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An inexact fixed-mix fuzzy-stochastic programming model for heat supply management in wind power heating system under uncertainty

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ABSTRACT

To better utilize electricity generated by wind power in northern China and ease the strain on local energy grids in the winter, the National Energy Administration (NEA) is committed to promoting the development of wind power heating projects in areas where conditions are suitable. However, multiple uncertainties and complexities that exist in the processes of wind power generation and heat supply present substantial challenges to the stability of wind power heating system and put its operation into risk. Therefore, an inexact fixed-mix fuzzy-stochastic programming (IFFSP) method was developed and applied to the heat supply management of an actual wind power heating system under uncertainties presented as interval values, random variables and fuzzy sets within a multi-stage context. Interval solutions associated with plausibility degrees of constraint violation can help decision makers identify the optimal heat supply management strategies and gain a comprehensive tradeoff between economic objectives and reliability risks of system. Moreover, the feasibility of wind power heating project in promoting wind power consumption and relieving wind curtailment is studied, and the results indicated that the effect is limited. Finally, suggestions aimed on resolving issues of integration and consumption of wind energy are proposed.

1. Introduction

In recent years, driven by concerns about CO_2 emissions and climate change, rising oil prices and energy security, the installation of wind power has rapidly increased in many countries (Daim et al., 2012). Since the introduction of Renewable Energy Law in 2005, the newly installed wind power capacity in China has roughly doubled every year. By 2010, China's cumulative installed capacity of wind power has reached 44 GW, which ranked the first in the world, surpassing the United States (Zhao et al., 2014; Yuan et al., 2015). During the 12th Five-Year Plan, development of wind power will carry on with the high speed growth inherited from the 11th and by its end the 12th Five-Year Plan can potentially see a total installed capacity of 130 GW (Tan et al., 2013).

However, in China, wind power resources are most abundant in the “Three North” (north, northeast, and northwest) regions with sparse populations and less developed economies. It means that less wind power electricity would be consumed close to the source (Li et al., 2012). A large amount of electricity has to be transmitted to the east and southeast coastal areas. This poses fundamental challenges to exiting inadequate grid infrastructure which could lead to power transmission congestion (Liao et al., 2010; Liu and Kokko, 2010; Zhang and Li, 2012).

Moreover, during the heating period in northern China, combined heat and power (CHP) units are running preferentially to avoid affecting heating. Thus, the thermal power peak regulation capacity is reduced and there is little scope for system balance dispatching (Zhao et al., 2012). These factors eventually lead to a prominent problem - wind power curtailment. For example, in 2011, wind curtailment rate in China was 12% and unconsumed electricity generated by wind reached about 10 billion kilowatt-hours. The problem was getting more severe in 2012 as capacity installation growth still outpaces grid construction growth, and about 20 billion kilowatt-hours of wind-generated power was curtailed. Though growth momentum of wind power began to improve in 2013 and the volume of wind power curtailment was 16.2 billion kilowatt-hours, 4.6 billion kilowatt-hours less than that

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in 2012, accommodation of wind power is still the critical issue to be resolved.

Aimed on promoting wind power consumption and relieving wind curtailment, the National Energy Administration (NEA) is now committed to promoting the development of wind power heating projects in areas where conditions are suitable. According to an NEA notice issued in 2013 (NEA, 2013a, 2013b), relevant authorities in the provinces of Jilin, Hebei, Shanxi, Heilongjiang, Liaoning, the Inner Mongolia Autonomous Region, and the Xinjiang Uyghur Autonomous Region are urged to start pilot testing of wind power heating technology. Specifically, new buildings are encouraged to use wind power for heating in order to step up wind power allocation over the next two to three years. However, due to the nature of wind, especially its intermittency, partly unpredictability and variability (Xydis, 2013), wind power has a negative impact on the continuity of heating process, which can present substantial challenges to the stability of wind power heating system and put its operation into risk (Swierczynski et al., 2010). Therefore, effective heat supply management method in wind power heating system is desired.

