Energy 67 (2014) 186–199

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

An inexact two-stage stochastic robust programming for residential micro-grid management-based on random demand

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A R T I C L E I N F O

Article history:
Received 10 August 2013
Received in revised form
3 January 2014
Accepted 27 January 2014
Available online 24 February 2014

Keywords:
Stochastic robust optimization
Interval linear programming
Two-stage stochastic programming
Micro-grid
Uncertainty

A B S T R A C T

In this paper a stochastic robust optimization problem of residential micro-grid energy management is presented. Combined cooling, heating and electricity technology (CCHP) is introduced to satisfy various energy demands. Two-stage programming is utilized to find the optimal installed capacity investment and operation control of CCHP (combined cooling heating and power). Moreover, interval programming and robust stochastic optimization methods are exploited to gain interval robust solutions under different robustness levels which are feasible for uncertain data. The obtained results can help micro-grid managers minimizing the investment and operation cost with lower system failure risk when facing fluctuant energy market and uncertain technology parameters. The different robustness levels reflect the risk preference of micro-grid manager. The proposed approach is applied to residential area energy management in North China. Detailed computational results under different robustness level are presented and analyzed for providing investment decision and operation strategies.

1. Introduction

Electricity is an integral part of social development, and the power generation continues to grow in order to meet the requirement of high-speed development. Meanwhile, with the improvement of living standard and the increasing demand for comfortable environment, the cooling and heating supply also continues to grow. Recently, in summer, electricity is still the major energy for refrigerator chiller in most parts of the world. Especially, in China, the cooling load of electric chiller counts for 1/4 of the total load demand in metropolis, which causes great burden to electricity system. Besides, traditional single type of heating or cooling supply results in plenty of energy waste. Due to resource constrained and environmental protection, the urban energy systems desperately need improvement and look beyond original energy supply patterns to new ways of doing energy structural adjustment and development. In addition, many countries are replacing energy systems based on large power plants with renewable energy systems adapted to local conditions with far more decentralized systems and energy efficiency at the community-level of consumption [1]. Under this background micro-grid, as a novel community-level electricity system, gains more and more concern. The micro-grid system can integrate distributed renewable energy, provide diversification of energy supply, and reduce the transmission losses and greenhouse gas emission [2]. On the other hand, micro-grid is a strong complement to power system and can operate not only in grid mode but also in island mode. Among different types of micro energy supply patterns, combined heat and power (CHP), and combined cooling, heating and power (CCHP) systems in micro-grid are efficiency, flexibility, dispersity and reliability, thus they have emerged as a viable alternative to the well known central power generating stations and have great potential in environment pollution reduction and energy efficiency improvement [3]. However, how to make an effective electricity, cool and heat supply scheme under different seasons, and adjust the ordering of various energy conversation technologies for different types of energy supply is a top priority problem for many micro-grid system, especially, due to multi-energy consumption patterns and multi-energy conversation technologies in CCHP (combined cooling heating and power) system.

Optimizing operation strategies is crucial to realize the security, economic and environmental targets in electricity system [4–7]. Due to its economic and environmental advantages, CCHP has been

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http://dx.doi.org/10.1016/j.energy.2014.01.099
0360-5442/

modeled and prioritized in many recent papers. Generally, there are two operation strategies of CHP systems, following the electric load (FEL) and the thermal load (FTL) [8]. In order to optimize the system design and operation, mixed-integer linear programming (MILP) and mixed-integer non-linear programming (MINLP) models have been developed in many researches [9–14]. However, CCHP systems are complicated with a variety of uncertainties. They may be derived from random nature of meteorological condition, as well as random energy demand, as well as the errors in estimated modeling parameters. All of those uncertainties will bring operation risk to micro-grid energy management [15], thus lacking of appropriate system configurations and suitable operation strategy may cause economic loss and not be able to produce potential benefits. Previously, several methods have been developed to deal with the uncertainties, including the energy demand prediction and energy system management problems in micro-gird system, and inexact optimization methods [16–22]. For example, Cai et al. (2009) proposed fuzzy-random interval programming model to identify optimal strategies in the planning of energy management systems within multi-period [23]. Zhou et al. (2013) utilized Monte Carlo method dealing with uncertainty for the distributed energy system in a hotel. Each type of energy demands at any point in time follows a normal distribution, and the probability distribution of solar and wind energy are adopted to handle the supply uncertainties [24]. Xue et al. (2012) developed an optimization model based on chance constrained programming for micro-grid operation with the uncertainties related to load and wind speed into consideration [25]. Dong et al. (2012) developed an inexact optimization model to support the energy system planning in Beijing [26]. Niknam and Golestaneh (2013) used the $2m+1$ point estimate method to handle the uncertainty in electric tariff, load demand and renewable energy output [27]. Moradi et al. (2013) proposed a hybrid fuzzy optimization method for combined heat and power systems management [28]. In general, the previous studies made a great effect in dealing with the uncertainties in energy and environmental system, and uncertainties have been handled and reflected as one particular form and a combination of different methods through the previous studies.

