P_m f_m \alpha}{\alpha - 1} \left[ \frac{P_{out}}{P_{in}} \right]^{(\alpha - 1)/\alpha} - 1$$

$$L_i = \frac{HP_{com}}{\eta C_{gas}} = f_{com}$$

Where:

$HP_{com}$ electric power consumed by the compressor (10$^5$W);

$f_{com}$ ($L_i$) natural gas flow consumed by the compressor (m$^3$/h);

$f_m$ inlet flow of compressor (m$^3$/s);

$p_{in}$ inlet pressure of compressor (bar);

$p_{out}$ outlet pressure of compressor (bar);

$\alpha$ variable index of compressor, take 1.27;

$\eta$ compressor efficiency, take 0.8;

$C_{gas}$ natural gas combustion value, take 39MJ/m$^3$.

In the flow analysis of the gas network, the limitations of the compressor should also be considered, mainly...
including pressure limitation and compression ratio limitation.

\[
p_{\text{out}}^{\text{min}} < p_{\text{out}} < p_{\text{out}}^{\text{max}}
\]

\[
k_{\text{com}}^{\text{min}} < k_{\text{com}} = \frac{\max(p_{\text{out}}, p_{\text{in}})}{\min(p_{\text{out}}, p_{\text{in}})} < k_{\text{com}}^{\text{max}}
\]

Where:
- \( p_{\text{out}}^{\text{min}} \): minimum outlet pressure of compressor (bar);
- \( p_{\text{out}}^{\text{max}} \): maximum outlet pressure of compressor (bar);
- \( k_{\text{com}}^{\text{min}} \): minimum of compressor ratio;
- \( k_{\text{com}}^{\text{max}} \): maximum of compressor ratio;

1) GAS NETWORK ANALYSIS WITH ELECTRIC COMPRESSOR

This paper assumes that the outlet pressure of the compressor is constant and the inlet flow is equal to the outflow. In the gas network topology, the electric compressor is used as load, and its load flow is zero. In the energy flow analysis, the gas network topology is transformed, the compressor is represented as a pair of auxiliary nodes (outlet and inlet nodes), the auxiliary nodes are disconnected, the inlet node is used as the load node (load flow is 0), and the outlet node is used as a reference node. Thereby forming a new topology. The solution process is shown in Fig. 3.

Set the initial value of string branch flow \( f_{c} \)

\[
f_{c} = -A_{c} \left( t_{c} + A_{c} f_{c} \right)
\]

\[
\Delta P^{c} = \Phi(f)
\]

\[
J^{c} = -A_{c}(R^{c})^{-1} A_{c}^{T}
\]

\[
H_{c}^{c+1} = -(J^{c})^{-1} A_{c}(R^{c})^{-1} (\Delta P^{c} - A_{c}^{T} \Delta f_{c}^{c})
\]

\[
\Delta f_{c}^{c+1} = f_{c}^{c} + \Delta f_{c}^{c}
\]

Where:
- \( A_{c_1} \), \( A_{c_2} \), \( A_{c_3} \): association matrix based on original topology;
- \( \Phi \): index based on the new topology;
- \( A_{c}^{+} \): association matrix of known pressure nodes;
- \( A_{c}^{-} \): association matrix of unknown pressure nodes;
- \( k \): times of iterations;

Note: For a new topology, the definitions of tree branch and string branch are the same as those of the original topology.

\[
R = \begin{bmatrix} R_{1} & 0 \\ 0 & R_{2} \end{bmatrix}
\]

2) GAS NETWORK ANALYSIS WITH GAS COMPRESSOR

The analysis method of the gas compressor is basically the same as the electric compressor. The main difference is that the gas compressor needs to consume gas to achieve pressure, and the consumed gas flow is equal to load flow. The solution process is shown in Fig. 4.

