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An inexact optimization model for regional electric system steady operation management considering integrated renewable resources

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ABSTRACT

In this study, an inexact two-stage stochastic fuzzy programming (ITSFP) is developed for regional power generation planning with considering the intermittency and fuzziness of renewable energy power output. ITSFP incorporates interval-parameter programming (IPP), two-stage stochastic programming (TSP), and fuzzy credibility constrained programming (FCCP) within a general optimization framework which can tackle uncertainties expressed as intervals, probability distributions, and fuzzy sets. The developed method is applied to a regional electric power system over a one-day optimization horizon coupled with air pollution control. The power generation schemes, imported electricity, and system cost under various environmental goals and risk preferences are analyzed. The obtained results indicate that the model can provide a linkage between predefined electric power generation schedule and the relevant economic implications, as well as more reasonable decision alternatives for decision makers by loosening system constraints at specified confidence level. Besides, the fuzziness of forecast error corresponding to the variability of renewable energy resources could be effectively reflected. Moreover, the results are useful for addressing the trade-off between system economy and system risk.

1. Introduction

With the rapid development of economic and prompt growth of population, electric power consumption has been continuously increasing over the past decades. Meanwhile, electric power generation relied primarily on fossil fuels has brought serious environmental problems, such as excess atmospheric pollution discharge, greenhouse gas emission, and water pollution. For example, in China, the electric power industry was responsible for approximately 31.4% of the total SO_2 emissions in 2014, which would be likely to exacerbate air pollution and impose impacts direct and indirect on public health. In recent years, with the increasing severe environmental pollution and aggravated energy shortage crisis, environmental friendly renewable energy is deemed to be the most appropriate option to replace conventional energy resources, which is received more and more attention all over the world. However, there are some crucial limitations existing in the effective development and utilization of renewable energy, such as high levels of variability and uncertainty, low conversion efficiency and time mismatch with load demand for renewable power. Among those questions, the intrinsic intermittence and fluctuation would cause the fuzziness and uncertainty of power output, resulting in difficulty for formulating efficient generation schedules and serious consequences to the dynamic economic dispatch in regional power grid [1–5]. Moreover, in regional electric power systems, varieties of processes corresponding to electricity generation, import/export distribution, as well as economic parameters associated with uncertainties and complexities should be considered by decision makers simultaneously [6–10]. Therefore, it is desired to develop an effective tool for dealing with uncertainties, reflecting better renewable energy operation characteristics, and modeling electric power system management considering pollutants emission control.

Previously, a significant amount of systems analysis techniques were employed for solving those generation scheduling problems. For example, Moura and de Almeida [11] developed a novel multi-objective optimization model for renewable energy system operation management considering demand-side management and response technologies. Considine and Larson [12] developed a

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system economic model for short term power generation technologies switching or substitution coupled with carbon cap and trade by introducing the European Union's emissions trading system. Ippolito et al. [13] proposed a multi-objective optimized management model of electrical energy storage systems for an existing islanded distribution network with renewable energy sources in the Mediterranean Sea. Guo et al. [14] presented an optimal model for power generation dispatch, where wind and coal-fired power generation technologies were integrated in a regional electric power system. Taha et al. [15] developed a bi-level multi-period optimization programming for a micro-grid system operation management under consideration of quasi-feed-in-tariff policy. Jebaraj et al. [16] presented an optimal model for electricity allocation and sustainable resource utilization in India. Based on predicted renewable generation and market information, Chen and Garcia [17] developed a generic methodology for the operations optimization of hybrid energy systems. Álvarez-Miranda et al. [18] proposed a novel scenario-based approach for wind power generation management, where dynamic characteristic of forecasting process and robust unit commitment policies were taken into account. Yuan et al. [19] developed a hybrid model for a short-term wind power forecasting based on the least squares support vector machine, which was optimized using gravitational search algorithm.

