Explicit cost-risk tradeoff for optimal energy management in CCHP microgrid system under fuzzy-risk preferences

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In this paper, a fuzzy risk-explicit interval parameter programming (FREIPP) approach was provided for multiple energy supply and demand management in microgrid system under uncertainties. The FREIPP method integrates risk-explicit interval linear programming and fuzzy theory within a general framework. It can tackle fuzzy and interval uncertainties in terms of various cost coefficients, forecasted load demand, decision maker’s risk attitude and other uncertainties in microgrid system management. Compared with traditional interval parameter programming, the proposed method has distinct advantages in minimizing the system cost and risk simultaneously and providing more risk explicit solutions with the regard of obscure risk preference of decision maker. The FREIPP approach was successfully applied in a microgrid system with combined cooling, heating and power (CCHP) generation for three types of decision maker (i.e. defensive, neutral and aggressive). The obtained results indicated that the proposed FREIPP approach could provide optimal operation strategies with explicit cost-risk tradeoff information for decision maker when facing multiple complex uncertainties. Furthermore, it could help decision maker with different risk tolerance select desired optimal risk-aversion strategies, which is more realistic in real-world decision making process.

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1. Introduction

Combined cooling, heat and power (CCHP) microgrid system, that can provide multiple energy demands simultaneously in a more effective way, and lead to a lower pollutant emission, a lower conventional energy consumption, and a higher primary energy utilization efficiency, has become an optimal alternative measure to relieve resources and environmental pressures in traditional electricity system (Homayouni et al., 2017; Jiang et al., 2017). It is usually closed to the end-user facilities, and consists of distributed generation (such as wind turbine, PV, fuel cell, and gas engine) and energy storage devices (Brahman et al., 2015; Jochem et al., 2015). Since multiple energy supply modes and demand patterns are integrated into a system framework, the coordination operation for these distributed energy devices is crucial for highlighting the advantages in system configuration, capacity investment portfolio, and operation strategy (Wang et al., 2015; Jabari et al., 2016). Thus, effective optimization decision-making tools are desired to make reasonable and flexible operation schemes in CCHP microgrid system.

Previously, a number of studies were proposed for searching the effective energy management schemes in microgrid systems with combined heating and power (CHP) or CCHP (Gu et al., 2014; Ünal et al., 2015; Li et al., 2017). Delicate models have been formulated to solve CHP/CCHP system management problems with single-objective or multi-objective purpose. For example, Li et al. (2014) formulated a nonlinear programming model to optimize CCHP system in the residential and office buildings with three competing objectives, i.e. annual total cost reduction, primary energy saving, and carbon emission reduction. Jabari et al. (2016) proposed a mixed–integer nonlinear programming for a micro–CCHP system dispatch management to minimize the total hourly energy cost purchased from the main grid. Zheng et al. (2016) developed a mixed integer linear programming model for CHP microgrid system management in a smart home with the aim of minimizing system daily cost and CO2 emission simultaneously.

