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Power system scheduling model considering period-to-period ramp-capability constraints with renewable power uncertainty

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Abstract. Power system scheduling with renewable power integration aims to determine the scheduled power of conventional power plants and renewable power plants. This paper proposes a day-ahead power system scheduling method considering period-to-period ramp-capability constraints with renewable power uncertainty. The renewable uncertainty cost is considered based on the overestimation and underestimation penalty cost and further converted to be a linear model. The period-to-period ramp-capability constraints with renewable power uncertainty are incorporated into the proposed day-ahead scheduling model, which ensures that any period-to-period power trajectory within upper and lower envelops are restricted by the ramping up and down limits. Finally, numerical studies in the IEEE 118-bus system are presented to demonstrate the merits of the proposed method.

1. Introduction

Recently, the uncertainty of renewable power such as wind power and solar photovoltaic power has greatly influenced the power system planning and operation. In day-ahead power system scheduling, how to fully consider the uncertainty of renewable power in the power system operation has become a frontier problem and concern.

Based on the renewable power model, such as distribution models, the power system scheduling with renewable power integration can be formulated as a stochastic optimization problem. Similar with the conventional power system dynamic scheduling model, the period-to-period ramp-capability constraints are considered in studies [1-4], in which the upwards and downwards power change of scheduled power of conventional power plants (CPPs) in adjacent time intervals are enforced within a maximum amount. However, because of the reserve of each CPP, the ramping could not be guaranteed in the actual power system operation. For example, if in the last time interval the positive reserve of CPP is employed while in the current time interval the negative reserve of CPP is employed, the ramping rate would be not enough. The above studies [1-4] have not considered the renewable power uncertainty in the period-to-period ramp-capability constraints.

In this paper, a day-ahead power system scheduling method considering period-to-period ramp-capability constraints with renewable power uncertainty is proposed. To consider renewable power uncertainty cost in the system, the overestimation and underestimation penalty cost is considered, which are widely formulated as an integral item of renewable power distribution as in [5]. As a result, iteration algorithms such as sequential linear programming are needed to solve the economic dispatch model in studies [5]. Iteration methods bring some new problems such as step size setup and sometimes lead to a bad convergence. Different from the method in [5], the integral form of renewable

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power uncertainty cost is converted into a linear form, which can be reliably solved based on off-the-shell commercial solvers.

The remainder of this paper is organized as follows. In Section II, the objective function of the power system scheduling considering renewable power uncertainty is formulated. In Section III, constraints of power system scheduling considering period-to-period ramp-capability constraints with renewable power uncertainty are introduced. Numerical studies using the IEEE 118-bus system are presented in Section IV. Section V provides conclusions.

2. Objective function of power system scheduling considering renewable power uncertainty

In look-ahead power system scheduling, the schedule power of conventional power plants (CPPs) and renewable power plants (RPPs) are determined to minimize the overall cost in the schedule horizon. The schedule horizon is denoted as the set of time intervals $\mathrm{T}:=\{1,2,...,T\}$, i.e., t=1,2…T time intervals.

2.1. Overall cost function

The overall cost consists of the CPP cost and RPP penalty cost (uncertainty cost) as follows

$$\begin{aligned}\min: E\{f\} &= \sum_{t\in\mathrm{T}}(f_{g,t}+E\{f_{w,t}\}) \\ &= \sum_{t\in\mathrm{T}}\left[\sum_{i\in\mathrm{I}}(C_{g,i,t}+C_{r,i,t})+E\{f_{w,t}\}\right]\end{aligned} \tag{1}$$

where f_t, $f_{g,t}$, $f_{w,t}$ are the total generation cost, CPP cost, and RPP cost at time t, respectively.

2.2. CPP cost function

The CPP cost consists of the CPP operation cost and reserve cost. The i-th CPP operation cost at time t can be calculated by

$$C_{g,i,t}(p_{i,t}) = a_i p_{i,t}^2 + b_i p_{i,t} + c_i \tag{2}$$

where a_i, b_i and c_i are the quadratic cost coefficients of the i-th CPP; $p_{i,t}$ is the scheduled power of the i-th CPP at time t.

The i-th CPP reserve cost at time t can be calculated by

$$C_{r,i,t}(r_{u,i,t}, r_{d,i,t}) = c_{u,i} r_{u,i,t} + c_{d,i} r_{d,i,t} \tag{3}$$

where $c_{u,i}$ and $c_{d,i}$ are the upward and downward reserve cost coefficient of the i-th CPP, respectively; $r_{u,i,t}$ and $r_{d,i,t}$ are the amount of upward and downward reserves provided by the i-th CPP.

2.3. RPP cost function

2.3.1. Integral function of penalty cost. The RPP cost consists of the overestimation penalty cost and underestimation penalty cost at each time interval as follows

$$\begin{aligned}E\{f_{w,t}(w_t)\} &= k_{ov}E_{ov,t} + k_{un}E_{un,t} \\ &= k_{ov}\int_0^{w_t}(w_t - w_{av,t})\,f(w_{av,t})dw_{av,t} + k_{un}\int_{w_t}^{w_r}(w_{av,t} - w_t)\,f(w_{av,t})dw_{av,t}\end{aligned} \tag{4}$$

where $E_{ov,t}$ is the expected overestimation renewable power; $E_{un,t}$ is the expected underestimation renewable power; k_{ov} and k_{un} are the penalty cost coefficients of renewable power overestimation and underestimation, respectively; w_r is the RPP capacity.

