Computational analysis of multi-energy flow in integrated energy systems

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Abstract. Integrated energy system (IES) has become the trend of energy development in the future, but the degree of coupling between energy systems in traditional systems is not high, and the power flow calculation method based on power system will be difficult to meet the need for coupled energy flow analysis. This paper firstly uses the coupling matrix of the energy hub to construct a coupled model of the integrated energy system that fully considers the coupling of the power network and the natural gas network; then we use the Newton-Raphson method to calculate the power flow; finally, an example is used to verify that the comprehensive coupled model will have practical significance in the construction and operation of the integrated energy system.

1. Introduction
The integrated energy system converts various energy forms such as solar energy, wind energy and biomass energy into forms of energy such as cold, heat and electricity[1]. Reasonable and effective planning of integrated energy systems is conducive to improving the energy efficiency of the system and reducing the impact of distributed power on the grid[2]. How to improve the coupling degree of various energy systems, and optimize the planning and design of integrated energy systems has become a problem we are facing now.

People often study the scheduling model of the power network in the integrated energy system, but always simplify the model outside the power such as the natural gas network[3]. It is essential to analyze the operational characteristics of each energy system and study the interaction between multiple energy systems and the mutual interaction of various forms of energy. Some people build energy hub models based on different energy conversion to solve the mixed power flow in different operating modes, but the disadvantage is that the energy demand and distribution needs to be set in advance in different modes, which results the optimal operation of the integrated energy system cannot be achieved[4].

Based on the above background and research basis, this paper uses the energy hub model to construct an energy coupling model for integrated energy systems to solve the unified power flow between the power-natural gas systems in the integrated energy system; it is verified by an integrated energy system example to ensure the safety and stability of the operation of the example system, and improves the energy efficiency.

2. Establishment of multi-energy flow model

2.1 A subsection power network power flow calculation model
As with ordinary power systems, the modeling of power networks in integrated energy systems is also based on the nodal equations and loop equations of the grid. For the power transmission branch \( ij \), the active power and reactive power balance equation of the branch is [5]:

\[
P_i = \sum_{j=1}^{n} V_i V_j \left( G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \right) \tag{1}
\]

\[
Q_i = \sum_{j=1}^{n} V_i V_j \left( G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij} \right) \tag{2}
\]

In the formula, \( V_i \) and \( V_j \) are the node voltages of \( i \) and \( j \), \( \delta_{ij} \) is the phase angle difference between the nodes, \( G_{ij} \) and \( B_{ij} \) are the conductance and susceptance of the lines between the \( i \) and \( j \) nodes.

Power network power flow distribution generally needs to meet certain constraints. The node balance constraint is:

\[
P_i = \sum_{j=1}^{n} P_{ij} \tag{3}
\]

\[
Q_i = \sum_{j=1}^{n} Q_{ij} \tag{4}
\]

The imbalance constraint is:

\[
P_{Gi}^{\text{min}} \leq P_{Gi} \leq P_{Gi}^{\text{max}} \tag{5}
\]

\[
Q_{Gi}^{\text{min}} \leq Q_{Gi} \leq Q_{Gi}^{\text{max}} \tag{6}
\]

\[
V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \tag{7}
\]

\[
P_i = P_j \leq P_i^{\text{max}} \tag{8}
\]

\[
Q_j \leq Q_j^{\text{max}} \tag{9}
\]

In the formula, \( P_{Gi}^{\text{min}} \) and \( P_{Gi}^{\text{max}} \) are the maximum and minimum values of the active output of the power supply, \( Q_{Gi}^{\text{min}} \) and \( Q_{Gi}^{\text{max}} \) are the maximum and minimum values of the reactive power output, \( V_i^{\text{min}} \) and \( V_i^{\text{max}} \) are maximum and minimum values of the node voltage, \( P_i \) is the transmission power of the transmission branch \( ij \).

### 2.2 Natural gas network power flow calculation model

For natural gas networks, we mainly consider the gas pipelines in the network and the pressure stations configured to compensate for the pressure loss caused by natural gas transportation.