However, the above deterministic optimization models are not effective enough for solving complex operation management problems in CCHP microgrid system because of the inherent uncertainties in energy conversion processes and various impact factors, such as the random energy consumption activities, the fluctuant electricity tariff and fuel price, and the intermittent renewable energy generation (Pazouki et al., 2014; Azizipanah-Abarghooee et al., 2016). These various uncertainties significantly affect the safety and effectiveness of optimal decision strategy for CHP microgrid system management. In order to deal with these uncertainties, several inexact optimization
approaches have been developed, such as stochastic mathematical programming, fuzzy mathematical programming, interval parameter programming, and their hybrid methods (Ersoz and Colak, 2016; Nie et al., 2017). In the framework of stochastic programming, according to probability distribution functions, various scenario generation and sampling selection technologies are used to model the uncertainties in energy system. For example, Li et al. (2010) and Díaz and Morena (2016) employed Monte Carlo simulation to describe energy demands and electricity price in the stochastic programming. Zamani et al. (2016) proposed a probabilistic model using a modified scenario-based decision making method for optimal day ahead scheduling of electrical and thermal energy resources for a virtual power plant with CHP. Fuzzy programming method is usually used to formulate the uncertain parameters in the objective function and constraints, and the satisfactory tradeoff of decision maker in multi-objective programming through fuzzy membership function. For example, Moradi et al. (2013) proposed a fuzzy programming model for energy management system strategy for CHP system, where the imprecise technological coefficients and input variables were represented by fuzzy numbers. Motevasel et al. (2013) developed an interactive fuzzy satisfying method to model the tradeoff between two conflicting objectives for optimal operation of a CHP-based micro-grid system. In general, stochastic mathematical programming and fuzzy mathematical programming require the detail information on scenarios or exact probability distribution of uncertain parameters, and cannot directly reflect the system risk that caused by the uncertainties. In contrast, for interval parameter programming where uncertainties are expressed as interval numbers with lower and upper bound, accurate probability distribution information is not necessary. Consequently, it requires less information and easier algorithm, and has become a popular tool for reflecting uncertainties in complex energy system (Cao et al., 2011; Ji et al., 2015). For example, Boloukat and Foroud (2016) presented an interval linear programming model for long-term optimal generation expansion planning of grid-connected microgrid containing various renewable energy generation. Bai et al. (2016) developed an interval programming model for the optimal operating strategy of the gas-electricity integrated energy system with the consideration of demand response and wind power uncertainty.

In spite of the above advantages, the main defects of interval parameter programming are that the obtained solutions expressed as interval value cannot provide accurate value, or reflect the risk attitude of decision maker (Chen et al., 2013). Especially, the larger wide coverage of interval value is, the vaguer the solution will be. This makes interval parameter programming less effective in real-world decision making. In order to overcome these limitations, by introducing a risk objective function and aspiration level, a risk explicit interval parameter programming (REIPP) method, that can guarantee both the feasibility and optimality of interval parameter programming, was proposed and verified through plentiful simplified numerical examples and complicated practical cases (Liu et al., 2011a, 2011b; Yang et al., 2016; Zou et al., 2010a). For example, Zou et al. (2010b) advanced a risk explicit interval linear programming algorithm and inverse mapping scheme to implicitly resolve the nonlinearity interval optimization for waste load allocation. Therefore, a fuzzy risk explicit interval parameter programming (FREIPP) model for CCHP microgrid system operation management under various uncertainties is developed as an extension study of our previous study (Ji et al., 2014) to deal with the obscure risk tolerance of decision maker in real world decision process. It would also expand the application scale of FREIPP in the energy system filed. Two distinguishing advantages of the proposed method are highlighted: (1) it not only inherits the advantages of interval parameter programming, but also reflects the explicit cost-risk tradeoff information for decision maker; (2) the ambiguous risk attitude from decision maker is taken into account, which makes the decision process more realistic. The rest of this paper is organized as follows. The relative theoretical knowledge and solution algorithm of the proposed FREIPP model is introduced in Section 2. The system configurations and uncertainties of the CCHP microgrid system for case study are described, and a FREIPP model for energy management in CCHP microgrid is formulated in Section 3. The obtained results of the typical case study are presented and discussed in Section 4. The main conclusions are drawn in Section 5.

2. Methodology

2.1. Interval parameter programming

In CCHP microgrid system, there are many uncertain factors whose randomness may not be expressed elaborately, which will bring disturbance on decision making. Usually, these uncertainties such as the multiple energy load demands, electricity price, and intermittent wind power output can be forecasted with certain error range. As a result, they can be expressed as interval numbers with maximum and minimum value, then modeled by interval parameter programming (IPP) (Allahdadi et al., 2016). A general IPP model with inequality constraints can be expressed as follows:

$$\min f^x = \sum_{j=1}^{n} c_j^x x_j^x \quad (1 - a)$$

s.t. \hspace{1cm} a_{ij}^x x_j^x \geq b_i^x \quad (1 - b)$$
$$x_j^x \geq 0 \quad (1 - c)$$

where superscript $\pm$ denotes the lower and upper bound of interval parameter; $f^x$ is the objective function; $c_j^x$ and $a_{ij}^x$ are the interval
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