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REAL TIME WIND POWER ACCOMMODATION CAPABILITY EVALUATION CONSIDERING SECURITY CONSTRAINTS OF POWER GRID

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ABSTRACT

The intermittent of wind power poses a challenge to operation security and stability of power system. The power grid has the potential to guide wind power to be accommodated in a wider geographical region, and its impact is more prominent in real-time dispatch and controlling. Considering the constraints of bus voltage and branch power flow, this paper focus on the of wind power accommodation capability (WPAC) of system and buses, the coupling relationship of the WPAC of different buses is analyzed. In order to assistant real-time dispatch, an evaluation method of WPAC in real-time dispatch considering security constraints of power grid is proposed, which transforms security constraints of power gird into bus output constraints, evaluates WPACs of the system and different buses at a certain period in real time dispatch. The reasonableness and effectiveness of the presented method is validated by case study.

Keywords: renewable energy resources, wind power accommodation capability, coordination control, real time dispatch.

NONMENCLATURE

Abbreviations	
WPAC	wind power accommodation capability

1. INTRODUCTION

In recent years, the renewable energy represented by wind power has achieved rapid development [1]. By the end of 2018, China's wind power grid exceed 148.6 GW, accounting for more than 9% of the installed capacity of the country's power generation [2].

Meanwhile, the phenomenon of abandoning the renewable energy represented by wind power is serious in China, which has aroused concern about the problem of wind power accommodation.

There are relevant factors affecting wind power accommodation in power system generation, transmission, distribution and utilization. As the only carrier connecting wind power generation and load center, power grid is not only the coordinating medium to guide the optimal allocation of wind power resources, but also the core platform to enhance wind power accommodation capacity.

The network topology of power system is designed and planned according to the distribution characteristics of power supply and load, while the grid-connected operation of wind farm will change the original power distribution of the system. Under the condition of relatively constant load demand, the distribution characteristics of power flow on the grid will be significantly changed, which will make the power grid face the risk of cross-section power flow exceeding the limit and bus voltage instability, thus making its security constraints. It has become the key factor to restrict the wind power accommodation. Especially in real-time dispatching, the power grid is essential to support wind power grid-connected system resources (including peak shaving capacity, ramp capacity, transmission capacity, etc.) further highlight its constraints. With the rapid development of wind power in China, it is urgent to incorporate the security constraints of power grid into the assessment of wind power accommodation capacity to support real-time dispatching decision-making more effectively. The development of this work is based on the shortcomings of the existing research.

1) The evaluation of wind power accommodation capacity focusing on medium and long-term planning and day-ahead generation planning, which can't provide

decision-making assistance for field dispatchers according to the real-time operation status of wind turbines and conventional units in real-time operation.

2) Most of the evaluation results can only reflect the wind power accommodation capacity of the whole system, but can't reflect the wind power absorptive capacity of the system when one or several buses in the network topology act as the wind power injection point, and lack of pertinent information support for actual dispatching and operation.

3) The evaluation results can not reflect the coupling relationship between different buses, nor can they reflect the difference of contribution of conventional units on different buses to the system's accommodation capacity, and lack of analysis on the topological dimension of wind power accommodation capacity.

From this point of view, considering the network bus voltage and line power flow constraints, considering the system and bus accommodation capacity, analyzing the coupling relationship between different bus accommodation capacity, and assisting the real-time dispatching of power system, this paper proposes a wind power absorptive capacity evaluation method considering network constraints in real-time dispatching. Starting from the current operating point, in view of the real-time dispatching operation of power system, not only the wind power absorption capacity of the whole system is evaluated, but also the accommodation capacity of different buses and their related factors are emphatically analyzed.

2. PROPOSED MODEL FORMULATION

The core idea of the evaluation method is to transform the branch power flow constraints into bus output constraints and bus voltage constraints into bus reactive power output constraints. The theoretical basis is: for a given power system operation state, based on the local linearization, the adjustable wind power output can be seen as bus fluctuation, the transfer distribution factor and sensitivity parameters are introduced to analyze the wind power accommodation capacity of the whole system and buses.