Assuming that the gas pipeline \( mn \) (\( mn \) are nodes) in the network, the flow rate \( F_{mn} \) of the pipeline \( mn \) under steady state conditions is [6]:

\[
F_{mn} = k_{mn} s_{mn} \left[ S_{mn} \left( \frac{n^2}{m^2} - \frac{n^2}{n^2} \right) \right]^{1/2} \tag{10}
\]

\[
s_{mn} = \begin{cases} +1 & \pi_m \geq \pi_n \\ -1 & \pi_m < \pi_n \end{cases} \tag{11}
\]

In the formula, \( k_{mn} \) is a constant related to the efficiency, inner diameter, length, temperature, and compression coefficient in the pipeline, \( s_{mn} \) reflects the flow direction of the pipeline, and \( \pi_m \) and \( \pi_n \) are the pressures of the \( mn \) node of the pipeline.

Additional energy is required when the compressor is used to raise the pressure. Generally, the gas turbine is used to drive the compressor. The energy consumed by the gas turbine is approximately equivalent to the gas load of the pressurizing station, as shown in the following figure.

![Figure 1. Compressor model for natural gas consumption](image-url)
The electrical energy consumed by the compressor is:

\[
H_{\text{com},k} = B_k F_{mn} \left( \frac{\pi_m}{\pi_n} \right)^{Z_k} - 1
\]  

(12)

In the formula, \( B_k \) and \( Z_k \) are constant, depending on the compressor temperature, efficiency and compression factor, \( F_{(\text{com}, k)} \) is the flow rate through the pressurization station. The flow consumed by the gas turbine is:

\[
\tau_{\text{com},k} = \alpha + \beta H_{\text{com},k} + \gamma H_{\text{com},k}^2
\]  

(13)

In the formula, \( \alpha, \beta, \) and \( \gamma \) are energy conversion efficiency constants.

The flow balance equation for nodes in a natural gas network is:

\[
\sum_{m \in C_m} F_{mn} + \sum_{k \in C_m} \tau_{\text{com},k} = \tau_m
\]  

(14)

Where \( C_m \) is the set of nodes connected to \( m \), and \( \tau_m \) is the flow of the pipe connected to point \( m \).

Assuming that the inflow is positive and the outflow is negative, then if \( m \) is the intake point, \( \tau_m \) is positive, if \( m \) is At the point of separation, \( \tau_m \) is negative.

2.3 Integrated energy system model

We use energy hubs to integrate multiple energy systems, the specific model is shown below [7].

![Energy Hub Model](image)

Figure 2. Energy Hub Model

According to the energy conversion efficiency of the equipment in the energy hub and the distribution ratio of electric energy and gas, the coupling relationship shown below can be obtained:

\[
\begin{bmatrix}
L_e \\
L_h \\
L_{eh}
\end{bmatrix}
= \begin{bmatrix}
C_{ee} & C_{ge} & C_{he} \\
C_{eh} & C_{gg} & C_{hh} \\
C_{ec} & C_{gc} & C_{hec}
\end{bmatrix}
\begin{bmatrix}
P_e \\
P_g \\
P_h
\end{bmatrix}
\]  

(15)

The coupling coefficient \( c_{ee} \) is determined by the efficiency, scheduling coefficients, and topology of each energy converter within the energy center.

The energy hub current constraints are the exchange power of the energy hub and the distribution network and the upper and lower limits of the gas power exchanged with the natural gas system.

\[
P_e^{\text{min}} \leq P_e \leq P_e^{\text{max}}
\]  

(16)

\[
P_g^{\text{min}} \leq P_g \leq P_g^{\text{max}}
\]  

(17)

\[
P_h^{\text{min}} \leq P_h \leq P_h^{\text{max}}
\]  

(18)

