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Failure probability estimation of gas supply using the central moment method in an integrated energy system

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HIGHLIGHTS

- This paper presents reliability estimation problems for gas supply.
- Mathematical modelling of probabilistic characteristics is analysed.
- Sufficient comparison with existing methods is conducted.
- The central moments of uncertainties are calculated.
- The proposed method is tested using a CHP based microIES.

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ABSTRACT

The reliable supply of natural gas ensures the safe and stable operation of an integrated energy system. Operational uncertainty of the integrated energy system (IES) such as a surge in heating load can exacerbate an unreliable supply situation of natural gas. This paper examines gas supply reliability. A central moment method is proposed to estimate the failure probabilities for the gas supply in a combined heat- and power-based microintegrated energy system. To make the calculation more relevant to an actual project, we considered the energy network constraints and energy stochastic characteristics. To demonstrate the use of the central moment method in the estimation of failure probability of a gas supply, the results were validated using sufficient comparisons with traditional methods. Classic traditional methods include the Iman and Stein methods, the first order reliability method, the mixed algorithm based on Latin hypercube sampling, the Cholesky decomposition and the Nataf transformation, and the principle of maximum entropy method. An actual integrated energy system is provided to promote practical solutions for failure probability estimation of the gas supply.

1. Introduction

With the coming of winter in 2017 in China, the supply situation for natural gas has become increasingly severe. From November 15, 2017, to March 15, 2018, for upstream Beijing non-residents, the price of natural gas will increase by 9.71%, or approximately 0.184 yuan/m^3. As natural gas consumption demand continues to be strong, the reliability of the gas supply chain becomes increasingly serious. Along with the development of the integrated energy system (IES), energy networks integrate gas networks, heating networks and power networks. The failure of the gas supply chain can have an adverse effect on the safety of other energy systems in a situation where energy systems are tightly coupled. Consequently, when the reliability of the gas supply is not guaranteed, the uncertainty can cause severe cascading failures in different energy systems. This problem is a matter of utmost importance. This paper focus on the reliability analysis of the gas supply in an integrated energy system under multiple uncertainties. To solve the issue of gas supply reliability, from the point of view of scientific theory, three facets should be involved: modelling integrated energy systems, analysis of energy uncertainties, and reliability analysis of the gas supply system.

Consider the first facet of the problem. Recently, Tattini et al. [1] developed MoCho-TIMES in the standalone transportation sector for the IES model for Denmark, and MoCho-TIMES can perform innovative policy analyses in an energy-economy-environment-engineering system. A solution to the problem of energy hub formulations is proving elusive in the extreme. Liu et al. [2] presented a novel electrical-hydraulic-thermal calculation technique, which has become a classic

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theory of combined heat and power flow calculation. It is imperative to present an automatic and linearized modelling method. Wang et al. [3] have replaced non-linearized models by using a linearized model to formulate energy conversion in an IES. Energy planning is a major problem in developing multiple energy systems. Instead of a newly built area, Hou et al. [4] focused on already-built regions and presented different ways to expand existing IESs. In addition to energy planning, energy dispatch is another major problem in developing multiple energy systems. To explore the dispatch flexibility of multiple energy, Li et al. [5] formulated energy dispatch models using mixed-integer linear programming theory for both the grid-connected and islanded IESs. Zheng et al. [6] emphasized both planning and dispatch, and the optimization model combining an operational planning model and dispatch strategy can show a good performance on multiple energy applications. With respect to integrated electricity and heating networks, Ayelea et al. [7] presented an extended energy hub model to couple different energy carriers, and the energy hub formulations can be solved using the Newton-Raphson iterative method. To improve energy efficiency of a combined heat and power system, Asensio et al. [8] presented an optimal cooling system control model based on the optimization strategies that can be developed in real time applications. With respect to integrated electricity and gas networks, McKenna et al. [9] investigated the electrical and gas distribution networks and presented federal state and different model regions to analyse the energy economy in Baden-Württemberg (BW), Germany. To make full use of gas energy in the integrated electricity and gas networks, Jiang et al. [10] presented a coordinated optimization model, in which power flow and gas hydraulic were considered.