2.3.2. Reformulation of penalty cost. In this paper, renewable power distribution in (4) are reformulated using discretization, i.e., 0.01p.u., 0.02p.u.,…,1.00p.u. with the corresponding probability. It could be generated from renewable power distribution models such as Gaussian

distribution [6], Beta distribution [7] and Truncated Versatile distribution [1] or empirical distribution [8]. The underestimation penalty cost can be rewritten as the following formula:

$$k_{ov}\int_0^{w_t}(w_t - w_{av,t})\,f(w_{av,t})dw_{av,t} = k_{ov}\sum_{s\in S}\pi_t^s u_t^s \tag{5}$$

s.t.

$$\begin{aligned} u_t^s &\geq 0 \\ u_t^s &\geq w_t - w_t^s \end{aligned} \tag{6}$$

where u_t^s is an intermediate variable; w_t^s is the discretization value of renewable power; π_t^s is the corresponding probability of w_t^s. The overestimation penalty cost can be rewritten as the following formula:

$$k_{un}\int_{w_t}^{w_r}(w_{av,t} - w_t)\,f(w_{av,t})dw_{av,t} = k_{un}\sum_{s\in S}\pi_t^s v_t^s \tag{7}$$

s.t.

$$\begin{aligned} v_t^s &\geq 0 \\ v_t^s &\geq w_t^s - w_t \end{aligned} \tag{8}$$

where v_t^s is an intermediate variable.

Combining (4)~(8), the renewable cost can be rewritten as:

$$\begin{aligned} E\left\{f_{w,t}(w_t)\right\} &= k_{ov}E_{ov,t} + k_{un}E_{un,t} \\ &= \pi_t^s\sum_{s\in S}\left[k_{ov}u_t^s + k_{un}v_t^s\right] \end{aligned} \tag{9}$$

s.t. (6) and (8).

3. Constraints of period-to-period ramp-capability constraints with renewable power uncertainty

All the constraints of the power system scheduling can be presented as follows.

3.1. Supply-demand balance constraints

Formula (10) is the supply-demand balance constraints; L_t is the forecast power demand at time *t*.

$$\sum_{i\in I} p_{i,t} + w_t = L_t, \forall t \tag{10}$$

3.2. CPP generation plus reserve constraints

Formula (11) are the CPP generation plus reserve constraints; $p_{\max,i}$ and $p_{\min,i}$ are the upper and lower generation limits of the *i*-th CPP, respectively.

$$\begin{aligned} p_{i,t} + r_{u,i,t} &\leq p_{\max,i}, \forall i,t \\ p_{i,t} - r_{d,i,t} &\geq p_{\min,i}, \forall i,t \end{aligned} \tag{11}$$

3.3. CPP period-to-period ramp-capability constraints

Formula (12) are the CPP period-to-period ramp-capability constraints with renewable power uncertainty, which ensure that any period-to-period power trajectory within upper and lower envelops are restricted by the ramping up and down limits, as shown in Figure 1; $\Delta p_{u,\max,i}$ and $\Delta p_{d,\max,i}$ are the maximum amount of up and down ramp rate of the *i*-th CPP within a specific time period (e.g., 5min, 15min), respectively; in other words, constraints (12) respectively enforce the feasibility of maximum

upwards and downwards power change that is possible within power-capacity operating range for adjacent time intervals.

$$\begin{aligned} p_{i,t} + r_{u,i,t} - p_{i,t-1} + r_{d,i,t-1} \le \Delta p_{u,\max,i}, \forall i,t \\ p_{i,t-1} + r_{u,i,t-1} - p_{i,t} + r_{d,i,t} \le \Delta p_{d,\max,i}, \forall i,t \end{aligned} \tag{12}$$

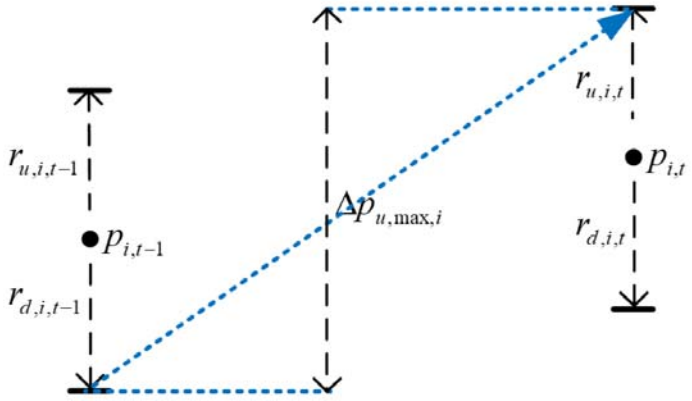

Figure 1. Period-to-period upward ramp-capability constraint with renewable power uncertainty.

