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Fuzzy chance constraints model based power reference optimisation of wind farm in system restoration

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Abstract: During power system restoration following a blackout, it is necessary to quickly restore as many generator units as possible to accelerate the speed of the system restoration. Considering that wind power of large capacity has the advantages of fast start-up speed, flexible access method etc., its participation in power system restoration can speed up grid recovery. However, due to wind power fluctuations, the integration of wind power during system restoration may impact the frequency of the restored system. In severe cases, the frequency of the restored system will exceed the limit, which will threaten the safety of the restored system. Consequently, the power reference of the wind farm needs to be optimised during the system restoration. Therefore, an optimisation model of power reference of the wind farm in power restoration based on the fuzzy chance constraints model was proposed in this study. The model maximises the power support of a wind farm on the basis of the safety of the restored system. Simulation results show that this method can provide more power under the condition that the system safety is guaranteed.

1 Introduction

During the system restoration, a large number of generator units need to be quickly restarted to restore the blackout system. However, it is difficult for conventional thermal power units to be restarted quickly under the limit of the number and starting power of black-start units [1, 2]. Wind farms which have a huge installed capacity and can be restarted rapidly can quickly provide a large amount of power support for system restoration and improve the efficiency of system restoration. With the development of wind power generation technologies, the cost of power generation continues to decline, and the penetration of wind power generation is increasing in total power generation. As a result, it is inevitable for wind power to participate in system restoration in the future [3, 4]. However, the intermittent and volatility of wind power may threat the security of the restored system, which may cause system frequency to exceed the limit and make the restored system collapse again. Consequently, stable output is required when the wind power participates in the system restoration. With the improvement of wind power control technology, wind farms have the ability to control power output and provide auxiliary services for power system operation, such as participation in power system dispatch [5, 6], frequency adjustment [7, 8], and reactive-voltage regulation [9]. From the above analysis, there are two issues that should be considered when wind power participates in system restoration. Firstly, wind power generations should be connected as much as possible into the system. Secondly, the reference value of wind power output must be reduced to reduce output fluctuations. Therefore, the power reference of wind farm needs to be optimised.

At present, there are few studies on the power reference optimisation of wind farm in system restoration. Some studies have assumed that wind power is a constant value, and the uncertainty of wind power output is not considered [10]. The constant power output of the wind farm needs to cut lots of output power. Consequently, it is necessary to take into account the effect of wind power uncertainty to provide more power for system restoration. In the studies of variable uncertainty, the common method is to obtain the probability distribution function of the research variable. Many methods are based on the probability distribution function of wind power output [11–13], but the probability distribution function of wind farm output is difficult to obtain. It is not suitable for the optimal model of the active power output of the wind farm. The robust optimisation model [14, 15] can solve the wind farm power reference when the accurate distribution of uncertainty parameter is unknown. However, the robust optimisation is very conservative, and wind power cannot be fully utilised. Compared to the above methods, the fuzzy chance constrained model is an effective method, which requires few wind farm power output distribution parameters and can maximise the total active power output of wind farm with safety constraints. Moreover, the fuzzy chance constrained plan can take the risks and costs into account, which has been widely used in the fields with uncertainty factors, such as the power system unit commitment [16], economic dispatch of power system [17], network reconfiguration of power system [18], transmission network expansion [19], and load restoration [20].

In this study, a power reference optimisation model of the wind farm is established for system restoration based on fuzzy chance constraints. Firstly, the deterministic optimisation model of the output power of the wind farm is introduced. Then the deterministic constraints are converted to the fuzzy chance constraints with fuzzy risk value parameter. Also, the fuzzy chance constrained optimisation model was established. Finally, the IEEE 39-bus system is employed to verify the effectiveness of the proposed method.

2 Deterministic model for optimising the wind farm output

The objective of optimising output power of the wind farm is to provide as much power as possible to accelerate the restoration procedure based on the security of the restored system. In this section, a deterministic optimisation model of output power is established.

2.1 Objective function

During the system restoration, the wind farms need to provide as much wind power as possible to speed up the efficiency of system restoration. Moreover, they must ensure the security of the restored system. Therefore, the objective is

$$\max \ f = \sum_{i=1}^{m} P_{\text{ref}_i}, \tag{1}$$

where f is the total output power of wind farms which are integrated into the system; m is the number of wind farms in the system; $P_{\mathrm{ref}i}$ is the dispatch power of the wind farm i.

