Steady State Energy Flow Analysis for Energy Internet Planning

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Abstract. The planning and design of the energy Internet is a primary and significant link of the energy Internet. For this paper, its basic work is to design, analyse and calculate the energy flow of the network. In this paper, a typical energy flow analysis model of power-gas interconnection system is established, and the algorithm of the model is given to solve the problem. Finally, the feasibility of the algorithm is verified by a classical example of electricity - gas interconnection.

1. Introduction

Nowadays, energy interconnection is not only a general concept, but also one of the new solutions to environmental problems and energy problems can be formed through interconnection and coupling of multiple systems such as electric power system, natural gas system and renewable energy system [1]. As the electricity market is deregulated and institutions such as the futures contract market and the electronic auction market developed, the result is likely to be consolidation in the electricity and gas sectors and the emergence of more competitive energy markets. The power and natural gas industries are highly interdependent and mutually supportive with each other, and when combined, they are bound to achieve the maximum optimization. It will have a competitive advantage over optimizing systems, systems planning and economic analysis, they form the basis and simple framework for energy interconnection.

The reasons for applying energy flow computing to interconnected systems are as follows:

1) On the basis of estimating the future trend of load growth and equipment supply, and in the context of programming the operating mode of interconnect systems, select more typical traffic calculations so that staff can quickly identify network weaknesses. For the weak links found, the dispatching department can be used as a reference for daily dispatching, and it also can determine the operation mode and state of the interconnection system to a certain extent.

2) In the interconnection planning phase, energy flow calculation can be used to reasonably plan the share of energy use, rationally design the network structure, and choose the most economical compensation scheme at the same time. In addition, it also needs to meet the control needs of all levels of systems and provide analysis and calculation basis for the stable operation of the interconnected system.

3) Analyzing the impact on accidents, sudden failures and equipment withdrawal from operation on the static security of the interconnected system in advance, the working state of all parts of the
By analyzing the results, it is determined whether the system is in the normal operation range, which provides the basis for the stability calculation of interconnected systems.

2. Modelling of energy Interconnection system
In the power-gas interconnection system, the change of power flow is analysed. When the load of a node changes, its change will also affect the change of network power flow of the whole system. [3].

As far as the power-gas interconnection system is concerned, it can be divided into two types: electric node and natural gas node. Different from PQ node, PV node and V/θ node in power system, there are two types of nodes in natural gas system: Constant flow node: The injection flow rate of the node is known, while the pressure of the node is unknown, which can be compared with PQ node in power system; Constant pressure node: In the case of sufficient node flow, given the node pressure, it can be compared to the V/θ node in the power system.

2.1. Analysis and modelling of power system energy flow
The power system in hybrid coordinate form is expressed as [4]:

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

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

2.2. Natural gas modelling
The natural gas pipe network with dendritic distribution consists of three parts: gas source, pressure station and pipeline. The natural gas is injected by the gas source and flows through the pipeline to the load. The function of the pressure station is to compensate the pressure loss during transmission [4].

2.3. Pipe modelling
Natural gas system is affected by many physical factors such as flow rate and pressure, in this system, assuming that under the steady-state condition, the pipeline flow rate of the natural gas system \( F_{mn} \) can be expressed as [5]:

\[ F_{mn} = k_{mn} s_{mn} \sqrt{s_{mn} \Pi_m^2 - \Pi_n^2} \]  
\[ s_{mn} = \begin{cases} +1, & \Pi_m - \Pi_n \geq 0 \\ -1, & \Pi_m - \Pi_n < 0 \end{cases} \]

Where, \( k_{mn} \) is a constant related to pipe inner diameter, length, 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.

2.4. Mathematical modelling of compressor
In the booster station, the main function of the equipment is the compressor, which not only reduces the economic input, but also supplements the energy needed for the compressor operation. The system uses the natural gas flowing through it as its power supplement. [4]. Under the steady-state condition, the energy consumption formula of the compressor is as follow:
\[ H_{\text{com}, k} = B_k F_{\text{com}, k} \left( \frac{\Pi_m}{\Pi_n} \right)^{Z_k} - 1 \]  

(5)

Where, \( F_{\text{com}, k} \) is the flow of natural gas through the pressurized station; \( H_{\text{com}, k} \) is the power consumption of the compressor; \( B_k \) is a constant that related to compressor efficiency and operating temperature; \( Z_k \) is a constant that related to the compression factor.