2.1 The Objective Function

In real-time operation, the current running time point is t, P_t and Q_t are the active and reactive power operation point respectively .

$$P_t = [(P_t^G)^T \quad (P_t^W)^T \quad (P_t^C)^T \quad (P_t^D)^T]^T \quad (1)$$

$$Q_t = [(Q_t^G)^T \quad (Q_t^W)^T \quad (Q_t^C)^T \quad (Q_t^D)^T]^T \quad (2)$$

where P_t^G and Q_t^G are respectively active and reactive output vector of conventional generators connected buses, dimensions are both $N_t^G \times 1$; P_t^C and Q_t^C are respectively active and reactive output vector of connected buses, dimensions are both $N_t^C \times 1$; P_t^D and Q_t^D are respectively active and reactive output vector of load connected buses, dimensions are both $N_t^D \times 1$; P_t^W and Q_t^W are respectively active and reactive output vector of wind power generators connected buses, dimensions are both $N_t^W \times 1$.

T is a time period for real-time dispatch and Δt is used to discretize the time t~t+T. For each discrete time point, the models used to evaluate the absorptive capacity are consistent. Therefore, we only take $t+\Delta t$ as an example to elaborate on it.

Taking t as the starting point, after Δt, the active and reactive power adjustment vectors of N^W wind power Grid-connected buses are $\Delta P_{\Delta t}^W$ and $\Delta Q_{\Delta t}^W$ respectively. $\Delta P_{\Delta t}^W$ will cause changes in the distribution of active power flow and the injected power of buses on the transmission line, $\Delta Q_{\Delta t}^W$ will cause changes in the distribution of active power flow and the injected power of buses on the transmission line. Thus affecting the operating security of the power system. Thus, the change of injection power of each bus at $t+\Delta t$ is expressed as a unified expression.

$$\Delta P_{\Delta t} = [(\Delta P_{\Delta t}^G)^T \quad (\Delta P_{\Delta t}^W)^T \quad (\Delta P_{\Delta t}^C)^T \quad (\Delta P_{\Delta t}^D)^T]^T \quad (3)$$

$$\Delta Q_{\Delta t} = [(\Delta Q_{\Delta t}^G)^T \quad (\Delta Q_{\Delta t}^W)^T \quad (\Delta Q_{\Delta t}^C)^T \quad (\Delta Q_{\Delta t}^D)^T]^T \quad (4)$$

Then the upper limit of wind power accommodation by the system at $t+\Delta t$ is

$$\max C(P_t + \Delta P_{\Delta t}) \quad (5)$$

The corresponding lower limit of wind power absorbed by the system is

$$\min C(P_t + \Delta P_{\Delta t}) \quad (6)$$

Where, C is vector and the dimension is $(N^G + N^W + N^C + N^D) \times 1$,the location element corresponding to the wind power Grid-connected bus is 1, and the rest is 0.

2.2 Constraints

2.2.1 Active power constraints

Because of the existence of $\Delta P_{\Delta t}^W$, the power flow of each line in the whole system will fluctuate. There is a risk of transmission power exceeding the limit, therefore, the variation of active power flow in transmission lines should meet the constraints.

$$-P^L_{\max} \le P^L_t + \Delta P^L_{\Delta t} \le P^L_{\max} \qquad (7)$$

In the formula: $P^L_{\max}$ is the maximum transmission capacity vector of the line, and it does not change with time. So Formula (7) is the first kind of constraint. P^L_t is the transmission power vector of the current operating point branch set; $\Delta P^L_{\Delta t}$ is the variation of transmission power of each branch after Δt, dimensions are all $N^L \times 1$.

Active power flow variation of branch k is

$$\Delta P^L_k = \frac{1}{x_k} M_k B_0^{-1} \Delta P_{\Delta t} \qquad (8)$$

In the formula, M_k is the line correlation vector describing branch k connection relationship, B_0 is the matrix of DC power flow calculation, and x_k is the reactance of line k.

