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A framework for uncertainty quantification and economic dispatch model with wind–solar energy

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ABSTRACT

More and more renewable energy generations are being connected to power system, such as wind power, solar power, together with the load forecasting deviation, so there is a growing need to study impacts of multiple different uncertainties on system. It is important that operators understand how these stochastic characteristics of uncertainties affect the stable operation of power system. In this paper, the combinations of uncertainties that are power fluctuation due to forecasting deviation of wind speed, solar radiation and load. Framework is established including joint probabilistic models of several uncertainties and the risk models of load shed under two different scenarios. An economic dispatch model considering unit commitment is proposed to minimize the generation cost and operational cost and starting-up cost of conventional power units, combined heat and power (CHP) units and heat-only units. However, high/low risk of load shed does not represent large/small of load loss in fact, thus the load loss is defined as multiplying of load shed risk and load loss amount, which is described by methodology of *α-superquantile*. Effectiveness of proposed model is examined by case studies and the numerical results are presented.
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Introduction

Wind power and solar power would be the most promising renewable resource throughout the world, are expected to be used more in the future, so as to replace conventional generation and reduce greenhouse gas emissions. However, the wind or solar leads to increased variance and uncertainty in net load, and also the higher operational cost will be faced [1]. However, a high penetration levels, the variability of wind and solar power sources can severely impact utility reserve requirements, so operators would face considerable challenges in satisfying load demand and maintaining the stable and reliable operation of power system [2].

Power fluctuation of wind power and solar power and load because of forecasting deviation would have great impact on the online dispatch of power system. According to [3], above discussed uncertainties could be identified as stochastic uncertainties rather than the non-stochastic uncertainties. Different uncertainty would have different level impact on security-economic operation of power system. In context of economic dispatch with renewable energy generation, there are many works focusing on this problem, the objective of optimal model was to minimize the total generation cost of units, subject to constraint of power balance and other system constraints. In [4], generation scheduling model considering the forecasting deviation of wind energy, solar energy and load is established, in addition to power balance equations and spinning reserve (SR) requirements, it also includes air emission limits and available water from each reservoir in storage and so on. Xian Liu [5] has developed an economic load dispatch model to minimize the emission considering thermal generators and wind turbines, and the effects of wind power on emission control are studied. David [6] proposed unit commitment chance-constrained optimization problem that is formulated subject to stochastic demand for energy scheduling and SR, and the optimization problem was transformed into deterministic mixed integer programming to solve. Recently, many other methods based on artificial intelligence have been proposed for solving economic dispatch problems, such as improved PSO [7], the fuzzy adaptive chaotic ant swarm optimization [8] and cuckoo search algorithm [9] and so on.

As future power systems may include a number of different intermittent power sources, such as wind power and solar power generation, it is interesting to study the effect on combined dispersed power outputs from such combinations. J. Widén [10] has considered the correlations between solar and wind power sources, which provided an important study direction such as

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economic dispatch and quantification of SR of power system integrating renewable energy power generation. Besides, relationship between wind power output and electricity demand is studied by G. Sinden in [11]. H. Park [12] has also considered the uncertainties of wind availability and system load, the approximation of continuous random variables is replaced with a finite number of discretized approximations, but joint probability distribution is not given. D. A. Halamay [13] and H. Lund [14] considered the variability of wind, solar and ocean wave power generation, and their characteristics of each power generation were introduced in detail, the combination of different sources was studied on the impact of power system, but the correlations of different power source are not involved. In fact, wind power, solar power and net load are correlated throughout an electrical network. A. Safdarian [15] has considered three types of uncertainties of wind power, solar power and system load, and proposed a framework to optimize the hybrid capacities of wind and solar energy resources in a power system, Monte Carlo simulation method is adopted to generate a set of discrete scenarios for all above uncertainties. But none that investigates the correlations of wind power, solar power and net load affecting the economic operation of power system in detail.