Previously, a number of optimization methods for dealing with wind power absorption problem were developed across the world (Hu et al., 2011), while most of them focused on wind power integration and dispatching difficulty, or utilizing energy storage technique to accommodate wind power. For example, based on the non-dominated sorting genetic algorithm (NSGA), Ochoa et al. (2008) developed a multi-objective programming approach and applied it to a medium voltage distribution network in order to find configurations that maximize the integration of distributed wind power generation (DWPG) while satisfying voltage and thermal limits. Wand and Yu (2012) proposed an optimization model to decide the rated power and capacity of compressed air energy storage (CAES) system, which is a mature and reliable bulk energy storage technique with promising potential to accommodate high wind power penetration in power systems. Fitzgerald et al. (2012) provided an electric water heating model to examine the potential to transform electric water heating into an intelligent responsive agent capable of reducing electricity consumption and peak demand, and possibly providing some balancing load to assist the integration of variable wind power. Zha et al. (2011) put forward a feasible solution methodology based on the wind power prediction and established two mathematical models of Unit Commitment (UC) and dynamic optimal dispatching in order to solve the actual power grid dispatching difficulty. In other words, few studies were undertaken for supporting decisions of heat supply management in wind power heating system.

In fact, with respect to wind power heating system, a variety of uncertain factors that should be considered by decision makers, including variation of wind power output related to wind speed's volatility, dynamics of system conditions, as well as the associated economic and technique parameters. Moreover, many processes are linked to heat supply management, such as conversion/processing, storage/transmission, and supply/demand of heat, further complicating the complexities in decisions making. The inherent uncertainties and complexities that exist in wind power heating system planning have essentially placed them beyond the deterministic optimization methods (Li and Huang, 2012). Therefore, it is desired to develop robust methods to deal with these uncertainties and complexities.

Generally, interval-parameter programming (IPP) can tackle uncertainties expressed as intervals that exist in the model's left- and/or right-hand sides as well as the objective function; however, it is incapable of dealing with uncertainties expressed as probabilistic distributions (Huang, 1996; Huang and Cao, 2011). The existing fixed-mix stochastic programming (FSP) methods are effective in handling probabilistic uncertainties in the model's right-hand sides (Xie et al., 2010); however, the increased data requirements for specifying the parameters' probability distributions can affect their practical applicability. Fuzzy mathematical programming (FMP) can deal with vagueness and ambiguity based on fuzzy set theory, where uncertainties are handled in a direct way without a large number of realizations; nevertheless, the main limitations of the FMP methods remain in their difficulties in tackling uncertainties expressed as probabilistic distributions in a non-fuzzy decision space (Li et al., 2009).

Inexact optimization methods mentioned above rely on individual interval, stochastic or fuzzy uncertainties. However, in heat supply management of wind power heating system, some parameters may present simply as intervals, while the others may be associated with probabilistic or vague information. As a result, if merely individual stochastic or fuzzy methods are employed under such complexities, robustness of the optimization results may be significantly influenced due to the problems of over-simplification for uncertainties (Li et al., 2009).

Thus, the objective of this study is to develop an inexact fixed-mix fuzzy-stochastic programming (IFFSP) method, and apply it to an actual wind power heating project in order to seek the desired heat supply management strategies under uncertainty. This is the first attempt that interval-parameter programming (IPP), fixed-mix stochastic programming (FSP) and fuzzy mathematical programming (FMP) are integrated into a general framework to manage heat supply under uncertainties presented as interval values, random variables and fuzzy sets within a multi-stage context. An actual case study will then be provided for demonstrating how the IFFSP method will support wind power heating system planning under uncertainty. Furthermore, the feasibility of wind power heating project in promoting wind power consumption and relieving wind curtailment is also studied, which could offer some theoretical reference to relevant managers, facilitating the rational development of wind power heating projects.

2. Methodology

2.1. Interval fixed-mix stochastic programming

In general, electric-power system planning problems usually involve in multiple periods (i.e. with dynamic feature), and uncertainties may be expressed as random variables with knowing probability distributions (Li and Huang, 2012). Thus the relevant decisions must be made at each time stage under varying probability levels. To deal with such a dynamic feature, a number of multi-stage stochastic programming (MSP) methods were developed as extensions of dynamic stochastic optimization methods (Takriti et al., 1996; Spangardt et al., 2006; Nolde et al., 2008). Fixed-mix stochastic programming (FSP) is a MSP method, which is based on the simple decision rule of constant rebalancing, and can permit revised decisions in each time stage based on the uncertainty realized so far (Fleten et al., 2002). Fig. 1 shows the structure of FSP, where uncertainties are allowed to be described in terms of outcome streams or scenarios, the nodes represent decisions, while the arcs are for realizations of the uncertain variables. Generally, a fixed-mix stochastic programming model with recourse can be formulated as follows:

$$\max f = \sum_{t=1}^{T} \left(\sum_{j=1}^{n_1} c_{jt} x_{jt} - \sum_{j=1}^{n_2} \sum_{h=1}^{H} p_{th} d_{jth} y_{jth} \right) \quad (1a)$$

subject to: