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GPNBI inspired MOSDE for electric power dispatch considering wind energy penetration

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This paper aims to solve wind energy integrated electric power dispatch (EPD) problem from the perspectives of stochastic modelling and multiobjective optimization. At first, the competing objectives in modern electric power and energy system is analyzed and a new interval optimization model for each objective is proposed based on the uncertainties with respect to wind power. Then, a novel strength differential evolution (SDE) algorithm is developed to address the interval optimization model. The SDE adopts a population selection process based on chaotic sequence and Boltzmann distribution to balance the tradeoff between local exploitation and global exploration. Afterwards, a multiobjective EPD model is established and a novel generalized piecewise normal boundary intersection (GPNBI) method is mooted to transform multiobjective EPD into a series of single-objective sub-problems which can be effectively solved by SDE. In order to deal with the highly constrains in GPNBI, a new heuristic constraint handling strategy is proposed accordingly to accelerate the convergence speed. At last, a hyper-plane based decision-making strategy is originally developed to identify the best compromise solution in the obtained Pareto frontiers (PFs). The feasibility and effectiveness of the interval optimization model and GPNBI inspired multiobjective SDE (MOSDE) have been comprehensively evaluated on a modified IEEE 30-bus system and a 118-bus system. The statistical results confirm that the proposed interval optimization model can approximately quantify the potential uncertainty in each objective and also demonstrate that the proposed MOSDE exhibits better performance than the algorithms of the state. Therefore, it is convinced that the proposed optimization model and method have high potentials to address the practical implementation problems in electric power and energy systems with wind energy penetration.

1. Introduction

Electric power dispatch (EPD) is one of the most significant issues for the operations of electric power and energy systems. In general, EPD is targeted to optimally allocate predicted system load among multiple generators at a specific objective function, usually the fuel cost, subjected to transmission and operational constraints [1]. Conventional EPD problem concerns only on thermal generators that make use of depletable resources such as fossil fuel, which would more or less cause environmental pollutions. Therefore, in recent years, renewable energy has undertaken an unexpected worldwide growth to reduce the environmental effect [2]. Among the renewable resources, wind energy is the most promising and potential alternative and its penetration in power system is continuously increasing than ever due to the involved low capital cost and operational cost, and plentiful primary resources. The increasing penetration of wind energy becomes to reshape the paradigm of system operation and poses several practical issues for EPD problem, which has attracted much attention from industry as well as academia in recent years.

On one hand, due to the chaotic nature of the weather system and climate change, wind energy always exhibits strong randomness and stochastics that will no doubt result in a high level of uncertainty for EPD. This is because when operators determine a dispatch solution, they would consider the uncertainty of wind power forecasting during the entire dispatching cycle [3]. Thus, the uncertainties in wind power forecasting have brought significant

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challenges to power system dispatch, as a result of which stochastic EPD has become a hot research spot. On the other hand, system operations have some common goals that conflict with each other. The improvement of one goal may degrade the performance of other goals. Therefore, multiobjective EPD (MOEPD), that aims to find a set of evenly-distributed Pareto optimal points to meet any particular requirements [4], has also attracted much attention. From these two aspects, this paper addresses wind energy penetrated optimal EPD problem from the perspective of stochastic modelling and multiobjective optimization.

Stochastic modelling is generally applied to evaluate the impacts of wind power uncertainties on EPD. In Ref. [5], a day-ahead stochastic power system dispatch model considering demand response and wind power of residential hybrid energy system was developed and verified on a modified IEEE 118-bus system. In Ref. [6], stochastic programming approach was used in unit commitment with security constraints to evaluate the uncertainties of wind energy. In Ref. [7], the uncertainties of wind power and system incidents were considered in stochastic optimization model with frequency constraints so as to make sure that the dispatch solution meets the requirement of frequency stability. In addition, the studies in Refs. [8,9] contribute to counteract the uncertainties in renewable energy resources and electric load by dispatching thermal plants. As a matter of fact, wind power can be probabilistically forecasted within an interval with upper and lower bounds under a specific confidence level [10]. Hence, it is reasonable to conclude that the solution of EPD with wind energy would be varied within interval bounds. Therefore, the uncertainties in EPD could be approximately quantified by using interval optimization. The upper and lower bounds of interval optimization can be modeled as two independent single objective EPD (SOEPD) subproblems. In reality, interval optimization has been applied in unit commitment [11], household load scheduling [12] and optimal unit sizing of integrated energy system [13]. However, in EPD, interval optimization was generally paid little attention [14].