3.4. Reserves boundary constraints

Formula (13) are the reserves boundary constraints; $r_{u,\max,i}$ and $r_{d,\max,i}$ are the maximum amount of up and down reserves that the *i*-th CPP can provide, respectively.

$$\begin{aligned} 0 \le r_{u,i,t} \le r_{u,\max,i}, \forall i,t \\ 0 \le r_{d,i,t} \le r_{d,\max,i}, \forall i,t \end{aligned} \tag{13}$$

3.5. Transmission constraints

Formula (14) is the transmission constraints; $\overline{F}_l$ is the capacity limit on transmission line *l*; $l \in \Gamma$, Γ is the set of transmission lines; N_b is the set of buses connected to the transmission line *l*; I_b and J_b are the set of CPPs and RPPs that connected on the transmission line *l*, respectively; K_{lb} is the generation distribution shift factor; L_{bt} is forecast power demand on bus *b* at time *t*.

$$-\overline{F}_l \le \sum_{b \in N_b} K_{lb} \left(\sum_{i \in I_b} p_{i,t} + \sum_{j \in J_b} \hat{w}_{j,t} - L_{bt} \right) \le \overline{F}_l, \forall l,t \tag{14}$$

3.6. Chance constraint risk constraints

Formula (15) is the chance constraints to assure the system security according to their desired levels of risk; where c_u and c_d are the levels of risk for having sufficient upward and downward system reserves, respectively.

$$\begin{aligned} \Pr\left\{ \sum_{i \in I} r_{u,i,t} \ge w_t - w_{av,t} \right\} \ge c_u, \forall t \\ \Pr\left\{ \sum_{i \in I} r_{d,i,t} \ge w_{av,t} - w_t \right\} \ge c_d, \forall t \end{aligned} \tag{15}$$

The chance constraints in (15) can be converted to the proposed linear and deterministic ones as follows.

$$\begin{aligned} w_t - \sum_{i\in \mathrm{I}} r_{u,i,t} \le F_t^{-1}(1-c_u), \forall t \\ w_t + \sum_{i\in \mathrm{I}} r_{d,i,t} \ge F_t^{-1}(c_d), \forall t \end{aligned} \tag{16}$$

The proposed day-ahead power system scheduling method considering period-to-period ramp-capability constraints with renewable power uncertainty consists of the objection function (1)(2)(3)(9) and the constraints (6)(8), (10)~(14), (16).

4. Case study

4.1. Data input

The IEEE 118-bus system with one 600 MW RPP is tested to demonstrate the merits of the proposed reliable algorithm for the proposed scheduling method. The renewable power data comes from the wind farm of the whole region of Ireland's power system with nominal capacity 1526 MW [9]. Truncated Versatile distribution is used to get the renewable power discretization w_t^s in this paper. The overestimation and underestimation penalty cost coefficients are 120 \$/MWh and 60 \$/MWh [10], respectively. T=24 and each time interval is 15min. The schedule horizon is from the current period (0min) to 240min later. The proposed algorithm is solved based on CVX in MATLAB R2016a on a Core-i7 2.70-GHz notebook computer.

4.2. Schedule results

The system cost of the proposed power system scheduling model and the method that do not consider the renewable power uncertainty in the ramping constraints, i.e., methods in [1-4] are compared in this section. The look-ahead scheduling model is proposed in a rolling manner for one month based on the above two methods. Then based on the actual renewable power, the daily average system costs of the above two methods are obtained, as shown in Table 1. We can see that the proposed method has more CPP operation cost compared with the method that not considers the renewable power uncertainty in the ramping constraints. This is because the proposed method has a relatively smaller feasible region in (12). The CPP reserve cost of the proposed method and the method that not considers the renewable power uncertainty in the ramping constraints are subequal. As for the RPP penalty cost, the method that not considers the renewable power uncertainty in the ramping constraints has much larger RPP penalty cost compared with the proposed method. The reason is that the reserve of the CPP could affect the actual ramping ability, as shown in Figure 1. This could cause more overestimation penalty cost and underestimation penalty cost compared with expectation. As a result, the total cost of the method that not considers the renewable power uncertainty in the ramping constraints is larger than the proposed method. Compared with the method that not considers the renewable power uncertainty in the ramping constraints, the proposed method could save 1.3% total cost.

Table 1. Daily average system costs.

	The proposed method	Method that not consider the renewable power uncertainty in the ramping constraints
CPP operation cost (\$)	1409853	1392854
CPP reserve cost (\$)	141117	141108
RPP penalty cost (\$)	232415	272795
Total cost(\$)	1783385	1806757

5. Conclusions

This paper proposes a power system scheduling model considering with renewable power uncertainty. The renewable uncertainty cost is considered based on the overestimation and underestimation penalty cost. The renewable power uncertainty is also considered in the period-to-period ramp-capability constraints, which ensures that any period-to-period power trajectory within upper and lower envelops are restricted by the ramping up and down limits. Results show that compare with the method that not considers the renewable power uncertainty in the ramping constraints, the proposed method could reduce the system cost.

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