In residential area, various loads are not in a stable state for long time, and usually change with season and time. The design and operation depend on the levels of electrical, thermal and cooling demands, with random characteristics, that could lead to difficulties in facilitating the examination of economic consequences for violated policies in micro-grid system management. Stochastic mathematical programming presents a set of solutions that take into consideration the randomness in input parameters. The probability distribution of the uncertain factors may not be easily obtained and exactly expressed. In addition, due to the minimum cost or maximum net benefit considered as the objective in a general stochastic mathematical programming, it could lead to the problems of low system stability and unbalanced generation risk. For the reasons above, it is desired to develop an effective and convenient tool for design and operation of residential micro-grid with multi-energy consumption patterns and multi-energy conversation technologies under stochastic demands.

Therefore, the objective of the paper is to develop an interval two-stage stochastic robust programming (ITSRP) model and demonstrate its performance with examples taken from the verification studies made. In the model, interval parameter programming, two-stage stochastic programming, and robust optimization technique are integrated into a framework for dealing with the uncertain market environmental and technologies parameters. It allows uncertainties presented as probability distributions and interval values, and reflect the preference of decision makers, such that the tradeoff between system economy and extreme expected loss could be analyzed. The paper is organized as follows: Section 2 is devoted to the description of the two-stage stochastic programming and interval parameter programming, and the proposed ITSRP model for stochastic optimization is specified. In Section 3, the ITSRP model for energy management of the residential area is proposed. In Section 4, the model is verified through a case study, while the main results are presented in Section 5. Conclusion is drawn in Section 6.

2. Methodology

In two-stage stochastic programming (TSP), an initial decision is made based on uncertain future events. The initial decision is called the first-stage decision, and the corrective action is the second-stage decision [29]. The fundamental idea of TSP is the concept of recourse that refers to the ability to take corrective actions after a random event has taken place. A general TSP model can be formulated as follows [30]:

$$\min f = c^T x + \sum_{s=1}^{N} p_s Q(y,\omega_s) \tag{1a}$$

subject to:

$$ax \le b \tag{1b}$$

$$T(\omega_s)x + W(\omega_s)y = h(\omega_s) \tag{1c}$$

$$x \ge 0, y(\omega_s) \ge 0 \tag{1d}$$

where x is vector of first-stage decision variables ω is random events after the first-stage decisions are made s is the scenario of the happening of random events p_s is probability of event $\omega_s \sum p_s = 1$,; $Q(y,\omega_s)$ is system recourse at the second-stage under the occurrence of event ω_s; thus, the first part in object function $c^T x$ presents the first-stage benefits; the second part $\sum_{s=1}^{N} p_s Q(y,\omega_s)$ is the expected penalties in the second-stage.

Generally, TSP models require probabilistic specifications for uncertain parameters. However, in many practical situations, discrete probability distributions of some parameters could not obtain through the limited data. In interval linear programming, the uncertainties without distributional information can be expressed as interval numbers [29,31]. Coupled with ILP and TSP, an inexact TSP model can be formulated as follows:

$$\min f^{\pm} = \sum_{j=1}^{n_1} c_j^{\pm} x_j^{\pm} + \sum_{j=1}^{n_1} \sum_{s=1}^{N} p_s d_j^{\pm} y_{js}^{\pm} \tag{2a}$$

subject to:

$$\sum_{j=1}^{n_1} a_{rj}^{\pm} x_j^{\pm} \le b_r^{\pm}, r = 1,2,\ldots,m_1 \tag{2b}$$

$$\sum_{j=1}^{n_1} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=1}^{n_1} e_{ij}^{\pm} y_{js}^{\pm} \le \widehat{w}_{is}^{\pm}, i = 1,2,\ldots, m_2; s = 1,2,\ldots, N \tag{2c}$$

$$x_j^{\pm} \ge 0, \; j = 1,2,\ldots,n_1 \tag{2d}$$

$$y_{js}^{\pm} \ge 0, \; j = 1,2,\ldots, n_1; s = 1,2,\ldots,N \tag{2e}$$

Obviously, model (2) can effectively reflect stochastic uncertainties and dynamic feature in long-term planning problems