Probabilistic Dynamic Optimal Energy Flow Calculation for the gas-electric coupling system

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Abstract. Due to pollution and energy shortage, the multi-energy interconnected system formed by natural gas and electricity coupling has attracted a lot of attention because of its cleanliness and high efficiency. The operation of natural gas system and electrical power system belong to different time scales. At the same time, more and more new energy sources such as wind and photovoltaic power generation in the electrical power system increase the uncertainty of power supply. The operation of gas-electric coupling system must consider the impact of these factors. In response to these problems, this paper considers the impact of timing on the operating state of gas-electric coupling system based on the multi-period optimization model, and proposes a probabilistic energy flow calculation method, namely the Latin Hypercube sampling Markov Chain simulation (LHMCS). This method can quickly obtain the influence of random factors on the operating state of gas-electric coupling system. Finally, a simulation example verifies the rationality and effectiveness of the method proposed.

1. Introduction

With the generation and development of Power to Gas (P2G) technology, surplus clean electricity can be converted into natural gas and pumped into the natural gas pipeline network, which is expected to realize large-scale storage of electric energy and ensure the consumption of renewable energy such as wind power and solar energy. It further strengthens the degree of coupling between natural gas system and electrical power system[1-2].

At present, scholars at home and abroad have conducted a lot of research on the operation of natural gas and electricity coupling system. Literature [3] calculated the available transmission capacity of the electrical power system under the condition of static safety constraints of gas-electric coupling system. Literature [4] and [5] studied the related issues of the operation safety and risk of gas-electric coupling system and operating state under the market environment, respectively.

However, the above studies are based on a small number of fixed scenarios for calculations, and do not take into account the multi-scene complex energy flow calculation when the system includes uncertain power sources such as wind power. To solve this problem, this paper proposes LHMCS method, which can accurately obtain the influence of random factors on the operating state of gas-electric coupling system with a small number of calculations. It can provide important reference information for the economic operation and reliability analysis of gas-electric coupling system.
2. Timing Impact Analysis of Dynamic Optimal Energy Flow

2.1. Dynamic optimal energy flow model of gas-electric coupling system

The dynamic optimal energy flow model of gas-electric coupling system used in this paper is based on the literature [6], and this paper further enriches the model by adding compressor equipment. Due to friction, natural gas will lose energy during long-distance transmission and accompanied by a large drop in gas pressure. To compensate for this part of energy loss, a certain number of compressors are usually configured in the natural gas system to consume power to adjust gas pressure. This article assumes that the compressor consumes electric energy and there is no mass loss when the gas flows through the compressor. The gas pressure ratio between the inlet and outlet of the compressor is constant. Power of the compressor is related to the flow of gas through it, and the specific relationship can be expressed by equation (1).

\[
P_{km}^{GC} = 745.7 \times 10^{-6} K_{GC} Z_K M_{km} \left( \frac{T_s}{E_c \eta_c} \right) \left( \frac{c_v}{c_s} - 1 \right) \left( \frac{P_m}{P_a} \right)^{\frac{s+1}{c_s}} - 1
\]

In this equation, \( M_{km} \) represents the gas flow through the pipeline \( k-m \) at time \( t \) and the unit is kg/s. \( K_{GC} \) is a constant 0.367. \( Z_K \) is the average compression factor and this paper takes 0.95. \( T_s \) is the suction temperature of the compressor with unit K, and this paper takes 530. \( E_c \) represents the dependency efficiency of compressor, usually taken as 0.99. \( \eta_c \) represents the compressor efficiency, and this paper takes 0.85. \( c_v \) represents the thermal coefficient of natural gas, usually taken as 1.3. The unit of \( P_{km}^{GC} \) is MW.

2.2. The topology of gas-electric coupling system

For analysis, this paper chooses a 12-node natural gas system shown in Figure 1 and a modified Graver’s 6-node electrical power system shown in Figure 2 as the gas-electric coupling simulation system. There are one gas source node (node 1) and three load nodes (node 8, 9, 10) in the natural gas system. There is also a compressor connected between node 4 and 5. There are a coal-fired unit (node 1), a wind farm (node 6), a gas-fired unit (node 3) and five load nodes in the electrical power system. The gas-fired unit in the coupling system is connected to node 11 of the natural gas system, and the PtG is connected to node 5 of the electrical power system and node 12 of the natural gas system.

2.3. Timing impact analysis

The most important feature of gas-electric coupling system dynamic energy flow model is the strong coupling between periods, which reflects that the calculation results at the previous moment will have
a direct impact on the next moment in the natural gas system. But for the electrical power system, the previous and next moments are two independent time sections, and the change in calculation results at the previous moment will not affect the latter moment. Take a specific example to illustrate the different effects of the time series of random variables changes on natural gas and electrical power systems.

The measured data of a wind farm in Texas is used as the input value for wind power of the coupling simulation system, including 1000 wind power daily curves with a time interval of 1 hour. The number of calculation cycles in the objective function is 24 hours, and the cost coefficient of the thermal power generator is 200 yuan/MWh. The price coefficient of natural gas consumed by gas-fired units is taken as 0.4 yuan/kg, and the efficiency parameter of gas-to-electricity is taken as 1.8 MW/s/kg. Namely, the operating cost of gas-fired units is 800 yuan/MWh. The efficiency parameter of electricity-to-gas is taken as 0.11 kg/(s·MW). In order to absorb as much wind power as possible and reduce load shedding, the wind abandonment penalty coefficient in the objective function is taken as 1000 yuan/MWh, and the load shedding penalty coefficient is taken as 2000 yuan/MWh.

In order to analyse the influence of time sequence on calculation results of the dynamic optimal energy flow of coupling system, exchange the positions of original data at moment 3 and moment 16 to form a new set of wind power. Then recalculate and compare the output variables results of electrical power system and natural gas system, and make the distribution of calculation results of some output variables at moment 3 and moment 4 as shown in Figure 3 and Figure 4.