2.2 Constraints

2.2.1 Output power constraint of wind farm: The power reference cannot exceed the maximum output power of a wind farm:

$$0 \le P_{\mathrm{ref}_i} \le n_i P_{\max\_i}(v_{\mathrm{pre}_i}), \tag{2}$$

where n_i is the number of wind generators in the wind farm i; $P_{\max\_i}$ is the maximum output power of wind farm i. The predicted wind speed of each wind generator in the wind farm is $v_{\mathrm{pre}i}$.

2.2.2 Transient frequency constraints: The transient frequency with the fluctuation of output power needs to be within the security range

$$\frac{\sum_{j=1}^{n} \Delta P_{\mathrm{ref}_j}}{\sum_{i=1}^{n_G} \frac{P_{G_i}}{df_i}} \le \Delta f_{\max}, \tag{3}$$

where $\Delta P_{\mathrm{ref}\_j}$ is the maximum fluctuation of wind farm output; n_G is the number of the conventional units that have been restored; P_{G_i} is the active power output that has been restored; df_i is the transient frequency response coefficient of unit i; $\Delta f_{\max}$ indicates the maximum allowable decrease in transient frequency. In this study, $\Delta f_{\max}$ is set as 0.5 Hz.

2.2.3 Power flow constraints:

$$\begin{cases} P_i + P_{\mathrm{ref}_i} = P_{Li} + V_i \sum_{j=1}^{N} V_j (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}), \\ Q_i = Q_{Li} + V_i \sum_{j=1}^{N} V_j (G_{ij}\sin\delta_{ij} + B_{ij}\cos\delta_{ij}), \end{cases} \tag{4}$$

where P_i and Q_i are the active and reactive power injection at node i, respectively; P_{Li} and Q_{Li} are the active and reactive load at node i; V_i is the voltage of node i; G_{ij} and B_{ij} are the conductance and susceptance between nodes i and j; δ_{ij} is the phase angle difference between V_i and V_j; and N is the number of nodes.

2.2.4 Unit output and voltage constraints:

$$\begin{cases} P_{Gi\min} \le P_{Gi} \le P_{Gi\max}, \\ Q_{Gi\min} \le Q_{Gi} \le Q_{Gi\max}, \\ V_{j\min} \le V_j \le V_{j\max}, \end{cases} \tag{5}$$

where P_{Gi} and Q_{Gi} are the active and reactive power of the conventional unit, respectively; $P_{Gi\min}$ and $P_{Gi\max}$ represent the minimum and maximum active power; $Q_{Gi\min}$ and $Q_{Gi\max}$ represent the minimum and maximum reactive power; V_j represents the voltage of node j, $V_{j\min}$ and $V_{j\max}$ are the minimum and maximum voltage of node j.

3 Fuzzy chance constrained model for power reference optimisation

Since the deterministic model does not consider the uncertainty of wind power, this section presents the fuzzy chance constrained model based on credibility theory [21].

3.1 Fuzzy model of wind power output

The key to the fuzzy model is determining the membership function of the fuzzy variables. Usually, the trapezoidal membership function has been employed to study the uncertainty of the load in [20, 22], which is adopted to model the uncertainty of wind output in this study. The output power of the wind farm is regarded as an ambiguity function. The mathematical expression of the membership function is

$$\mu_w(P_{\mathrm{ref}_i}) = \begin{cases} 0, & P_{\mathrm{ref}_i} < P_{w\_i1}, \\ \frac{P_{\mathrm{ref}_i} - P_{w\_i1}}{P_{w\_i2} - P_{w\_i1}}, & P_{w\_i1} \le P_{\mathrm{ref}_i} \le P_{w\_i2}, \\ 1, & P_{w\_i2} \le P_{\mathrm{ref}_i} \le P_{w\_i3}, \\ \frac{P_{w\_i4} - P_{\mathrm{ref}_i}}{P_{w\_i4} - P_{w\_i3}}, & P_{w\_i3} \le P_{\mathrm{ref}_i} \le P_{w\_i4}, \\ 0, & P_{\mathrm{ref}_i} > P_{w\_i4}, \end{cases} \tag{6}$$

$$P_{w\_ij} = w_j P_{\mathrm{av}}, \tag{7}$$

where w_j ($j = 2\ 3\ 4$) is the membership degree parameter of the wind farm which is determined by the historical data of the output power of the wind farm and determines the shape of the membership function; P_{av} is the average predicted output power of the wind farm at each period.

