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Interval optimization combined with point estimate method for stochastic security-constrained unit commitment

Ming Zhou, Shu Xia *, Gengyin Li, Xiao Han

State Key Laboratory for Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

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ABSTRACT

To the stochastic nature of unit commitment problem induced by wind power fluctuation, an interval optimization combined with point estimation method (IO-PEM) is proposed to model and solve stochastic security constrained unit commitment (SCUC) problem. Considering reasonable fluctuation range of wind power, an interval optimization model is established which takes two worst-case scenarios to replace all scenarios in the interval. This model accelerates the solution speed on the premise that the scheduling result meets security constraints. At the same time, in order to accurately evaluate corrective dispatching cost caused by wind power fluctuations and make the scheduling scheme more economic, two kinds of point estimation method: $2M$ and $2M + 1$ schemes, are introduced to improve the accuracy of the interval optimization approach. Comparison studies are done with the proposed method over three conventional methods: Monte Carlo method, the scenario reduction method and the interval optimization method, on the six-bus system and the modified IEEE 118-bus system, the simulation results show that the proposed method has the merits in computation speed and accuracy, in the meanwhile keeping security and economy of the dispatching scheme.

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Introduction

The security-constrained unit commitment (SCUC) problem schedules the unit's on/off status as well as it output in order to satisfy load demand and network security constraints at minimum operating cost over a given scheduling period (e.g., a day) [1,2]. The SCUC plays an important role in power system short-term operation, and it is a high-dimensional multi-constrained mixed integer programming problem [3]. In recent years, with the increase of wind power penetration into power systems, the randomness of wind power imposes large amount of uncertainty to the system operation, and this turns the SCUC problem into a stochastic and more complicated optimization problem [4].

In order to properly deal with wind power fluctuation, the conventional SCUC modeling methods have been improved by researchers in different ways. In [5], the additional up and down reserves to compensate for wind power fluctuation are added to the spinning reserve constraints. On the basis of [5], the maximum wind power penetration limit is considered where the ramping capacity available is compared against wind generation fluctuation [6]. The above models only analyze the base scenario corresponding to the expected or forecasted wind power, and they are deterministic models. These models are relatively simple in the aspects considering the impact of wind power fluctuation on the system security and the operating cost. Actually, those scenarios deviate from the base one, here called "deviation scenarios", have greater impact on network security and operating cost, but not been well evaluated yet in the existing achievements.

To better consider the volatility of wind power in SCUC, stochastic SCUC model is presented in [7], based on the theory of chance constrained programming, risk constraints with a specific probability are introduced to deal with the stochastic factors. In some other studies, a set of possible scenarios are selected to model uncertainties in the SCUC problem relating to, e.g., wind power [8], load [9], generator and branch contingencies [10] and price variations [11]. In each scenario, the outputs of non-wind units are varying and the operating cost is calculated when satisfying the unit constraints and system constraints. In [12], the relationship between the base scenario and the deviation scenarios for wind power volatility has been established. It is assumed that adjusting non-wind units from the base scenario to a deviation scenario should be completed in ten minutes to meet rapid wind power volatility. In above stochastic SCUC models, each deviation scenario is separately modeled and calculated, which can make the scheduling scheme meet any scenario at any hour. However,

* Corresponding author. Tel.: +86 1061773830.
E-mail addresses: zhouming@ncepu.edu.cn (M. Zhou), 870828@ncepu.edu.cn (S. Xia), ligy@ncepu.edu.cn (G. Li).

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Nomenclature

Indexes
t index of time period (in h), $t \in \{1,\ldots,T\}$, T is the scheduling time horizon (24 h)
g index of thermal unit, $g \in \{1\ldots,G\}$, G is the number of thermal units
i index of curve segments, $i \in \{1\ldots,I\}$, I is the number of segments of the piecewise linear production cost function
s index of possible wind power volatility scenario, $s \in \{1\ldots,S\}$, S is the number of possible wind power volatility scenarios
w index of wind farm, $w \in \{1\ldots,W\}$, W is the number of wind Farms
d index of load node, $d \in \{1\ldots,D\}$, D is the number of load nodes
l index of line
k index of estimated location for the input random variable of the point estimated method
m index of the input random variable of the point estimated method