Thus all line power flow variation vectors can be expressed as

$$\Delta P^L_{\Delta t} = B^L M^L B_0^{-1} \Delta P_{\Delta t} = H \Delta P_{\Delta t} \qquad (9)$$

In the formula: B^L is a diagonal matrix whose diagonal element is $(x_k)^{-1}$; M^L is a system correlation matrix, $H = B^L M^L B_0^{-1}$,

$$\Delta P^{(1)}_{\min} = -(P^L_{\max} + P^L_t) \qquad (10)$$

$$\Delta P^{(1)}_{\max} = P^L_{\max} - P^L_t \qquad (11)$$

Formula (7) can be rewritten as a constraint on $\Delta P_{\Delta t}$

$$\Delta P^{(1)}_{\min} \le H \Delta P_{\Delta t} \le \Delta P^{(1)}_{\max} \qquad (12)$$

Formula (12) is the first constraint

At the same time, due to the existence of $\Delta P^W_{\Delta t}$,It will also cause the active injection fluctuation of other buses. This makes all kinds of units have the risk of exceeding the output limit. So need to satisfy the constraints.

$$P^G_{\min} - P^G_t \le \Delta P^G_{\Delta t} \le P^G_{\max} - P^G_t \qquad (13)$$

$$-P^W_t \le \Delta P^W_{\Delta t} \qquad (14)$$

$$P^C_{\min} - P^C_t \le \Delta P^C_{\Delta t} \le P^C_{\max} - P^C_t \qquad (15)$$

$$(1-c)P^D_{t+\Delta t} - P^D_t \le \Delta P^D_{\Delta t} \le (1+c_1)P^D_{t+\Delta t} - P^D_t \qquad (16)$$

Where, c_1 describes the proportion of acceptable range of load active power fluctuation; $P^D_{t+\Delta t}$ is the bus load vector of time point t given by ultra-short term load forecasting; Formula (13) - (15) are the upper and lower limit constraints for conventional units, the output constraints for wind turbines, and the contract constraints for tie-line, which are obviously the first kind of constraints; Formula (16) is acceptable fluctuation constraint for load, Since $P^D_{t+\Delta t}$ changes over time, so formula (16) is the second type of constraint. Thus, constraints (13) - (16) can be rewritten in the following form:

$$\Delta P^{(2)}_{\min} \le \Delta P_{\Delta t} \le \Delta P^{(2)}_{\max} \qquad (17)$$

Where

$$\Delta P^{(2)}_{\min} = [(P^G_{\min} - P^G_t)^T, -P^W_t, (P^C_{\min} - P^C_t)^T, (P^D_{t+\Delta t} - c_1 P^D_{t+\Delta t} - P^D_t - \qquad (18)$$

$$\Delta P^{(2)}_{\max} = [(P^G_{\max} - P^G_t)^T, (+\infty)^T, (P^C_{\max} - P^C_t)^T, (P^D_{t+\Delta t} + c_1 P^D_{t+\Delta t} - P^D_t)^T]^T \qquad (19)$$

At the same time, conventional units still have output adjustment rate constraints.

$$\Delta P^G_{\Delta t} \le R^{up,\max}_G (\Delta t) \qquad (20)$$

$$-\Delta P^G_{\Delta t} \le R^{\mathrm{down},\max}_G (\Delta t) \qquad (21)$$

$R^{up,\max}_G$ is the maximum augmented output vector of conventional units in time interval Δt, $R^{\mathrm{down},\max}_G$ is the maximum reduction force constraint in time interval Δt .These two parameters change over time, so formulas (20), (21) are the second kind of constraints and can be written as

$$\Delta P^{(3)}_{\min} \le \Delta P_{\Delta t} \le \Delta P^{(3)}_{\max} \qquad (22)$$

