Steady State Energy Flow Analysis for Energy Internet Planning

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Abstract. The planning and design of energy Internet is an important work. The basis of this work is energy flow analysis of the design network. In this paper, the energy flow analysis model of typical gas-electricity interconnection system is established. The mismatch equations and iterative algorithm for energy flow solution are given. The effectiveness of the algorithm is verified by a typical gas-electric interconnection example.

1. Introduction
The electricity and natural gas industries are both network industries, which are transported to various regions through the transmission network and connected to energy users through the distribution network [1]. With the deregulation of the electricity market, the development of institutions such as the futures contract market and the electronic auction market may lead to the consolidation of the power and gas industries and the emergence of more competitive energy markets. The electricity and natural gas industries are strongly interdependent with each other, and when they combined, they are bound to achieve the maximum optimization. It will have a competitive advantage over optimizing systems, systems planning and economic analysis [2].

The purposes of energy flow calculation in interconnected systems are as follows:
1) When compiling the operation mode of the interconnection system, the typical energy flow calculation is selected by the expected future growth trend of load and equipment operation. It can make the employee quickly discover the weak links with the network of the reference to the daily dispatch of the dispatch department, it can put forward improvement suggestions for the infrastructure construction department of the network and it also can determine the operation mode and state of the interconnection system to a certain extent.
2) In the stage of interconnection system planning and design, energy flow calculation can be used to reasonably plan the proportion of energy use, reasonably design the network structure, and choose the most economical compensation scheme at the same time. In addition, it can meet various control requirements of the system and provide the basis of analysis and calculation for the stable operation of the interconnected system.
3) Analyzing in advance the impact on accidents, equipment withdrawal and other conditions on the static safety of the interconnected system, analyzing the working state of each component in the monitoring system under the operation mode adjustment scheme, and determining whether the system
is within the normal working range according to the analysis results, so as to provide a basis of the stability calculation of the interconnected system.

2. **Modeling of energy Interconnection system**

There are three types of nodes in a power system: 1) PQ nodes: P and Q are the specified variables; 2) PV node: also known as voltage control node; 3) V/θ node: also known as the equilibrium node, for which U and θ are the specified variables. There are two types of nodes in a natural gas system [3]: Constant flow node: known node injection flow and unknown node pressure, which can be compared with PQ node in power system; Constant pressure node: the pressure of the node is known and the flow of the node is sufficient, which can be compared with V/θ Node (in the power system).

2.1 **Analysis and modeling of power system energy flow**

The power system can be expressed as [4]:

\[
P_i = U_i \sum_j U_j G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \tag{1}
\]

\[
Q_i = U_i \sum_j U_j G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \tag{2}
\]

Where, \( P_i \) is the active power of the node; \( Q_i \) is the reactive power of the node; \( U_i, U_j \) are node voltage; \( \theta_{ij} \) is the voltage phase difference between two points.

2.2 **Pipe modelling**

Under the steady-state condition, the pipeline flow rate of the natural gas system \( F_{mn} \) can be expressed as [5]:

\[
F_{mn} = k_{mn} s_{mn} \sqrt{s_{mn} \Pi_m^2 - \Pi_n^2} \tag{3}
\]

\[
s_{mn} = \begin{cases} +1, & \Pi_m - \Pi_n \geq 0 \\ -1, & \Pi_m - \Pi_n < 0 \end{cases} \tag{4}
\]

Where, \( k_{mn} \) is a constant related to pipe inner diameter, length, efficiency, compression factor and other factors; \( s_{mn} \) relates to the flow direction of the pipeline; \( \Pi_m, \Pi_n \) are the pressure at the gas node.

2.3 **Mathematical modeling of compressor**

Under the steady-state condition, the energy consumption formula of the compressor is as follow:

\[
H_{com,k} = B_k F_{com,k} \left( \frac{\Pi_m}{\Pi_n} \right)^{Z_k} - 1 \tag{5}
\]

Where, \( F_{com,k} \) is the natural gas flow through the pressurized station; \( H_{com,k} \) is the electrical energy consumed by the compressor; \( B_k \) is a constant that depends on compressor efficiency and operating temperature; \( Z_k \) is a constant that depends on the compression factor.

Therefore, assuming that the injected flow rate of each node is \( F_m \), and the flow balance equation of each node in the natural gas system can be written as follows:
\[ F_m = \sum_{m \in M} F_{m} + \sum_{m \in M} \text{sgn}(m, n) F_{\text{com}, k} \] (6)
\[ \text{sgn}(m, n) \begin{cases} +1, & m \text{ is the entrance to pressurized station } k \\
-1, & M \text{ is the outlet of pressure station } K 
\end{cases} \] (7)

Where, \( F_{m} \) is the pipeline flow of natural gas.