3. Integrated energy system power flow calculation algorithm

The integrated energy system of this paper has two modes of operation: following the thermal load (FTL), following the electric load (FEL). Aiming at the characteristics of multi-system and multi-energy coupling in integrated energy system, this paper adopts unified solution method based on Newton-Raphson method to calculate the power flow of this model.
The basic idea of the unified solution method is: On the basis of the power flow calculation of the AC power system, the natural gas system variables and the thermal system variables are regarded as extended variables, and then solved together with the power system variables. The iterative formula for the calculation of multi-energy flow in an integrated energy system based on the unified solution method is as follows:

\[
\begin{align*}
\Delta x^{(k+1)} &= J^T \Delta Y^{(k)} \\
x^{(k+1)} &= x^{(k)} - \Delta x^{(k+1)}
\end{align*}
\]  

(19)

In the formula, \(\Delta Y = [\Delta Y_e, \Delta Y_g, \Delta Y_h]^T\) represents the imbalance of the power system, natural gas system, and thermal system, \(x = [x_e, x_g, x_h]^T\) is the power system natural gas system and thermal system state quantity, \(\Delta x = [\Delta x_e, \Delta x_g, \Delta x_h]^T\) represents the correction amount of the state quantity, and \(J\) is the Jacobian matrix, and its formula is as follows:

\[
J = \begin{bmatrix}
J_{ee} & J_{eg} & J_{eh} \\
J_{ge} & J_{gg} & J_{gh} \\
J_{he} & J_{hg} & J_{hh}
\end{bmatrix}
\begin{bmatrix}
\frac{\partial \Delta Y_e}{\partial x_e} \\
\frac{\partial \Delta Y_g}{\partial x_g} \\
\frac{\partial \Delta Y_h}{\partial x_h}
\end{bmatrix}
\]

(20)

In the formula, the diagonal elements represent the relationship between the system's own energy flow and its own state quantity; the non-diagonal elements represent the coupling relationship between different systems.

4. Case analysis

The structure of the integrated energy system used in this paper is shown in the following figure.

Figure 3. Structure diagram of the integrated energy system

The integrated energy system includes a 10-node power system and a 9-node natural gas system, as well as an energy hub. In the figure, ES represents the system bus of the system, GS represents the natural gas system pipe network, and the number is the corresponding system network node number.
Table 1. Power loss of each branch of the power system

| Signpost | Power loss (kVA) | FEL | FTL |
|----------|-----------------|-----|-----|
| 1-5      | 7.565+201.4i    | 7.565+201.3i |
| 2-5      | 5.119+165.7i    | 5.118+165.7i |
| 5-6      | 0.00085+0.0221i | 0.00085+0.0221i |
| 3-10     | 0.158+3.685i    | 0.158+3.684i |
| 5-9      | 18.4+265.9i     | 18.4+265.9i |
| 5-8      | 122.3+1303.4i   | 122.3+1303.4i |
| 4-8      | 15.22+400.31i   | 15.22+400.31i |
| 8-7      | 0.00128+0.0415i | 0.00128+0.0409i |
| 8-9      | 23.86+234.69i   | 23.86+234.68i |
| 9-10     | 0.4509+5.844i   | 0.4509+5.842i |
| **Total loss** | 193.08+2581i    | 193.07+2580.8i |

Table 2. Power loss of each compressor in natural gas system

| Compressor number | Power loss (kVA) | FEL | FTL |
|-------------------|-----------------|-----|-----|
| 1 (1-2)           | 49.098          | 48.362 |
| 2 (6-8)           | 28.612          | 16.641 |
| 3 (7-9)           | 47.455          | 29.926 |
| **Total loss** (kW) | 125.165        | 94.929 |

The experimental results show that the losses of each branch in the power system are approximately equal regardless of FEL or FTL, but in order to maintain a certain compression ratio, the power loss of some compressors in the natural gas system differs greatly in FEL mode.

5. Conclusion
In this paper, the energy hub is used to deepen the coupling degree of each energy part of the system and build the integrated energy system coupling model which can enhance the complementarity of each part. This paper adopts the unified solution method to carry out the system coupling model. The example verifies the validity of the proposed model and algorithm, reflects the energy interaction between the integrated energy systems, which ensures the safe and stable operation of the system.

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