Where

$$\Delta P^{(3)}_{\min} = \{[-R^{down,\max}_G(\Delta t)]^T, (-\infty)^T, (-\infty)^T, (-\infty)^T\}^T \qquad (23)$$

$$\Delta P^{(3)}_{\max} = \{[-R^{\mathrm{up},\max}_G(\Delta t)]^T, (+\infty)^T, (+\infty)^T, (+\infty)^T\}^T \qquad (24)$$

Constraints (17) and (22) have the same form and can be jointly written as

$$\max\{\Delta P^{(2)}_{\min}, \Delta P^{(3)}_{\min}\} \le \Delta P_{\Delta t} \le \min\{\Delta P^{(2)}_{\max}, \Delta P^{(3)}_{\max}\} \qquad (25)$$

In addition, the injection power of each bus of the whole power system should be balanced.

$$E \Delta P_{\Delta t} = 0 \qquad (26)$$

The constraints are the first kind of constraints. E is a vector whose elements are all 1 and the dimension is $(N^G + N^W + N^C + N^D) \times 1$.

2.2.2 Reactive power constraints

The change of active power injection in wind power Grid-connected bus $\Delta P^W_{\Delta t}$ will be accompanied by the change of reactive power injection $\Delta Q^W_{\Delta t}$. The change of reactive power will cause the fluctuation of bus voltage, which will lead to the risk of exceeding the limit of bus voltage. Therefore, voltage constraints need to be met.

$$U_{\min} \le U_t + \Delta U_{\Delta t} \le U_{\max} \qquad (27)$$

$U_{\min}$ and $U_{\max}$ are the minimum and maximum voltage constraints for each bus of power gridgrid respectively.

U_t is the voltage of each bus at the current operating point; $\Delta U_{\Delta t}$ is the variation of voltage at each bus after Δt .

Obviously, Formula (27) is also the first kind of constraint.
From P-Q decomposition :

$$\Delta U_t = -(B'')^{-1}\Delta Q_{\Delta t} \qquad (28)$$

In formula B'' is the imaginary part of nodal admittance matrix without PV bus.

$$\Delta Q_{\min}^{(1)} = -B''(U_{\max} - U_t) \quad (29)$$

$$\Delta Q_{\max}^{(1)} = -B''(U_{\min} - U_t) \quad (30)$$

Then the constraint (27) can be further rewritten as

$$\Delta Q_{\min}^{(1)} \le \Delta Q_{\Delta t} \le \Delta Q_{\max}^{(1)} \qquad (31)$$

For conventional units, tie lines and loads, their reactive power output also has limitations, which need to be met.

$$Q_{\min}^{G} - Q_t^{G} \le \Delta Q_{\Delta t}^{G} \le \Delta Q_{\max}^{G} - Q_t^{G} \quad (32)$$

$$Q_{\min}^{C} - Q_t^{C} \le \Delta Q_{\Delta t}^{C} \le \Delta Q_{\max}^{C} - Q_t^{C} \quad (33)$$

$$(1-c_2)Q_{t+\Delta t}^{D} - Q_t^{D} \le \Delta Q_{\Delta t}^{D} \le (1+c_2)Q_{t+\Delta t}^{D} - Q_t^{D} \quad (34)$$

In the formula, c_2 is the proportion describing the acceptable range of load reactive power fluctuation, and $Q_{t+\Delta t}^{D}$ is the load bus reactive power demand at time point $t+\Delta t$ given by ultra-short term load forecasting. So formula (34) is the second type of constraint. Obviously, formulas (32) and (33) are the first constraints. Formula (32) - (34) can be written together as follows:

$$\Delta Q_{\min}^{(2)} \le \Delta Q_{\Delta t} \le \Delta Q_{\max}^{(2)} \qquad (35)$$