Set the initial value of the gas compressor consumption flow \( L_{c}^{0} \)

\[
k = 0
\]

Run pipeline flow

Calculate compressor consumption \( L_{c}^{k+1} \)

\[
\Delta L_{c}^{k} = L_{c}^{k+1} - L_{c}^{k}
\]

\[
|\Delta L_{c}^{k}| < 0.01
\]

\[
\text{pressure at each node flow at each branch}
\]

N

Y

FIGURE.3. The flowchart of solving natural gas network including electrical compressor

FIGURE.4. The flowchart of solving natural gas pipeline network including gas compressor

C. PIPE NETWORK ANALYSIS WITH MULTIPLE GAS SOURCES

For a gas network with \( b \) pipes and \( n \) nodes, if there are two gas source nodes, the number of load nodes is \((n-2)\), and the number of tree branches is \((n-1)\), the order of \( A_{c} \) matrix is \((n-2)\times(n-1)\), so it is irreversible. And the tree branch flow \( f_{c} \) cannot be directly calculated using (4), the aforementioned
traditional analysis method fails. Although the previous research involved multiple gas source gas networks, it did not give a solution to the above problems.

In order to adapt to the situation of multi-gas sources network, this paper defines the classification method of generalized tree branch and generalized string branch on the basis of continuous tree branch and string branch. First, gas source nodes other than the first gas source node are defined as "excess" gas source nodes. Such as, for a two-source gas network, a tree branch connecting the second gas source node (the "excess" gas source node) is changed into a string branch, and the remaining tree branches can ensure that all load nodes are included. At this time, $A_{tt}$ is a square matrix of $(n-2)\times(n-2)$, which can be used to find the generalized tree branch flow according to the generalization string branch flow in (13), and the irreversible problem of the tree branch correlation matrix also is solved under the condition of multiple gas sources. For gas networks with $m$ gas source, there are $(m-1)$ "excess" gas source nodes, and each "excess" gas source node needs to change a connected tree branch into a string branch, and ensure that the remaining tree branches include all load nodes.

$$L_1 = -[A_{tt} | A_{tc}] [f_n] = -A_{tt}f_n - A_{tc}f_c$$ (13)

$$f_n = -A_{tt}^d (L_1 + A_{tc}f_c)$$ (14)

Where:

$tt$ represents a generalized tree branch;
$cc$ represents a generalized string branch;

The flow analysis method of the multi-source gas network is similar to the Newton mesh-node method, and there are differences in the branch classification method. The other solving steps are the same as the foregoing methods, and will not be described in detail herein.

### III. POWER FLOW CALCULATION OF MULTI-BALANCE NODES IN POWER GRID

In reference [22-23], the power flow algorithm in the form of injection current is used to deal with the problem multi-balance nodes, considering the case of only balanced nodes and PQ nodes. Based on this, the paper considers the case of containing PV nodes and gives the corresponding modified equation form.

Let the system have $n$ nodes, among which nodes 1, 2, ..., $m$ are both PQ nodes, nodes $m+1$, ..., $m+r$ are PV nodes, nodes $m+r+1$, ..., $n$ are balanced nodes. Among them, the selection principle of the three types of nodes is the same as the traditional power flow algorithm. For the PQ nodes, deviation amount of the injection current is taken as the unbalanced variable; for the PV nodes, the deviations of the active power and the voltage are used as the unbalance variables. Nodal balance equations of node $i$ are modeled by (15).

$$\Delta I_{pi} = I_{pi} - I_{phi} \ (i = 1, \ldots, m)$$

$$\Delta I_{m} = I_{m} - I_{phi} \ (i = m+1, \ldots, m+r)$$

$$\Delta P = \sum_{i=m+1}^{m+r} [U_{i} (G_{i} U_{j} + B_{i} U_{j})] - P_i$$

$$\Delta U_i^2 = (U_i^2 + U_{phi}^2)$$ (15)

Where:

$x$ real parameter;
y imaginary parameter;
$I_{phi}$ injection current of PQ node;
$I_{phi}$ injection current of balance node;
$\Delta I_i$ deviation amount of the injection current at $i$th node;
$P_i$ active power at $i$th node (p.u.);
$U_i$ voltage magnitude at $i$th node(p.u.);
$G_i$ conductance of the nodal admittance matrix(p.u.);
$B_i$ susceptance of the nodal admittance matrix(p.u.);

The modified equation form is given as (16). The order of sub-blocks $H$, $N$, $J$, and $L$ corresponding to the PQ nodes in the Jacobi matrix is $m(m+r)$ dimension matrices, and the matrix element expressions are referred to [22]. The order of sub-blocks $N'$, $H'$, $S'$, and $R'$ corresponding to the PV nodes is $r(m+r)$ dimension matrices, and the matrix elements are similar to the rectangular coordinate form of the conventional power flow calculation.