Parameters
v_t, $\bar{v}_t$ actual value and forecast value of wind speed at hour t
$\sigma_{v,t}$ forecast standard deviation of wind speed at hour t
$P_{w,t}$, $\bar{P}_{w,t}$ actual value and expected value of wind power at hour t
N_w number of wind turbine generator in wind farm w
P_{rate} rated power of wind turbine generator
v_{in}, v_r, v_{out} cut-in, rated and cut-out wind speed
p^s probability of scenario s
$S^u_{g,t}$, $S^d_{g,t}$ start up cost and shut down of unit g
$P^{\min}_g$, $P^{\max}_g$ minimum output and maximum output of unit g
$c_{g,i}$ slope of segment i of the linear cost function of unit g
$P_{d,t}$ load value of node d at hour t
r^d_g, r^u_g ramp-down limit and ramp-up limit of unit g
$R_{L,t}$ System spinning reserve requirement at hour t
$R^{\max}_g$ maximum response rate constrained spinning reserve contribution of unit g
$X^{on}_{g,t}$, $X^{off}_{g,t}$ on and off time of unit g at hour t
T^{on}_g, T^{off}_g minimum on and off time of unit g
ΔP^d_g, ΔP^u_g down/up limits for corrective dispatch of unit g
$K_{l,g}$, $K_{l,w}$, $K_{l,d}$ shift factor of unit g, wind farm w and load d with respect to line l
$P^{\max}_l$ maximum capacity of line l
$P^s_{w,t}$ power output of wind farm w at hour t in scenario s
$P^{\max}_{w,t}$, $P^{\min}_{w,t}$ upper and lower bounds of wind power output interval at hour t
$\beta^u_{w,t}$, $\beta^d_{w,t}$ up and down confidence level of wind power at hour t
$P^{\max}_{Wl,t}$, $P^{\min}_{Wl,t}$ upper and lower limits of power flows under all possible scenarios at hour t
x_m input random variable of the point estimated method
$M_j(x_m)$, $\lambda_{m,j}$ j-th order central moment and standardized central moment of x_m
$x_{m,k}$ k-th estimate point locations of x_m
$\omega_{t,m,k}$ weighting factor of the scenario corresponding to the k-th estimation point of the m-th random variable at hour t

Variables
F basic cost under the base scenario
$E(\Delta F^s_Z)$ expected corrective dispatching cost under all deviation scenarios
$U_{g,t}$ status of unit g at hour t
$F_{g,t}$ fuel cost of unit g at hour t in the base scenario
$\Delta F^s_{g,t}$ corrective dispatching cost of unit g at hour t in scenario s
$P_{g,t}$, $P^s_{g,t}$ dispatching output of unit g at hour t in the base scenario and the scenario s
$P_{g,i,t}$, $P^s_{g,i,t}$ dispatching output of unit g at hour t at segment i in the base scenario and scenario s
$\Delta P^s_{g,i,t}$ corrective dispatching output of unit g at hour t at segment i in scenario s
$R_{g,t}$ spinning reserve of unit g at hour t
$\Delta F^{m,k}_{g,t}$ corrective cost of unit g in the scenario corresponding to the k-th estimation point of the m-th random variable at hour t

the number of deviation scenarios is huge when accuracy is considered, which brings a great amount of computation. So it is necessary to find out an efficient method for solving stochastic SCUC problem with wind power generation. In the current studies, two approaches have been used to solve stochastic SCUC problem, one is scenario reduction method based on Monte Carlo simulation [13], another is interval optimization method.

Scenario reduction method uses different probabilistic metrics to select the best set of scenarios from large number of scenarios generated by Monte Carlo simulation [12], and then the selected scenarios as the representatives are used to solve the stochastic problem. The common scenario reduction technique includes simultaneous backward reduction [8], fast forward reduction [14], intelligent optimization algorithms [15], and so on. For the scenario reduction method, the accuracy of solution is closely related to the number of the selected scenarios. If the number of the selected scenarios is too small, the solution is poor and even infeasible. If the number is too large, the computation amount could increase significantly. So selecting the reasonable number of the scenarios is still a difficulty.

Interval optimization method adopts the upper and lower bound of the confidence interval to indicate the uncertainty spectrum of random variables, and introduces interval numbers into the model. The interval number optimization theory [16] is implemented to find out the worst-case scenarios for satisfying all constraints requirements. In [17], interval optimization method *is* presented to analyze the impact of bus load uncertainty on power system security in SCUC problem. By using full-scenario analysis, two worst-case scenarios are obtained, and all operation constraints corresponding to a large number of volatility scenarios turn to the constraints to two worst-case scenarios. This method is also applied to deal with wind power uncertainty. Interval optimization method can ensure operation security only by analyzing the worst-case scenarios, so it has high computation efficiency. However, interval optimization method cannot accurately evaluate the dispatch cost of those scenarios in the interval, and it cannot take the expected cost as the objective function like [8–11] either. To overcome this problem, this paper introduces point estimate method to evaluate the operating cost of deviation scenarios in the interval.

Point estimation method can calculate the statistical moments of random output of a stochastic function with several random input variables [18]. For a random function Z with M random input variables, K points (K is usually taking 2 or 3) are selected as

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