Where:

$$\Delta Q_{\min}^{(2)} = [(Q_{\min}^{G} - Q_t^{G})^T, (-\infty)^T, (Q_{\min}^{C} - Q_t^{C})^T, (Q_{t+\Delta t}^{D} - c_2 Q_{t+\Delta t}^{D} - \mathrm{Q}_t^{D})^T]^T$$
(36)

$$\Delta Q_{\max}^{(2)} = [(Q_{\max}^{G} - Q_t^{G})^T, (-\infty)^T, (Q_{\max}^{C} - Q_t^{C})^T, (Q_{t+\Delta t}^{D} + c_2 Q_{t+\Delta t}^{D} - \mathrm{Q}_t^{D})^T]^T$$
(37)

Formula (31) and Formula (35) have the same form and can be jointly written as:

$$\max\{\Delta Q_{\min}^{(1)}, \Delta Q_{\min}^{(2)}\} \le \Delta Q_{\Delta t} \le \min\{\Delta Q_{\max}^{(1)}, \Delta Q_{\max}^{(2)}\} \quad (38)$$

At the same time, the reactive power balance of the whole system needs to meet the constraints:

$$E\Delta Q_{\Delta t} = 0 \qquad (39)$$

This constraint is the first kind of constraint.
For wind turbines, active and reactive power are dependent.
This paper considers that all wind turbines adopt the operation mode of constant power factor. For wind power Grid-connected bus w, if its power factor is constant at $\cos\varphi_w$, then there are:

$$\frac{Q_t^{w} + \Delta Q_{\Delta t}^{w}}{P_t^{w} + \Delta P_{\Delta t}^{w}} = \tan\varphi_w \qquad (40)$$

The current operating point also satisfies the requirements.

$$\frac{Q_t^{w}}{P_t^{w}} = \tan\varphi_w \qquad (41)$$

Thus, there are equality constraints between active and reactive power of wind power Grid-connected buses.

$$R^{W}\Delta P_{\Delta t}^{W} - \Delta Q_{\Delta t}^{W} = 0 \qquad (42)$$

Where, R^W is a diagonal matrix with $\tan\varphi_w$ as the diagonal element. dimension is $N^W \times N^W$. Formula (42) is the first kind of constraint. Based on the above analysis, the integrated model takes the active and reactive power variation of each bus as the optimization object and solves the above linear programming problem. The wind power accommodation capacity of the bus $t+\Delta t$ can be obtained.

$$z = [(\Delta P_{\Delta t})^T \quad (\Delta Q_{\Delta t})^T]^T \qquad (43)$$

Then the upper limit of wind power accommodation capacity of $t+\Delta t$ is

$$\max[C \quad 0]z \qquad (44)$$

The lower limit of wind power accommodation capacity of $t+\Delta t$ is

$$\min[C \quad 0]z \qquad (45)$$

Based on this, the next time $t+2\Delta t$ can be further analyzed, but the parameters of the second kind of constraints (including constraints (16), (22), (34) need to be adjusted. From this recurrence, the wind power accommodation capacity of a real-time dispatching time period T can be evaluated from the current time point t.

3. CASE STUDY

3.1 System Parameters

To illustrate the effectiveness of the proposed model, Selecting the IEEE-39 Bus System as an Example, Taking the current operating point as the starting point, the changes of wind power accommodation capacity of system and bus over time are analyzed in the next period.
As shown in Figure 1, there are 10 generator access points in the IEEE 39-bus system, ranging from No.30 to No.39. In the example, No.32, No.35 and No.37 are modified to wind turbines and run in a constant power factor mode.