The algorithm is based on the power flow equation in rectangular coordinate. The iterative process uses the Newton method as well as the traditional power flow algorithm. The advantage is that the non-diagonal elements of the corresponding sub-blocks of the PQ node in the Jacobi matrix are unchanged during the iterative process, and only the diagonal elements and the sub-blocks corresponding to the PV nodes need to be corrected. This method simplifies the variable elements of the Jacobian matrix and has an accurate iterative format that is not required for the initial value, even does not require changes to the network parameters of the system.

$$\begin{bmatrix}
H_{11} & \ldots & H_{1n+r} & N_{11} & \ldots & N_{1n+r} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
N_{m1} & \ldots & H_{rn+r} & N_{m1} & \ldots & N_{rn+r} \\
K_{11} & \ldots & K_{1n+r} & E_{11} & \ldots & E_{1n+r} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
K_{m1} & \ldots & K_{rn+r} & E_{m1} & \ldots & E_{rn+r} \\
J_{11} & \ldots & J_{1n+r} & L_{11} & \ldots & L_{1n+r} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
J_{m1} & \ldots & J_{rn+r} & L_{m1} & \ldots & L_{rn+r} \\
S_{11} & \ldots & S_{1n+r} & R_{11} & \ldots & R_{1n+r} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
S_{m1} & \ldots & S_{rn+r} & R_{m1} & \ldots & R_{rn+r} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\end{bmatrix}
\begin{bmatrix}
\Delta U_{1,1} \\
\vdots \\
\Delta U_{m+1,1} \\
\Delta U_{1,m} \\
\vdots \\
\Delta U_{m+1,m} \\
\Delta U_{1,m+1} \\
\vdots \\
\Delta U_{m+1,m+1} \\
\end{bmatrix}
= \begin{bmatrix}
\Delta I_{1} \\
\vdots \\
\Delta I_{m} \\
\Delta P_{m+1} \\
\vdots \\
\Delta P_{m+r} \\
\Delta I_{m+1} \\
\vdots \\
\Delta I_{m+r} \\
\Delta U_{m+1} \\
\vdots \\
\Delta U_{m+r} \\
\Delta U_{m+1}^2 \\
\vdots \\
\Delta U_{m+r}^2 \\
\end{bmatrix}$$ (16)

### IV. LOOP ITERATIVE METHOD OF ENERGY FLOW ANALYSIS
The basic coupling components of the gas-electric interconnect system are mainly electric compressors and gas turbines, and mathematical models should be established for both. The electric compressor has been introduced in (8) and will not be repeated. The relationship between gas turbine inlet flow and active power is shown in (17).

\[ f^i = \frac{P^i}{\mu C_{\text{gas}}} \quad (17) \]

Where:
- \( P^i \) active power output of gas turbine;
- \( f^i \) consumption flow of gas turbine;
- \( \mu \) the efficiency of the gas turbine, take as a typical value of 0.55;
- \( C_{\text{gas}} \) natural gas combustion value, take 39MJ/m³;

Typical gas-electric interconnected system coupling mode: the gas network supplies gas to the gas turbine of the power grid, and the power grid supplies power to the electric compressor in the gas network. The coupling mode is shown in Fig 5. In this paper, the coupling variables (electric compressor power, gas turbine inlet flow) are divided into two categories (input coupling variables and output coupling variables). For example, the power of electric compressor is input coupling variable for the grid, but it is the output coupling variable for gas network. Adopting cyclic iteration to continuously update gas turbine consumption and power consumption of electric compressor until the grid and gas network meet the requirements. On the basis of sequential algorithm, this algorithm also highlights the coupling relationship between gas network and power grid. Based on the above ideas, this paper uses the method of iteration from the grid first in the example. The specific process is shown in Fig 6.