![Figure 3](image1.png)

(1) Moment 3

![Figure 3](image2.png)

(2) Moment 4

Figure 3. Output distribution of thermal power unit in electrical power system at different times

![Figure 4](image3.png)

(1) Moment 3

![Figure 4](image4.png)

(2) Moment 4

Figure 4. Gas pressure distribution of node 7 in natural gas system at different times

It can be seen from the figures that for moment 3, the distribution of output variables changes due to the timing change of random variable regardless of whether they are in the electrical power system or natural gas system. Figure 4 shows that in the natural gas system, the change of output variable at the previous moment will have impacts on the later moment. There is strong coupling between time
periods. Therefore, the continuity between input variables should be fully considered when calculating dynamic optimal energy flow of the gas-electric coupling system.

3. Probabilistic dynamic optimal energy flow calculation

3.1. Method introduction
Latin Hypercube Sampling (LHS) method belongs to stratified sampling, and the sampling value can reflect the overall distribution of random variables. This method consists of arrangement and sampling two steps. By dividing the cumulative probability density curve of random variables into equally spaced non-overlapping intervals and rearranging them for sampling, the distribution area of random variables can be completely covered. The specific steps of LHS method can refer to the literature [7]. However, LHS method cannot consider the correlation between sampling values of random variable at different times. Thus, LHS method cannot be directly used in the probabilistic dynamic optimal energy flow calculation.

Markov Chain Monte Carlo (MCMC) method is based on the transition probability matrix of Markov chain, using Monte Carlo sampling to determine the transitions of random variable between states. The specific steps of MCMC method can refer to the literature [8]. MCMC method can consider the correlation between sampling values of random variable at the previous and latter moment, but when the sampling number is relatively small, the values sampled cannot cover the whole value space of random variable.

3.2. Latin Hypercube sampling Markov Chain simulation method
Combining the characteristics of LHS method and MCMC method, the LHSMC method is proposed for probabilistic dynamic optimal energy flow calculation of the gas-electric coupling system. The input random variables are new energy outputs, electrical loads and gas loads. The output variables are the power of energy conversion equipment such as PtG, generator output in the electrical power system, gas pressure of each node and pipeline flow in the natural gas system.

This paper takes the gas-electric coupling system with a single wind farm shown in Figure 1 and Figure 2 as an example to illustrate the process of LHSMC method used to solve the calculation of probabilistic dynamic optimal energy flow.

(1) Input data of the gas-electric coupling system and sampling times N.
(2) Calculate the transition probability matrix $P$ of the input wind power series.
(3) Generate $N \times 1$ order Latin hypercube sampling matrix $W_1$ as the sampling value of the first period of wind power daily output curve.
(4) For each element in the matrix, use the MCMC method to generate curves with a length of 24 periods to form $N \times 24$ order wind power daily output sampling matrix $W_s$.
(5) Calculate deterministic dynamic optimal energy flow for each row element in the sampling matrix $W_s$.
(6) Make statistical analysis of output variables.

4. Simulation verification and analysis

4.1. Introduction
The actual data of a wind farm in Texas mentioned above is still used for simulation testing. In order to verify effectiveness of the LHSMC method, the following two methods are used to calculate and the results of output variables are statistically analysed and compared.

Method 1: LHSMC method, the sampling number $N$ is 100.
Method 2: LHS method (used independently in each period), the sampling number $N$ is 100.
4.2. Simulation result analysis

The relative errors of expected value and standard deviation are used to measure the accuracy of output variable calculation. The expected value and standard deviation of output variable calculated by using the measured data are represented by \( \mu_a \) and \( \sigma_a \). The expected value and standard deviation of output variable calculated by using the simulated data are represented by \( \mu_m \) and \( \sigma_m \). The calculation formula is as follows, and the smaller the values, the more accurate the calculation result is considered.

\[
\varepsilon_\mu = \left| \frac{\mu_m - \mu_a}{\mu_a} \right| \times 100\% \\
\varepsilon_\sigma = \left| \frac{\sigma_m - \sigma_a}{\sigma_a} \right| \times 100\%
\]

Due to the large number of each type of output variables, the average value of relative errors is used to indicate the accuracy of output variable calculation.

Table 1 shows the calculation results of different output variables. It can be seen intuitively that the calculation results of LHSMC method are significantly better than those of LHS method, which verifies the effectiveness of the LHSMC method proposed in this paper.

| Method      | Gas-fired unit output in the power system | Gas pressure of nodes in the natural gas system | Flow of pipelines in the natural gas system |
|-------------|------------------------------------------|-----------------------------------------------|---------------------------------------------|
|             | \( \varepsilon_\mu \) | \( \varepsilon_\sigma \) | \( \varepsilon_\mu \) | \( \varepsilon_\sigma \) | \( \varepsilon_\mu \) | \( \varepsilon_\sigma \) |
| LHSMC       | 0.0302 | 0.5286 | -0.4620 | 0.7621 | 0.7397 | 0.3161 |
| LHS         | 1.1617 | 1.7547 | -1.4412 | 1.7147 | 1.2291 | 1.6023 |

5. Conclusion

Aiming at the calculation of probabilistic dynamic optimal energy flow in the gas-electric coupling system, this paper proposes a method that can consider the continuity of input random variables in each period for probabilistic calculation. This method has the following advantages:

1. Using the LHSMC method to calculate can accurately obtain the impacts of input random factor changes on the operating state of gas-electric coupling system with a small number of calculations, saving a lot of time.
2. The LHSMC method is suitable for gas-electric coupling systems of different scales, and the larger the system scale, the more obvious the advantages of the method.

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