Let us move on to the second facet of the problem. To explore the flexibility to accommodate intermittent renewable energy and random demand, Baker et al. [11] presented stochastic optimization and parametric analysis theories considering the financial stability and operational reliability for a nuclear hybrid energy system consisting of a reactor, wind generation, battery storage, and a desalination plant. Wind power is a typical intermittent renewable energy. An analysis of wind power must assess the impact of uncertainty on forecasting and dispatching. Wang et al. [12] presented a novel architecture for forecast model of wind speed aimed at quantifying and suppressing uncertainty. Zheng et al. [13] harnessed the thermal inertia of a district-heating network to explore the flexibility of combined heat and power (CHP) to accommodate intermittent wind power in integrated electricity and heating networks. Typically, not only wind power but also other intermittent renewable energies are involved in the IES. Considering the influence of interaction among multiple uncertainties in IES, Yu et al. [14] presented a flexible-stochastic programming method for identifying optimal schemes for planning energy systems. Qiao et al. [15] harnessed the multiple energy complementary to improve the maximum permissible capacity of intermittent wind power generation. Chen et al. [16] presented a mixed algorithm that combines Latin hypercube sampling, Cholesky decomposition and Nataf transformation to ensure the calculation accuracy of probabilistic power flows.

The third facet of the problem has been described in different ways. The reliability analysis of gas supply reliability is an issue that China takes very seriously. Different compartments and ecological networks were analysed by Lu et al. [17] to improve the reliability of the gas supply in China. Su et al. [18] deliberated on the reliability analysis of the gas supply system, and uncertainty and physical constraint are modelled to be close to the actual and complex gas system. Rimkevicius et al. [19] presented a reliability analysis method for gas networks based on degradation mechanisms and structural integrity of pipes, and their method has been used successfully in reliability analysis of the gas supply system in Lithuania. To ensure the reliability of the gas supply system, Bekkering et al. [20] presented an economic option that can make full use of the flexibility of the gas supply, instead of adding expensive gas storage to a supply chain. The study in Ref. [21] indicated that, when gas-fuelled generations increase in an IES, the substantial increase in natural gas consumption can challenge the reliability of both the gas supply system and the power system. The reliability analysis of the gas supply system plays an important part in the safe operation of an IES. Lei et al. [22] presented a new reliability analysis method for an IES based on a reduction technique of higher order contingencies, and their method has been used successfully in reliability analysis of the Belgian natural gas network. This paper is on the reliability analysis of the gas supply system from a different perspective. The same point between previous papers and this paper is that the reliability of the gas supply is estimated. The different point is that the uncertainty of the gas supply and consumption are considered in this paper, while the uncertainty and correlation are not considered in previous papers. Additionally, this study is based on our previous work [23–26]. The model of building heating loads in Ref. [23], the probability model of temperature in Ref. [24], model of IES in Ref. [25], and the method for reliability analysis in Ref. [26] are used in this paper to verify the effectiveness of the proposed method.

The novel contributions of this paper can be summarized as follows. (1) This paper has remarkable significance for practical engineering to consider and model both the energy network constraints and the uncertainty of the gas supply and consumption in a CHP-based microIES in northern China. (2) To the best of our knowledge, this paper reports the first time that central moments are used for the failure probability estimation of the gas supply. (3) The proposed central moment method is not restricted to nonlinear computation and probability distribution types, and the proposed central moment method has better performance on computing speed and precision than traditional methods.

2. Problem description

The traditional methods of modelling uncertainties of an integrated energy system are usually introduced with probability distribution models. Probability distribution models are based on the correct distribution probability types and accurate statistical parameters. Both the distribution probability types and the statistical parameter values of random variables are affected by the sample sizes and statistical inference methods such as parameter estimation and hypothesis testing methods. Therefore, the estimation results of failure probability of integrated energy systems using the traditional methods can be affected by the sample sizes and the statistical inference methods. The cumulative probability distribution is a complete description of the statistical characteristics of random variables. Digital characteristics such as central moments can also provide a way to describe the important characteristics of random variables. In the case of an integrated energy system suffering from uncertainties of stochastic wind power, heat loads or gas supply deliverability, the central moments of observation variables in statistics can be computed to estimate the failure probabilities of the gas supply rather than calculate actual probability distributions.

The central moment method is proposed to enrich uncertainty modelling methods rather than to improve the traditional methods, which can have good enough performance based on known probability distributions. The central moment method is compared with and checked against traditional methods such as the mixed algorithm in Ref. [16], the Iman method in Ref. [27], the Stein method in Ref. [28], the first order reliability method (FORM) in Ref. [26], and the principle of maximum entropy (POME) method in Ref. [24]. The premise of mixed algorithms, the Iman method, the Stein method, and the FORM method is that one can determine the accurate distribution types such as normal distributions, type 1 extreme value distributions, and lognormal distributions. The POME method and the proposed method make use of a maximum entropy probability distribution to model an unknown distribution probability. This paper analyses the different probability statistics of different methods, as shown in Fig. 1.