The primary issue of multiobjective optimization is to generate a family of Pareto points as uniformly as possible [15]. One feasible solution for the issue is to make use of Pareto evolutionary algorithms, such as strength Pareto evolutionary algorithm (SPEA) [16], nondominated sorting genetic algorithm (NSGA) [17], NSGA-II [18] and multiple group search optimization (MGSO) [15]. In Ref. [19], a multi-objective optimization algorithm based on learning automata was proposed for economic emission dispatch, and a competitive performance was achieved. In Ref. [20], a generalized framework based on gravitational search algorithm was developed to simultaneously optimize the fuel cost and emission. In Ref. [21], a novel flower pollination algorithm was mooted to solve the environmental/economic hydrothermal scheduling problem and its feasibility and effectiveness were numerically demonstrated. These Pareto evolutionary algorithms operate on a group of nondominated solutions which are further optimized using diverse search mechanisms in a single simulation cycle. The most significant demerit of Pareto evolutionary algorithms is that they cannot produce even PFs with high-quality because they may get clustered stochastically, and are, therefore, far from successful in solving MOEPD. In practice, another valid way to generate uniform PFs is to transform MOEPD into a series of single objective optimization (SOO) sub-problems through scalarization methods, such as weighted sum (WS) [22], normalized normal constraint (NNC) [23] and normal boundary intersection (NBI) [24]. In Ref. [25], economic-emission dispatch problem was approximated as a polynomial multi-objective model and then solved by a nonlinear weight selection approach. In Ref. [26], a piecewise NNC method was proposed to minimize the voltage deviation and active power loss in an AC-DC hybrid system. In Ref. [27], two-layers multiobjective optimal bidding model was established. The upper level model optimizes the individual supplier payoff and lower level deals with the market clearing problem. This hybrid multiobjective model was solved by using normal boundary intersection method. However, the uniformity of PFs obtained from these scalarization methods varies with the surface shape of the created PFs [28], and thus the ability of these methods to generate an evenly-distributed PFs is, to some extent, hugely limited. Recognizing this limitation, one of the goals of this research is to develop an enhanced scalarization algorithm to generate more evenly-distributed PFs. Consequently, MOEPD is converted to a set of SOEPD sub-problems.

From above analysis, it can be seen that both the interval optimization and multiobjective optimization for EPD can be modeled as SOEPD problems. Up to date, mathematical programming techniques and modern heuristic algorithms have been reported as two typical methodologies in the literatures to fulfill the SOEPD task. However, the cost function in real life's generating units turns to be non-smooth and non-convex due to the valve-point effect [29] and prohibited operating zones (POZ) [30]. Thus, conventional mathematical programming methods cannot be directly implemented to solve the real world's SOEPD problems because of the required convex properties of the cost function [31]. Consequently, as an alternative to mathematical programming methods, various heuristic algorithms, e.g., particle swarm optimization (PSO) [31], genetic algorithm (GA) [32], differential evolution (DE) [33], and soft-computing based hybrid approaches [34,35], have been implemented to solve the SOEPD problem with high-efficiency. In Ref. [36], a hybrid framework combining firefly algorithm and bat algorithm was proposed to solve the combined economic/environmental problem. In Ref. [37], a hybrid grey wolf optimizer was proposed to deal with the economic dispatch problem with nonlinear and discontinuous objective. Among these algorithms, DE adopts non-uniform crossover and mutation operators, and meanwhile exploits arithmetical difference of selected vectors to incrementally optimize the candidates. In addition, DE has fewer parameters to be optimized and can thus be easily implemented. These specifics endow DE with rotational invariance and self-adaption, making DE to be more robust and efficient than other heuristic algorithms [38]. Hence, DE is recommended to be implemented in real-life's optimization problems. However, standard DE appears to stage at the fine-tuning process due to the diversity of differences and thus may fail to provide satisfactory global optimal solutions when applied to real world's problem with numerous local peaks [34,38], such as SOEPD. To overcome this drawback, many modified DE, like interior-point assisted DE [39], integer-programming based DE [40], chaotic DE [41], proximity based DE [42], have been reported.

Therefore, this research is devoted to investigating DE based interval optimization and multiobjective optimization methodologies for EPD issue with wind energy penetration. Compared with existing studies on similar topics, the contributions of this paper are mainly summarized as below. First, a new interval optimization model is proposed to determine the variation bounds of each optimization objective under a given confidence level. These bounds are modeled as a dual nonlinear programming problem subjected to wind power uncertainty. Second, a novel heuristic algorithm, termed as SDE, is developed to solve the SOEPD task. The SDE algorithm employs chaotic sequence and Boltzmann distribution to facilitate global exploration and local exploitation. Third, a GPNBI inspired MOSDE algorithm that can produce evenly-distributed PFs, is originally proposed. The GPNBI method is applied to transform MOEPD into a set of SOEPD sub-problems. In addition, a stochastic constraint handling strategy is integrated in MOSDE to speed up the convergence rate, and a hyper-plane based