![Flowchart of energy flow analysis of gas-electric interconnected system](image)

**FIGURE6.** Flowchart of energy flow analysis of gas-electric interconnected system

Where:
- \( \Delta P^k_{\text{com}} \) correction amount of the \( k \)th iteration;
- \( \epsilon \) convergence accuracy;

V. CASE ANALYSIS

This paper takes the gas-electrical interconnection system in [8] as an example, and the electric compressor in the gas network is changed from external power supply to power supply by the grid, as shown by the dotted line in the Fig7. Among them, the red line indicates the natural gas pipeline, and the black line indicates the transmission line. The grid is a 4-node system (expressed by E1–E4), the E2nd and E4th nodes are gas turbine nodes, the generator connected to node E1 is traditional steam turbine, and all nodes are loaded; the gas network includes 10 nodes (expressed by N1–N10) and...
11 pipelines. There are two gas sources and two compressors, #I is a gas compressor and #II is an electric compressor. And nodes N4 and N8 are connected to the gas turbines to provide natural gas. For ease of analysis, the rated power of the gas turbine is set to 250 MW. Other system parameters are shown in the [8]. The computer used is Intel(R) Core(TM) i7-8550U CPU @ 1.80GHz (8 CPUs), ~2.0GHZ. The programming language is Matlab 2016a.

The example is a complex gas-electric interconnect system with multiple gas sources, multiple gas turbines, gas compressors and electric compressors. Next, the traditional unified algorithm and traditional sequential algorithm will be compared and analyzed with the multi-balance algorithm proposed in this paper. For the improved sequential energy flow analysis method based on multi-balance nodes proposed and the unified algorithm, given the same convergence accuracy, the energy flow calculation of the gas-electric interconnect system is performed. The unified algorithm takes 0.226218 seconds and iterates 5 times; the multi-balance node algorithm takes 0.193782 seconds and iterates 2 times. The values of the variables of the gas-electric interconnection network are shown in Table 2-4. Column 1 represents the multi-balance node algorithm and column 2 represents the unified algorithm.

![The network topology of combined natural gas and electric system](image)

**FIGURE 7.** The network topology of combined natural gas and electric system

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Flow (10^3 m³/h)</th>
<th>Pipeline</th>
<th>Flow (10^3 m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.2085</td>
<td>7</td>
<td>1.1547</td>
</tr>
<tr>
<td>2</td>
<td>0.9977</td>
<td>8</td>
<td>0.9723</td>
</tr>
<tr>
<td>3</td>
<td>0.9975</td>
<td>9</td>
<td>3.9629</td>
</tr>
<tr>
<td>4</td>
<td>0.6622</td>
<td>10</td>
<td>1.4906</td>
</tr>
<tr>
<td>5</td>
<td>0.7108</td>
<td>11</td>
<td>1.4906</td>
</tr>
<tr>
<td>6</td>
<td>0.6830</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3** FLOW RATES OF THE GAS NETWORK

<table>
<thead>
<tr>
<th>Bus</th>
<th>$P_{eo}$ (MW)</th>
<th>$U_l$(p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>203.13</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>200.6896</td>
<td>0.9980</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.9689</td>
</tr>
<tr>
<td>4</td>
<td>201.0319</td>
<td>1.0200</td>
</tr>
</tbody>
</table>

**TABLE 4** THE RESULTS OF THE ELECTRIC GRID

Since the gas-to-electricity load and the natural gas supplier usually have an interruptible contract, that is, when there is any abnormal operation of the natural gas system, the gas-to-electricity load will be cut off preferentially, which will have a huge impact on the power grid [24]. Therefore, for the sake of simplicity, this paper considers the availability of gas network to be sufficient to simplify the constraints imposed on gas turbines.