2.4 Mathematical modeling of electric-gas coupling
In this power-gas interconnection system, the coupling nodes have both the characteristics of the power system and the characteristics of the natural gas system, so it should be comprehensively analyzed.

1) Electrically driven compressor
Here, the compressor can be taken as the equivalent load of the power system, and this idea can be incorporated into the formula. So that the electric energy consumed by the load \( P_{\text{com}}^{i,k} \) can be expressed as [3]:
\[ P_{\text{com}}^{i,k} = H_{\text{com}, k} \left( \frac{0.7457}{10^5} \right) \] (8)

Where, \( P_{\text{com}}^{i,k} \) is the equivalent load (the reference power is 100 MVA).

2) Energy hub
The energy hub can complete the transformation and distribution of various forms of energy. In this paper, the transformation of electricity, gas and heat is mainly considered to deal with the system [3], and the energy hub is shown in Figure 1:

Figure 1. Energy hub

The input terminal of the energy hub is supplied by the electric power system and the natural gas system. The energy hub output electric energy and thermal energy, which are provided for the users.

The specific conversion formula is as follows:
\[ \begin{bmatrix} L_e^{\prime} \\ L_h^{\prime} \end{bmatrix} = \begin{bmatrix} \eta_{\text{trans}} & \eta_{\text{CHP}}^{\epsilon} \\ 0 & \eta_{\text{CHP}}^{h} + 1 - \nu \eta_{\text{Fur}} \end{bmatrix} \begin{bmatrix} P_{\epsilon}^{\prime} \\ P_{h}^{\prime} \end{bmatrix} \] (9)

Where, \( \eta_{\text{trans}} \) is the conversion efficiency of the transformer, it can be evaluated at 1; \( \eta_{\text{CHP}}^{\epsilon} \) is the electric efficiency of gas turbine, and the value is 0.3; \( \eta_{\text{CHP}}^{h} \) is the thermal efficiency of gas turbine, and the value is 0.4; \( \eta_{\text{Fur}} \) is the thermal efficiency of the burning boiler, which is 0.9; \( L_e^{\prime}, L_h^{\prime} \) are the electrical energy and thermal energy output from the energy hub respectively; \( P_{\epsilon}^{\prime}, P_{h}^{\prime} \) are the electric energy and natural gas energy input from the energy hub respectively.
3. Energy flow equilibrium equation and solution

In the electrical and gas interconnection network, each node may involve five equations, the active power equation, reactive power equation, gas flow equation and the energy hub input and output equation. But there are more electric nodes and gas nodes without coupling relationship. So we must pay attention to the node types, to find the variables, to write balance equations accurately.

According to the listed formulas, five equilibrium equations of the analyzed system are obtained, which are expressed as follows:

\[
\begin{align*}
\Delta P_i &= P_{G,i} - P_{L,i} - P_{i}^{s}\ast - P_{i}^{k}\ast - P_i \\
\Delta Q_i &= Q_{G,i} - Q_{L,i} - Q_i \\
\Delta F_m &= F_{G,m} - F_{L,m} - F_{m}^{s}\ast - F_{m}^{k}\ast - F_m \\
\Delta L_e^s &= L_e^s - \eta_{\text{shr}} P_e^{s}\ast - \nu \eta_{\text{CHP}} P_m^{s}\ast \\
\Delta L_h^s &= L_h^s - \nu \eta_{\text{LHR}} + 1 - \nu \eta_{\text{FGR}} F_g^{s}\ast
\end{align*}
\]

(10)

Where, \(P_{G,i}\) is the active power generated by the generator; \(P_{L,i}\) is the load active power of the node; \(P_i\) is the node's active power; \(Q_{G,i}\), \(Q_{L,i}\) are the reactive power of the generator; \(F_{G,m}\) is the gas source injection flow rate of nodes in the natural gas system; \(F_{L,m}\) is the gas load flow rate of nodes in the natural gas system; \(F_g\) is the flow rate of gas node.

The first two equations of formula (10) need only be listed in the nodes which only in the power system. Only the third equation needs to be written in the nodes which only act on the natural gas system. In the compressor nodes, the first equation needs to be listed because of the coupling of electric-driven compressor. While in the electric-gas coupling nodes, the first five equations need to be listed. And then solve them.

3.1 Setting the initial value of iterative solution

In the analysis and calculation of system energy flow, the selection of appropriate calculation method can effectively and high-quality complete the task. Similarly, the selection of appropriate initial values can also speed up the calculation, save the memory of the computer and improve the stability of the solution. The selection of initial values and the judgment on convergence is one of the important problems affecting the convergence and convergence times of N-R method.

The setting of initial values in the system mainly consists of three parts:

1) Setting the initial value of voltage phases Angle of the electric nodes. In the power system, the phase angle difference between nodes is very small and almost of them are near 0, so in order to facilitate iterative calculation, the initial value of phase Angle is generally chosen to be 0.

