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Risk constrained stochastic economic dispatch considering dependence of multiple wind farms using pair-copula

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HIGHLIGHTS

- A stochastic economic dispatch model for wind power comprehensive uncertainties.
- A pair-copula method for the complicated dependence among multiple wind speeds.
- A predefined level of confidence interval for a scenario set of wind power.
- Considering economic risk to better accommodate large fluctuations of wind power.

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ABSTRACT

With higher and higher penetration of wind power into power systems, dependence among the wind speeds of different wind farms should be considered when modeling the wind power outputs. In this paper, a novel pair-copula method is applied to formulate the dependence of multiple wind farms. A large number of stochastic scenarios, in which the complicated dependence of multiple wind farms are considered, are generated to represent the uncertainties of wind power based on quasi-Monte Carlo (QMC) simulations. To find an optimal dispatch solution, a risk constrained mean-variance (MV) model is constructed for the stochastic economic dispatch (SED) problem. The MV model considers economic cost and economic risk under the uncertainties of wind power simultaneously, among which economic risk is calculated by means of least variance of fuel cost. Moreover, with the probability density function (PDF) obtained for fuel cost, a predefined level of confidence interval is proposed to improve the MV model to acquire more practical dispatch solutions. For solving the multi-objective SED problem, group search optimizer with multiple producers (GSOMP) is employed in this paper. The effectiveness of the proposed pair-copula method and the improved MV model are validated via numerical simulations with a modified IEEE 30-bus system.

1. Introduction

The penetration of wind power into power systems has increased rapidly in recent years, and the randomness and fluctuation of wind power generation have brought great challenges to the safe and stable operation of power systems, including unit commitment, power dispatch, reserve deployment and reliability analysis, etc. Therefore, it is urgent for system operators to take the uncertainties of renewable energy sources (RESs) into account to search for a robust dispatch strategy [1–5]. Traditional economic dispatch, also known as deterministic dispatch, is a commonly used dispatch solution in which RES outputs are assumed to be a certain value forecasted between dispatch intervals. However, deterministic dispatch becomes less attractive because it neglects the significant variability and intermittent of RESs. To deal with the uncertainties, system operators have to deploy excessive reserve capacity which will certainly result in substantial extra cost. In order to better accommodate the large fluctuations of RES outputs and maintain the reliability of the power system, recent studies have proposed three mainstream methods, the fuzzy optimization dispatch, the robust optimization dispatch and the stochastic economic dispatch (SED), to improve the schedule of generating units [6–10].

Fuzzy optimization generally converts the uncertainty into min-max problems, but the membership function is too subjective to represent the uncertain situation. Robust optimization dispatch is often over-conservative since the solution is obtained based on the most unfavorable circumstance. It promotes the robustness at the expense of

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economy, however, extreme cases hardly take place in practice. Different from the former two, SED considers scenario-based uncertainties in the traditional ED problem to find the optimal solution [11–13]. The more scenarios are contained in the scenario set, the more cases of uncertainties can be involved in the SED problem which is characterized by its stochastic uncertainties.

Therefore, a large number of stochastic scenarios should be generated to represent the randomness of RES outputs. Each scenario has a unique configuration on RES outputs that are sampled according to their probability density functions (PDFs). Niederreiter and Harald in [14,15] proposed the quasi-Monte Carlo (QMC) method to yield low-discrepancy sequences, avoiding the probabilistic error between approximate sequences and real sequences as well as reducing the computational complexity. Papers [16–18] put forward the Sobol sequence and further verified the advantages of QMC in generating uniformly distributed sequences. Thus, the stochastic scenarios based on the generated high quality sequences can better trace the uncertainty of RES outputs.

