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Multi-objective unit commitment with wind penetration and emission concerns under stochastic and fuzzy uncertainties

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ABSTRACT

Recent years have witnessed the ever increasing renewable penetration in power generation systems, which entails modern unit commitment problems with modelling and computation burdens. This study aims to simulate the impacts of manifold uncertainties on system operation with emission concerns. First, probability theory and fuzzy set theory are applied to jointly represent the uncertainties such as wind generation, load fluctuation and unit outage that interleaved in unit commitment problems. Second, a Value-at-Risk-based multi-objective approach is developed as a bridge of existing stochastic and robust unit commitment optimizations, which not only captures the inherent conflict between operation cost and supply reliability, but also provides easy-to-adjust robustness against worst-case scenarios. Third, a multi-objective algorithm that integrates fuzzy simulation and particle swarm optimization is developed to achieve approximate Pareto-optimal solutions. The research effectiveness is exemplified by two case studies: The comparison between test systems with and without generation uncertainty demonstrates that this study is practicable and can suggest operational insights of generation mix systems. The sensitivity analysis on Value-at-Risk proves that our method can achieve adequate tradeoff between performance optimality and robustness, thus help system operators in making informed decisions. Finally, the model and algorithm comparisons also justify the superiority of this research.

1. Introduction

As one of the most important optimization problems in power systems, UC (unit commitment) aims to maximize supply reliability and minimize generation cost by properly arranging the commitment and output of each unit. Conventional UC were normally modeled as deterministic problems and various authentic solutions have been developed, such as priority list, Lagrangian relaxation and mixed integer programming. Recent challenges caused by the ever-increasing penetration of renewables such as wind power raise salient difficulties in solving modern UC under manifold uncertainties that exist in both supply and demand sides [1].

To handle the above uncertainties, recent researchers have developed various effective techniques, which can be categorized into two groups: stochastic UC optimization (stochastic UC) and robust UC optimization (robust UC). Stochastic UC utilizes scenario-based uncertainty representation in formulation [2], and has been recommended as a suitable tool to tackle many UC problems. In the literature, a lot of stochastic methods have been proposed, for example, Gooi et al. introduced the concepts of ELNS (expected load not served) and LOLP (loss-of-load probability) to evaluate system performance in stochastic environment [3]. Vazquez and Kirschen applied the ELNS and LOLP to measure the reliability under unit outage uncertainty, while an off-line method for determining the SR (spinning reserve) was utilized prior to the conventional dispatch to prevent load shedding [4]. Similarly in Refs. [5], the ELNS was also considered as a probabilistic criterion when estimating UC solutions. Especially, the authors used operating reserve facility to jointly represent the interruptible load and SR. Recently, Trivedi et al. constructed a multi-objective stochastic programming which minimizes the operation cost and maximizes the supply reliability simultaneously [6]. In addition, the load uncertainty was incorporated by using a seven-step approximation of the Gaussian distribution of future load. Although the aforementioned studies shows certain advantages of cost saving and reliability improvement when comparing with deterministic models, the generation

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Acronyms

UC	Unit commitment
VaR	Value-at-Risk
ELNS	Expected load not served
LOLP	Loss-of-load probability
LLNS	Largest load not served
SR	Spinning reserve
SOs	System operators
ORR	Outage replacement rate
CPM	Cumulative probability method
PL	Priority list
DPL	Descending order of PL
PDF	Probability density function
W-MOUC	Wind penetration-based multi-objective UC
PSO	Particle swarm optimization
MOPSO	Multi-objective PSO
FS-MOPSO	Fuzzy simulation-based MOPSO
DT	Dominance times

uncertainty of renewables has not been considered. In view of significant wind penetration in modern power systems, Tuohy et al. employed scenario trees to represent the stochastic nature of wind and studied the impact of planning the system more frequently to account for updated wind and load forecasts. Experimental results show that the proposed method outperforms conventional deterministic optimizations [7]. Ji et al. applied scenario generation and reduction technique to simulate the wind power uncertainty and developed a quantum-inspired binary gravitational search algorithm to solve the proposed UC model. The effectiveness of this study is verified via comparisons between test systems with and without wind integration [8]. Papavasiliou and Oren investigated the supply systems that involve large-scale wind generation, where transmission constraints as well as component failures are addressed in modelling. And, a scenario selection and decomposition algorithm was designed to solve a realistic UC optimization [9].