Uncertainty of power system increases operation risk largely, so the operators must ensure adequate operating SR to maintain reliable load supply. In order to evaluate impact of uncertainty on power system, in recent years, the method of conditional value-at-risk (CVaR) has been a wide research and application in financial risk assessment and now in electric market. In [16], a risk-constrained electricity procurement model is established, in which risk is expressed using method of CVaR. The model allows different risk preference customers to decide their optimal hedging strategies. In [17], it focuses on assessment of price risk, and presents hedging instruments to manage market price risk for suppliers, distributors and traders. R. G. [18] has quantified risk for bidding strategies in a day ahead market with respect to expected profit, and [19,20] have also used method of CVaR to deal with price uncertainties as a risk measure in optimization problem. Therefore, CVaR method can be used in electric market for risk assessment widely, the reason is that it can reflect a potential loss exceeds the value-at-risk, and it is more tractable in portfolio optimization. Most importantly, CVaR method can convert the nonlinear constraints of optimization problem into linear constraints, which is advantage to solve optimization model. However, CVaR method has also limitations for usable range, which could not portray all uncertainties in engineer problem. Thus R.T.Rockafellar has presented *superquantile* in 2009, which was suggested to deal with the general risk uncertainty problem of engineering application [21], such as the stability and reliability uncertainty problem of power system. The combination of different uncertainties affect stable operation of power system is more complex, but *super-quantile* method could quantify risk stable and reliable problem in electrical engineering effectively.

Based on the references researched uncertainties of renewable energy generation on economic operation of power system, the uncertainties of wind, solar power and load forecasting deviation have been studied individually, but it is few to consider the combinations of above uncertainties in a paper, let alone study relationship of uncertainties and their impacts on economic operation of power system. In this paper, it would propose a risk-constrained economic dispatch strategy considering the combination of wind power, solar power and load forecasting deviation. Specifically, the joint probabilistic models and load shed risk models are established under different typical scenarios, the method of α-*superquantile* is utilized to change the chance-constrained into linear programming constraint, so as to reduce computational effort of the complex economic dispatch model of power system.

The rest of paper is organized as follows. α-*superquantile* method is introduced in Section '*Superquantile* as risk measures'. Sections 'The probability distribution of uncertainty' and 'Risk model of typical mode' propose joint probabilistic model of combination of different uncertainties and risk models of load loss. Then the economic dispatch model with uncertainty is proposed in Section 'Problem formulation'. In Section 'Case study and result analysis' case studies is implemented to analyze the validity of proposed model and method, Section 'Conclusions' concludes this paper.

Superquantile **as risk measures**

Superquantile definitions

Comparing with the Value-at-risk (VaR), CVaR method could measure the potential losses exceeding VaR. By calculating the mean of the loss exceeding the VaR value, CVaR provides a better indication of the potential losses exceeding the assumed confidence level. So CVaR is utilized to provide quantification for a company portfolio exposure to the risk in financial industry, which have been studying many years [16,19]. To quantify different types of uncertainties in engineer problem conveniently, R.T.Rockafellar and J.O.Royset presented *superquantile* method first time in 2009 [21], which was proposed application-independent named α-*superquantile*, and it was suggested to deal with risk uncertainty problem of other engineering application, such as the security and stable operation engineering problem of power system.

Let $g(x,U):R^n \times R^m$ be a loss function depending on decision vector $x \in R^n$ and the random vector $U \in R^m$, and it is assumed that the probability distribution of vector U is $p(U)$. So the probability of $g(x,U)$ not exceeding a threshold a is written

$$\Psi(x,a) = \int_{g(x,U)\leqslant a} p(U)dU \tag{1}$$

For any fixed x, $\Psi(x,a)$ is strictly continuous and strictly increasing about variable a.

As for confidence level α, the α-*quantile* of $g(x,U)$ is denoted by $q_\alpha(x)$, the expression is given by

$$q_\alpha(x) = \min\{a \in R: \ \Psi(x,a) \geqslant \alpha\} \tag{2}$$

However, α-*quantile* cannot deal with the extent of the losses that might be suffered beyond the threshold and is very difficult to be solved. At this situation, α-*superquantile* is introduced, because it could quantify risk that might be encountered in the tail. And for any probability level α, α-*superquantile* is defined as

$$\bar{q}_\alpha(x) = E[g(x,U)|g(x,U) \geqslant q_\alpha(x)] \tag{3}$$

where α-*superquantile* represents conditional expectation of the loss is equal or greater to α-*quantile*.

The loss probability in design optimization

As stated in the foregoing paragraphs, the risk measures of optimization problems with randomness would be estimated by the method of α-*superquantile*. Consequently, if a optimization problem with a α-*superquantile* constraint, which could be transformed to the minimization of expected values of loss function $E[g(x,U)]$

$$\begin{cases} \min E[g(x,U)] \\ s.t.\ h(x) \leqslant 0 \\ \bar{q}_\alpha(x) \leqslant q_\beta \end{cases} \tag{4}$$

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