Consequently, assuming that the \( F_m \) is the injected flow rate of each node, the flow balance equation of each node in the natural gas system can be expressed:

\[ F_m = \sum_{n|m} F_{mn} + \sum_{n|m} sgn \ m, n \ F_{\text{com}, k} \]  

(6)

\[ sgn \ m, n \begin{cases} +1, & m \ is \ the \ entrance \ to \ pressurized \ station \ k \\ -1, & M \ is \ the \ outlet \ of \ pressure \ station \ K \end{cases} \]  

(7)

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

2.5. Mathematical modelling of electric-gas coupling

Based on the power-gas interconnection system studied in this paper, coupling nodes have the characteristics of both natural gas system and power system, so comprehensive analysis ought to be carried out.

Combining the coupling of natural gas system and electric system, this paper mainly considers two aspects:

1) Electrically driven compressor

In this paper, the equivalent load of the power system of the compressor is substituted into the formula. So that the electric energy consumed by the load \( P_{\text{com}}^{i,k} \) can be written as [6]:

\[ P_{\text{com}}^{i,k} = H_{\text{com}, k} \left( \frac{0.7457}{10^3} \right) \]  

(8)

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

2) Energy hub

The energy hub is suitable for the conversion and distribution of various forms of energy. Applied to this system, energy hubs are used for the conversion of electricity, gas and heat [3], and the energy hub is shown in Figure 1:

![Figure 1. Energy hub](image)

The dual supply system of natural gas and electric power together constitutes the input end of the energy hub, through which electric energy and heat energy are output for users to use.
The specific conversion formula is as follows:

$$\begin{bmatrix}
L_e \\
L_h
\end{bmatrix} =
\begin{bmatrix}
\eta_{trans} & \nu \eta^{h}_{CHP} \\
0 & \nu \eta^{h}_{CHP} + 1 - \nu \eta_{Fur}
\end{bmatrix}
\begin{bmatrix}
P^{e}_{\text{out}} \\
\end{bmatrix}$$

(9)

Where, $\eta_{trans}$ is the transformer is set to 1 for conversion efficiency; $\eta^{h}_{CHP}$ is the gas turbine is set to 0.3 for electrical efficiency; $\eta^{h}_{CHP}$ is the gas turbine is set at 0.4 for thermal efficiency; $\eta_{Fur}$ is The combustion boiler is set to a thermal efficiency of 0.9; $L_e$ and $L_h$ represent the output of electrical energy and thermal energy respectively; $P^{e}_{\text{out}}$, $P^{\text{n}}_{\text{g}}$ are the electric energy and natural gas energy input.

3. Energy flow equilibrium equation and solution

In the power-gas interconnection system studied in this paper, each node may be related to the five equations of active power equation, reactive power equation, natural gas flow equation, and energy hub input and output equation. However, most nodes - electricity or gas are not coupled, so be careful about node types when writing equations.

According to the listed formulas, the equilibrium equations of the five analysed systems are obtained as:

$$\begin{align}
\Delta P_i &= P_{G_i} - P_{L_i} - P^{e}_{\text{out}} - P^{h}_{\text{out}} - P_i \\
\Delta Q_i &= Q_{G_i} - Q_{L_i} - Q_i \\
\Delta F_m &= F_{G_m} - F_{L_m} - F^{m}_{\text{out}} - F_m \\
\Delta L_e &= L_e - \eta_{trans} P^{e}_{\text{out}} - \nu \eta^{h}_{CHP} P^{g}_{\text{out}} \\
\Delta L_h &= L_h - \nu \eta^{h}_{CHP} + 1 - \nu \eta_{Fur} P^{\text{n}}_{\text{g}} \\
\end{align}$$

(10)

Where, $P_{G_i}$ stands for the active power generated by the generator; $P_{L_i}$ stands for the load active power of the node; $P_i$ stands for the node’s active power; $Q_{G_i}$, $Q_{L_i}$ stand for the reactive power of the generator; $F_{G_m}$ stands for the gas source injection flow rate of nodes in the natural gas system; $F_{L_m}$ stands for the gas load flow rate of nodes in the natural gas system; $F_m$ stands for the flow rate of gas node.

Only in the nodes of the power system, the first two equations in (10) are sufficient to express; only the third node equation in (10) can be listed in the natural gas system node. Since the compressor is driven by electricity, the first equation should be written. At the electrically coupled node, all the equations in (10) need to be written out. After the formula column is written, the subsequent iteration can be solved.

3.1. Setting the initial value of iterative solution

Choosing the appropriate initial value and calculation method will speed up the calculation, improve the stability of the solution, and save the memory of the computer. The selection of initial value and the judgment of convergence are one of the key factors affecting the convergence and convergence time of N-R method.