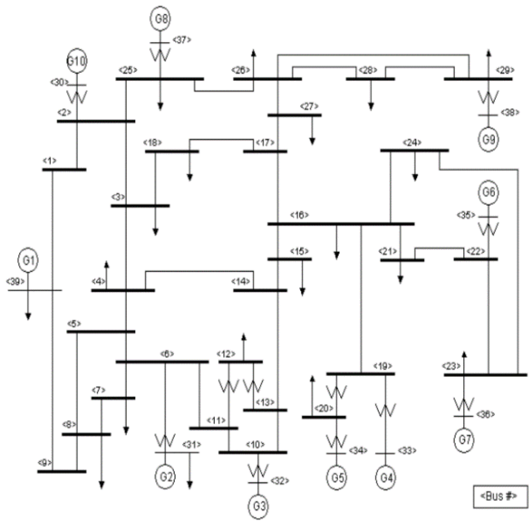

Fig. 1 IEEE 39-bus test system

3.2 Results

Using the evaluation method described in this paper, The variation of system wind power accommodation capability in the next 15 minutes can be obtained., including upper and lower limits, is shown in Fig. 2. Using the evaluation method described in this paper, The variation of system wind power accommodation capability in the next 15 minutes can be obtained., including upper and lower limits, is shown in Fig. 2.

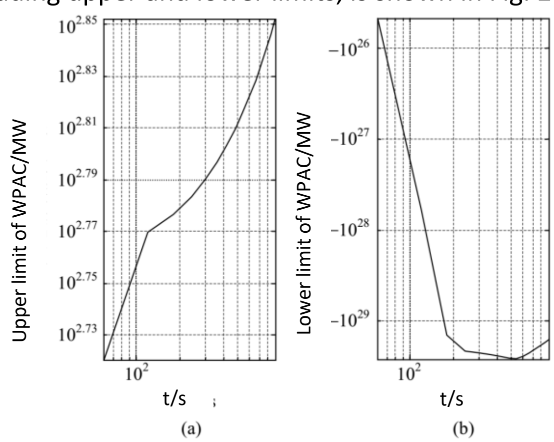

Fig. 2 Changes of WPAC over time

As can be seen from Fig. 2, after 15 minutes from the current operating point, the system can absorb 711.013 MW of wind power at most and abandon 832.112 MW of wind power at most.

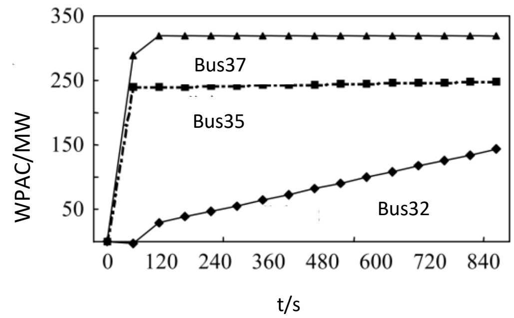

Fig. 3 Corresponding buses' WPAC with different system's upper WPAC

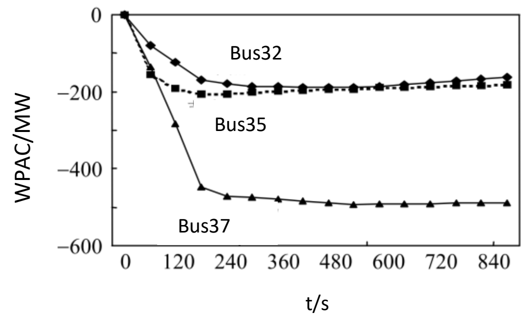

Fig. 4 Corresponding buses' WPAC with different system's lower WPAC

Corresponding to the WPAC of the system, the change of bus accommodation capacity with time can be further analyzed. According to the results shown in figs. 3 and 4, there are significant differences in the accommodation characteristics of No. 32, No. 35 and No. 37.

This is mainly due to the constraints of its location in the network topology and the optimization objective of maximizing (or minimizing) the system-wide absorptive capacity. Taking the absorptive capacity of each bus corresponding to the upper limit of system absorptive capacity as an example, the WPAC of buses No. 35 and No. 37 is saturated rapidly, while the WPAC of bus No. 32 keeps increasing after a period of fluctuation.

4. CONCLUSIONS

In order to accommodate random fluctuating wind power, It is necessary to establish a scientific evaluation method for wind power accommodation capacity. The power grid is an important factor affecting the WPCA of the system. In this paper, A wind power accommodation capacity evaluation method considering security constraints of power gird is presented. Which make the proposed wind accommodation evaluation system applicable to both the system level and some special areas or buses. The presented method is applicable, Especially in real-time dispatch.

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