In addition, in order to tackle the interrelated complexities existing in the electric power system, especially the uncertainties for renewable energy resources, a series of inexact optimization approaches have been developed in recent years, that include interval-parameter programming, stochastic mathematical programming (e.g. two-stage stochastic programming, multi-stage stochastic programming, stochastic robust programming, chance-constraint programming), fuzzy mathematical programming, and interacted methods [20–23]. Among these methods, interval two-stage stochastic programming (ITSP) model, incorporated interval-parameter programming (IPP) and two-stage stochastic programming (TSP), is a potential approach for electric power planning and receive much attention [24–26]. It can handle multiple uncertainties expressed as discrete intervals and known probability distributions in a model's both sides and achieve management strategy adjustment after real events happened. Moreover, ITSP method could provide an effective way for tackling decision problems, where synthetic analysis of different policy scenarios is desired. For example, Chen et al. [27] proposed a two-stage inexact-stochastic programming model for CO_2-emission trading management. However, in a coupled traditional and renewable power generation system, the fluctuation of wind and solar power output poses a grave threat to electric power dispatch, wherein power load forecast is extremely expected [28]. In general, due to the lack of long time sequenced climate and meteorological information, load forecast are usually estimated by fuzzy information with different confidence levels through analyzing large scale meteorology data. In addition, forecast error would appear unavoidably in the forecasting process, and should be incorporated into generation scheduling process by decision makers to reduce its effect. However, ITSP method could not adequately reflect those characteristics of renewable power generation, and bring forecast errors into the optimization model. The drawback would lead to the loss of vague information as well as unreliable solutions when dealing with electric power generation scheduling problems, especially in traditional and renewable power generation system.

Fuzzy credibility constraints programming (FCCP) is a generally accepted fuzzy mathematical programming method that can tackle uncertain information identified as fuzzy sets within a measure of confidence level [29]. It would not only help decision makers to quantitatively evaluate trade-offs between economic objectives and system risks existing in the dispatch scheduling process, but also provide compromising schemes for managers regarding the safety of fuzzy constraints with various credibility satisfaction level. Especially, it is a novel method for reflecting the fuzziness of forecast error in decision-making. FCCP had been successfully applied in many real-world practices, which was mostly attributable to its advantages in capturing the ambiguous uncertainties and enlarging the uncertain decision space. For example, Ji et al. [30] proposed a hybrid inexact stochastic-fuzzy chance-constrained programming for pollutants and CO_2 emissions management in a regional micro-grid system over a one-day horizon. Rong and Lahdelma [31] presented a fuzzy chance constrained linear programming model for scrap charge optimization of steel production. Based on integer fuzzy credibility constrained programming method, Zhang et al. [32] advanced an inexact optimization model for regional power system management. Nevertheless, FCCP method has limitations in tackling uncertain parameters that exist in the model's left-hand sides and coefficients, and reflecting the random characteristics in electric power generation system. One potential approach is to integrate ITSP and FCCP method within a general optimization framework to handle these issues.

Therefore, the objective of this paper is to develop an inexact two-stage stochastic fuzzy programming model for regional electric power system steady operation management considering pollutants emission control, which will incorporate interval-parameter programming, two-stage stochastic programming, and fuzzy credibility constrained programming. It can effectively address uncertainties expressed as interval parameters, probability distributions, and fuzzy sets. In the model, the fluctuation for renewable power output can be incarnated as the fuzziness of forecast error by transforming the fuzzy credibility constraints into their crisp equivalent forms. The model will be applied to a planning of power generation scheduling in regional electric power system over a one-day horizon under consideration of air pollutant control and renewable energy power applications. The modeling results can help decision makers acquire multiple optimal alternatives and applicable solutions, and also gain a comprehensive trade-off between system economy and reliability risk.

2. Methodology

2.1. Interval two-stage stochastic programming

Two-stage stochastic programming (TSP) is available for handling problems where an analysis of different policy scenarios is conceivable and uncertain coefficients are random with known probability distributions. A TSP model can be described as follows [33]:

$$\min\ f = C_{T_1}X + \sum_{h=1}^{s} p_h D_{T_2} Y \tag{1a}$$

subject to:

$$A_r X \le B_r,\ \ r\in M, M = 1,2,\dots,m_1 \tag{1b}$$

$$A_i X + A_i^{'} Y \ge \tilde{w}_{ih}, i\in M; M = 1,2,\dots,m_2; h = 1,2,\dots,s \tag{1c}$$

$$x_j \ge 0,\ \ x_j\in X, j = 1,2,\dots,n_1 \tag{1d}$$

$$y_{jh} \ge 0,\ \ j_{jh}\in Y, j = 1,2,\dots,n_2; h = 1,2,\dots,s \tag{1e}$$

where x_j and y_{jh} represent the first- and second-stage decision variables, respectively; $C_{T_1}X$ denotes the first-stage costs or