2) Setting the initial value of voltage amplitude of the electric nodes. In order to ensure the convergence of the calculation results, the flat starting mode is selected, and the initial voltage value is generally selected as 1.

3) Setting the initial value of pressure of gas nodes. The initial values of natural gas system should be screened according to the selected system, and then adjust the pressure coefficient and flow direction of the compressor of the built system. The details can be adjusted according to the iteration situation.

3.2 Iterative solution of N-R method

The core of N-R method is to expand the equilibrium equation of energy flow into Taylor series, and then approximate the real value step by selecting the initial value and omitting the high order term appropriately. Therefore, the criterion of convergence of N-R iteration is making the mismatch less than the accuracy, so that the obtained solution can approximate the real value infinitely. The sliding convergence speed is one of its advantages in the calculation process, which can greatly to reduce the
calculation time. In the references, some scholars put forward a method combining N-R and Broyden, which has fewer iterations of Jacobian matrix and it gives full play to the fast convergence of N-R method [6].

The central idea of N-R iterative solution is to change the solution of nonlinear equations into multiple solutions of corresponding linear equations. This method is especially strict in the selection of initial values, because the appropriate initial value can be more rapidly convergent, while the improper initial value may lead to non-convergence of calculation results. Therefore, different methods can be used to obtain the required initial value of faster calculation.

For the equilibrium equation mentioned in this paper, the modified equation can be expressed as:

\[
\begin{bmatrix}
\Delta P \\
\Delta Q \\
\Delta F
\end{bmatrix} = 
\begin{bmatrix}
\frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial V} & 0 \\
\frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial V} & 0 \\
0 & 0 & \frac{\partial \Delta F}{\partial \pi}
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta V \\
\Delta \pi
\end{bmatrix}
\]

The Jacobian matrix is the most important and difficult point in the whole energy flow calculation, so when determining the model for energy flow simulation, it is necessary to write the specific Jacobian matrix carefully.

4. Simulation example

This paper uses the simulation model which consists of a simple two-machine five-node power system and a 14-node natural gas system(see Fig 3)[7]. The power system consists of two generators, two transformers, five nodes (NO.5 is the balance node, NO.4 is the PV node, and the rest is the PQ node) and five power lines. The natural gas system consists of 14 nodes (NO.1 and NO.10 are the gas source nodes, and NO.13 is the gas supply node to the energy hub. All 4 compressors are supplied with NO.3 node of the power system), 12 gas transmission pipelines, four pressure stations, and 2 gas source points.

Using the parameters for simulation, and the iterative calculation results of the natural gas system are shown in Table 1:

| m  | Pressure value/Psia | m  | Pressure value/Psia | m  | Pressure value/Psia |
|----|---------------------|----|---------------------|----|---------------------|
| 1  | 1200                | 6  | 796                 | 11 | 1100                |
| 2  | 7406                | 7  | 1400                | 12 | 793                 |
| 3  | 2173                | 8  | 511                 | 13 | 896                 |
The result shows that the pressure in the natural gas system has been obtained, and the constraints between the pressure required in the subject are also verified in the iteration results. As the paper stated, according to the relationship between flow rate and air pressure between two points, the flow rate between pipelines can be calculated. The gas network is dendritic. From the initial guess as to all branch flows, the standard N-R method can be used for iterative calculation, but due to the complexity of flow equations, the calculation of pipeline flow of natural gas system is usually more error prone than that of power system, so it should be taken more seriously to deal with it.

The results of the compressor part and the power system part are shown in Table 2 and Table 3.

Table 2. Compressor flow after iteration

| m  | Load/MMCFD |
|----|------------|
| 1  | 425        |
| 2  | 477        |
| 3  | 1246.4     |
| 4  | 5077.9     |

Table 3. Power parameters after iterative convergence

| i  | U     | Theta   | P     | Q     |
|----|-------|---------|-------|-------|
| 1  | 0.37968 | 0.24128 | 0.8055 | 0.0080 |
| 2  | 0.35383 | 0.24128 | 0.1800 | 0.4805 |
| 3  | 0.33828 | 0.29874 | 0    | 0.4795 |
| 4  | 1      | 0.34786 | 0.5000 | 0.5119 |
| 5  | 1      | 0       | 0.4968 | 0.5119 |

Note: power parameters are expressed by per unit value

In Table 3, the energy flow calculation of the power system adopts the flat-start mode, and after several iterations, the required accuracy (0.001) is achieved, which basically meets the initial presupposition of the design.

5. Conclusion
Firstly, the solution method of electric-gas Internet energy flow was determined, then a simplified electric-gas interconnection model was established, and the coupling of the two systems was completed by electric drive compressor and energy hub. Finally, the energy flow calculation of the model was completed by MATLAB programming module and the calculation results were analyzed.

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