It can be seen from Table 2-4 in the multi-balance algorithm that the gas consumption of the gas compressor #I (N3) is 16.5582 m³/h, and the power consumption of the electric compressor #II (N7) is 1.6917MW according to the (8) and (9). Compared with the results of the energy flow, it is found that the influence of the compressor is small and does not change the flow distribution of the entire energy system. Therefore, the results of the unified algorithm and the multi-balance node algorithm are compared. Based on the unified power flow results, the relative errors of the multi-balance nodes are shown in the Table 5. It can be found that the values of the variables of the gas network and the grid are very close in the calculation results of the two algorithms, which verifies the correctness of the multi-balance node algorithm proposed in this paper.

<table>
<thead>
<tr>
<th>Variate</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active power</td>
<td>5.1595x10⁻³</td>
</tr>
<tr>
<td>Voltage</td>
<td>-4.1267x10⁻⁴</td>
</tr>
<tr>
<td>Pressure</td>
<td>-1.4997x10⁻³</td>
</tr>
<tr>
<td>Flow</td>
<td>4.6609x10⁻³</td>
</tr>
</tbody>
</table>

**TABLE 5** COMPARISON OF THE RESULTS OF THE TWO ALGORITHMS

It can be seen from Table 4 that the output of the gas turbines under normal operating conditions obtained by the multi-balance node algorithm are 200.6896MW and 201.0319 MW respectively, and the traditional sequential algorithm in [8] makes the output of the gas turbine to 200 MW to solve the gas-electric interconnection system. The results obtained by the comparison of the two algorithms are
the same. The traditional sequential algorithm is to make the gas turbine output prescribed, as a constant power node in the power grid, and as a prescribed gas load in the gas network, the two networks respectively calculate the power flow, which completely weakens the coupling of the gas-electric interconnect system.

In addition, based on the computational requirements of the sequential algorithm, the prescribed value of the gas turbine is crucial in the solution process. Different gas turbine output situations will have a great impact on the power flow distribution of the grid and the gas network, as shown in the Table 6.

<table>
<thead>
<tr>
<th>Variable</th>
<th>180MW</th>
<th>200MW</th>
<th>220MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>U (p.u.)</td>
<td>-0.0033</td>
<td>0.0002</td>
<td>0.0033</td>
</tr>
<tr>
<td>( P_0 ) at E1(MW)</td>
<td>40.34</td>
<td>0.01</td>
<td>-40.07</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>-1.4232</td>
<td>-0.6312</td>
<td></td>
</tr>
<tr>
<td>Flow (m³/h)</td>
<td>-212.5701</td>
<td>120</td>
<td>428.96</td>
</tr>
</tbody>
</table>

The E1 node is a generator in the power grid. When changing the output of the gas turbine, in order to ensure the balance of the power grid, the generator will adjust its own power generation, and the adjustment amount is the change amount of the gas turbine output based on the multi-balance node algorithm. It can be seen from the Table 6 that when the gas turbine output is at different prescribed values, the pressure and flow of the gas network change greatly, and the power of the gas grid generator also changes. The energy distribution of the entire interconnected system changes with the change of the gas turbine output. The multi-balance node algorithm overcomes this disadvantage, makes the output of the gas turbine determined in the multiple cycles of the gas network and the grid, which is more practical.

VI. CONCLUSION

In the gas-electric energy interconnection system, a more applicable and more realistic energy flow calculation method is needed to calculate and analyze electricity and natural gas. In this paper, an improved sequential energy flow analysis method based on multi-balance nodes in gas-electricity interconnection systems is proposed, by improving the Newton node method for multi-gas source problems, analyzing the importance of multi-balance nodes and the inevitable requirements in sequential algorithms. The example shows that the proposed method is correct, and the convergence speed is fast, and the number of iterations is small. The idea of using multi-balance nodes also avoids to make output of gas turbine prescribed in the traditional sequential power flow, affecting the flow distribution of the system. The algorithm also increases the applicability of dealing with systems with multi-coupling variables and typical multi-balance nodes. The research in this paper mainly focuses on the energy flow analysis of gas-electric interconnected systems. In the future, the interaction between gas and electricity will be considered, and the stability and safety analysis of gas-electric interconnected systems will be studied.

REFERENCES