In this paper the uncertainty under research mainly targets at the randomness of wind power. Traditional ways of modeling wind power rarely pay attention to the dependence among wind farms, and the wind speeds of different wind farms are generally supposed to be independent to one another [19–21]. However, as the penetration of wind power increases, dependence among wind farms becomes more and more complicated and should not be neglected. Otherwise, it will result in power imbalance, increase the operational risk of power systems and cause unexpected high operation cost. Therefore, it is necessary to formulate the dependence among wind speeds of multiple wind farms. According to the linear invariance rule of Gaussian mixture model, Wang in [22] found the joint distribution of the transmission line power regardless of the correlated and non-Gaussian power outputs of multiple wind farms. However, the relationship between the transmission line power and wind power output is generally non-linear and difficult to describe with coefficient vectors. For [23], based on the vine-copula theory, the authors proposed a versatile model using advanced statistical modeling to model the spatiotemporal dependence of multiple wind generations. However, they did not study the tail behavior of multivariate and the choice of different copula functions for each tree. Paper [24] proposes the ninth-order polynomial normal transformation to formulate the dependence, however, the transformation can only be used to represent linear dependence while the non-linear or tail dependence features are ignored. In [25], Usaola modeled the dependence through the dependence matrix of multivariate normal variables in a similar way as Nataf transformation that was proposed in [26], assuming the wind power is subject to normal distribution. Xie et al. in [27] used copula functions to formulate the stochastic dependence between wind farms. However, the aforementioned methods either capture only the symmetrical dependence of multiple wind farms, or fail to describe the tail behavior, which means they are not accurate enough to model the wind power outputs. In fact, the dependence among wind farms are always asymmetrical and complicated. Archimedean copulas have a better performance in formulating complicated dependence of variables [28]. However, Guzman in [29] concludes that as the number of wind generators increases, the multivariate Archimedean copulas perform worse than Gaussian copula. Paper [30] illustrates that Archimedean copulas are inefficient in high dimensions, for they need to compute the nth order successive derivation of the copula distribution when modeling the dependence structure of n-dimensional vector [31]. To make up for the deficiency, the pair-copula method, which specializes in high dimension dependence analysis, is employed in this paper to build the joint distribution model of the wind speeds of multiple wind farms to represent the complicated mutual dependence [32,33].

With the integration of wind power, economic cost varies from scenario to scenario with a chosen scheduling strategy. In [34], risk is regarded as the variance of fuel cost and the mean-variance (MV) model not only pays attention to the economic cost, but also attaches great importance to the economic risk brought by the uncertainties of wind power. Therefore, risk constraints should also be taken into account when seeking the optimal dispatch solution in SED. Meanwhile, inspired by [35], confidence interval constraint is proposed in this paper. Some extreme scenarios corresponding to unusually high or low fuel cost rarely happen. If such scenarios are all considered in the optimization model, it will certainly have a negative impact on the choice of the optimal dispatch solution. As a result, to improve the MV model, a predefined level of confidence interval is applied to the PDF of fuel cost to yield an appropriate scenario set that will be evaluated in SED. The scenario set can be changed in cardinality by varying the confidence level to adjust conservativeness of system security. Afterwards, the group search optimizer with multiple producer (GSOMP) is employed to solve the multi-objective optimization of the improved MV model [36,37].

The main contributions of this paper include:

- The SED model is proposed in this paper to fully take the comprehensive uncertainties of wind power into account. Pair-copula method is carried out to formulate the complicated dependence among wind speeds of different wind farms to acquire more accurate results.
- Economic risk is taken into consideration in this paper when searching for the optimal dispatch solution, in terms of realizing the minimal expectation and variance of fuel cost.
- In the SED optimization, the optimal solutions might be over-conservative under the influence of extreme scenarios. In this paper, a predefined level of confidence interval is applied to the PDF of fuel cost to yield an appropriate scenario set before dispatch solutions are obtained by the MV model. In this manner, the obtained results become more practical.

The rest of the paper is organized as follows: Section 2 models the dependence among the wind speeds of multiple wind farms based on pair-copula. Section 3 elaborates the objective functions of the SED problem, formulates SED as multi-objective optimization with the risk constrained improved MV model, and obtains the Pareto fronts by GSOMP. The simulation studies are presented in Section 4. Finally, the last section draws the conclusion of this paper.

2. Modeling the dependence among wind farms based on pair-copula

2.1. Pair-copula construction

A copula function provides a flexible and intuitive way to build the joint distribution of multiple random variables, as illustrated in Sklar's theorem [38]. For every n-dimensional distribution function F, with univariate marginal distributions $F_i(x_i)$, $i = 1, ..., n$, there exists a unique copula function C if all marginal distributions are continuous, which is formulated as:

$$F(x_1, x_2, ..., x_n) = C(F_1(x_1), F_2(x_2), ..., F_n(x_n)) \tag{1}$$

where $F(\cdot)$ is the joint cumulative distribution function (CDF) of the n-dimensional vector $[x_1 \ldots x_n]$, and $C(\cdot)$ is the copula function that describes the dependence of the multi-variables, it is also denoted as the copula distribution function.

To formulate the dependence among wind speeds of multiple wind farms, we have to choose an appropriate copula function for the n-dimensional vector $[u_1 \ldots u_n]$, in which u_i is the abbreviation of $F_i(x_i)$, representing the marginal distribution of wind speeds in the i^{th} wind farm. Fig. 1 shows the family tree of copula functions, in which elliptical copulas can only describe the specific symmetric dependence characteristics. Thus, it is difficult for them to model the wind speeds of multiple wind farms accurately since the dependence among them