This system initial value setting has three points to note:

1) Setting the initial value of voltage phase Angle of electric node. In the power system, the phase Angle difference between nodes is approximately 0, so the initial value of phase Angle is generally chosen as 0 for the convenience of iterative calculation.
2) The setting of the initial voltage amplitude of the electric node. In order to ensure the convergence of the calculated results, the flat starting mode with the initial voltage value of 1 was selected.

3) The setting of the initial pressure at the node. The selection of the initial value of the natural gas system is subject to system constraints, and then adjusts 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 key to the N-R method is the treatment of the energy flow equilibrium equation. The energy flow equation is developed into Taylor series, the higher order terms are properly ignored, and the appropriate initial values are selected to approach the real value step by step, and the computational workload is also reduced. Only by using the N-R iterative criterion that the mismatch is less than the accuracy can the obtained solution approach the real value infinitely. The advantage of N-R iteration lies in its slide convergence speed, which greatly reduces the calculation time. By combining N-R method with Broyden method, the iteration times of Jacobian matrix are reduced, and the fast convergence of N-R method is given full play.

The central idea of N-R iterative solution is to transform the solution of the nonlinear equation into the corresponding linear equation for multiple solutions, so it has very strict requirements on the selection of initial values. The appropriate initial values have a faster convergence effect, while the inappropriate initial values may lead to non-convergence of the calculation results. Therefore, different calculation methods should be adopted for the required initial values in order to calculate faster.

In this paper, the modified equilibrium equation can be written as:

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

(11)

The Jacobian matrix is a difficult and important part in the whole energy flow calculation, it is necessary to write the specific Jacobian matrix carefully.

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Figure 2. Energy flow calculation process.

Figure 3. Power-gas interconnection simulation model.
4. Simulation example

The simulation model used in this paper is shown in Figure 3.5 nodes structure of a simple power system for 2 machines (2 generators, 2 transformers, 5 to balance power lines and five nodes--4 for PV nodes, and the rest for the PQ nodes), gas system in 14 nodes (12 gas pipelines, four pressure stations, two gas source points, 14 nodes--1 and 10 for gas source nodes, 13 nodes to the energy hub nodes of gas supply, 4 sets of compressor are 3 nodes for power system).

Simulation is carried out by using parameters, and the iterative calculation results of the natural gas system are given in Table 1:

| m | Pressure value/Psia | m | Pressure value/Psia | m | Pressure value/Psia |
|---|---------------------|---|---------------------|---|---------------------|
| 1 | 1.20e3              | 6 | 0.80e3              | 11| 1.10e3              |
| 2 | 7.41e3              | 7 | 1.40e3              | 12| 0.79e3              |
| 3 | 2.17e3              | 8 | 0.51e3              | 13| 0.90e3              |
| 4 | 5.96e3              | 9 | 1.00e3              | 14| 0.69e3              |
| 5 | 1.20e3              | 10| 0.92e3              |

According to the simulation results shown in Table 1, the constraint relationship between the obtained gas pressure and the pressure required in the question can be verified, and then the pipeline flow can be calculated using the relationship between the flow rate and the pressure between the two points. Referring to the network structure of natural gas network, N-R method is used to solve the problem effectively. However, due to the complexity of the flow equation, the solution needs to be very careful.

The results of the compressor are shown in Table 2; the power system is shown in Table 3.

| m | Load/MMCFD | m | Load/MMCFD |
|---|------------|---|------------|
| 1 | 425        | 3 | 1246       |
| 2 | 477        | 4 | 5078       |

Table 3. Power parameters after iterative convergence

| i | U     | Theta | P     | Q     |
|---|-------|-------|-------|-------|
| 1 | 0.380 | 0.241 | 0.806 | 0.008 |
| 2 | 0.354 | 0.241 | 0.180 | 0.481 |
| 3 | 0.338 | 0.299 | 0.000 | 0.480 |
| 4 | 1     | 0.348 | 0.500 | 0.512 |
| 5 | 1     | 0     | 0.497 | 0.512 |

Note: power parameters are expressed by per unit value

In Table 3, the power system energy flow is calculated by using the flat start method, the required accuracy (0.001) is achieved, which basically meets the conditions.

5. Conclusion

To ensure that the scheme is feasible, this article first to the electrical and gas can flow was analysed, and the feasibility of the Internet division of the electrical model and the model of natural gas, in turn, the simplified model is established in this paper, using the power to drive the compressor and the energy hub two ways to complete the two coupling of the system, and can use the flow balance equation, N - R method is adopted to improve the iteration, the results compared with the simulation results, found that this model can be used.

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