Although stochastic UC provides an effective way to handle the uncertainty, there are still some problems and barriers to be resolved [2]: 1) Exact probabilistic information on each uncertain parameter is critical for the stochastic model but may not be obtained easily. Especially, some type of uncertainties such as wind speed and future load are determined by various factors, while expert knowledge could be incorporated with available data information to improve the forecasts [10]. 2) Computational burden restricts the practical implementation of stochastic UC in large-scale power systems, especially when various uncertainties should be addressed. 3) Stochastic UC models seek for the optimal expected value, thus ignore the system robustness which is of importance to the operation of power systems. To tackle these shortcomings, robust UC models have been studied extensively in recent years. Compared with stochastic UC, robust UC aims to capture ambiguity by using uncertainty sets, and robust programming is carried out to minimize the worst-case cost regarding any realization of the uncertainty sets [2]. Therefore, robust UC is capable of hedging against uncertainties, but probably lead to a very conservative decision, which will incur an expensive operation cost. In order to enhance the tradeoff between optimality and robustness, recent studies mainly improve robust UC from two aspects: the development of two-stage robust UC models and the construction as well as operation on the uncertainty sets. In contrast to single-stage robust UC models, two-stage models are less conservative as it essentially offers SOs (system operators) a recourse opportunity [11]. Over the last few years, a lot of two-stage robust UC formulations were proposed to ensure a reliable generation scheduling [12]. From uncertainty set perspective, the notion of a budget on uncertainty is utilized to balance cost and reliability by improving the definition and/or adding significant constraints to bound the uncertainty sets [2]. For example, considering the sophisticated uncertainty of renewable generation, An and Zeng utilized various subsets to jointly define an uncertain factor, where each subset is assigned to a weighted coefficient [11]. In *N-k* contingency models [13], the maximal allowance of equipment failures can be varied to adjust the budget of uncertainty easily. Similarly, the total number and span of wind generation cases defined in Ref. [14] can be updated as well to achieve a more reliable solution.

Unfortunately, SOs are also in doubt about the efficacy of the robust UC-based approaches. On one hand, extreme scenarios play a pivotal role in robust UC; on the other hand, the uncertainty sets are distribution-free and indifferent to any realization, which results in a loss of data information and/or expert knowledge that the original uncertain variables carry [15]. Therefore, due to the nature of robust UC, the decision may bear underlying conservativeness. For instance, conservative UC scheduling generally requires a large amount of SR from thermal units, which not only increases the operation cost but also makes the system deviate from the ambitious carbon emission control target.

Motivated by above discussion, this study proposes a day-ahead hourly UC optimization model with wind penetration, which contributes to existing literature from the following aspects: Firstly, the uncertainties due to unit outage, load forecast error and wind generation are characterized by using probability theory and fuzzy set theory respectively. Especially, a convenient way to describe wind speed as fuzzy Weibull distribution is provided. This modelling treatment allows us to utilize the data information and expert knowledge to the best. The detailed motivations and advantages of using these two mathematical tools are presented in next section. Secondly, a unified reliability measurement based on VaR (Value-at-Risk) measure is employed to evaluate comprehensive supply reliability under aforementioned uncertainties. Generally, VaR represents the greatest loss under a predefined confidence level, which has been widely-used in various engineering problems including power systems. For example, Wang et al. utilized fuzzy VaR to measure the supply reliability under load forecast and unit outage uncertainties [16]. Huang et al. established conditional VaR as the risk index of loss of loads [17]. The details of this measurement to our problem is provided in late portions. Thirdly, emission cost is also addressed in the proposed model, since environmental concern is an increasingly important factor in designing power systems, and a number of countries and regions have set carbon reduction targets. Compared with previous work which calculate emission cost by using a quadratic function [16], this research takes the cost as two parts: One is the capital paid to normal emission treatment; the other is the cost or revenue from market trading incurred by carbon emission control. Theoretically speaking, the computation result is more realistic and the method is in accordance with recent development of power systems, especially in China. Finally, considering that some SOs could be interested in the inherent conflicts between cost and reliability, and they may want a recourse opportunity to select a UC scheduling that satisfies the system best after analyzing various feasible solutions, we develop a multi-objective UC model (W-MOUC), and design an improved FS-MOPSO (fuzzy simulation-based multi-objective particle swarm optimization) algorithm to handle the operation cost and supply reliability simultaneously. The effectiveness of the improved algorithm is justified on benchmark problems, which is presented in Section 4.2.

The rest of this paper is organized as follows: In Section 2, we