3.2 Objective function

In order to further improve the security of system restoration, this study introduces risk value to quantify the overload risk under a certain confidence level.

The mathematical expression of the fuzzy risk value [23] applicable to fuzzy variables is

$$R_{\mathrm{FVaR}} = \sup\{\gamma | C_r(\xi \le \gamma) \le \beta\}, \tag{8}$$

where γ is a real number; β is the confidence level of risk value.

The objective function of the deterministic model is converted into the fuzzy expectation form with the fuzzy parameter. The maximum value of the total active power output of the wind farm can be expressed as

$$f_{\mathrm{wind}} = E_{\mathrm{fuz}}\left(\sum_{i=1}^{m} \tilde{P}_{\mathrm{ref}i}\right). \tag{9}$$

The fuzzy risk value of the output power of the wind farm is described as

$$f_{\mathrm{FVaR}} = \sup\left\{\gamma \middle| C_r\left\{\tilde{P}_{\mathrm{ref}i} - n_i P_{\max\_i}(v_{\mathrm{pre}i}) \le 0\right\} \le \beta\right\}. \tag{10}$$

Finally, the objective function can be expressed as

$$\max f = f_{\mathrm{wind}} - \lambda \sum_{i=1}^{n} f_{\mathrm{FVaR}}, \tag{11}$$

where λ indicates the risk participation factor.

3.3 Constraints

The deterministic conditions in Section 2.2 are transformed into fuzzy constraints as follows.

Wind farm output power constraint is

$$C_r\left\{0 \le \tilde{P}_{\mathrm{ref}i} \le n_i P_{\max\_i}(v_{\mathrm{pre}i})\right\} \ge \beta_1. \tag{12}$$

Frequency constraint when the wind power is integrated into the system is

$$C_r\left\{\frac{\sum_{j=1}^{n} \Delta \tilde{P}_{\mathrm{ref}_i}}{\sum_{i=1}^{n_G} \frac{P_{G_i}}{df_i}} \le \Delta f_{\max}\right\} \ge \beta_3. \tag{13}$$

Since the fluctuation of wind power output is a very fast dynamic process, system power flow constraints, output constraints of conventional generators and wind turbines are the same as deterministic models.

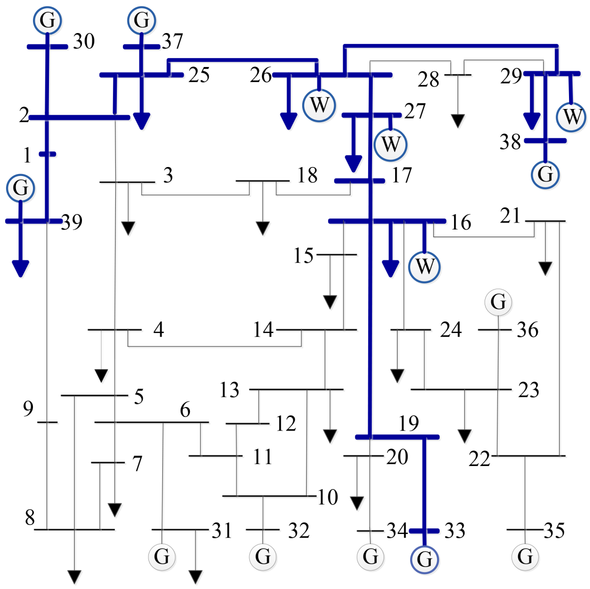

Fig. 1 *IEEE-39 system*

Table 1 Current predicted output of wind farms

Power output	Node 26	Node 27	Node 29	Node 16
no. of wind generators	80	120	100	100
current output	70	100	90	75
average predicted output	120	180	150	150

Table 2 Wind power dispatch through three methods

Wind farm no.	26, MW	29, MW	27, MW	16, MW	Total output, MW
deterministic model	88.5	120	90	76.5	375
robust model	63.2	106.3	87.7	89	346.3
fuzzy model	70.5	115.5	91.5	90	367.5

In summary, the fuzzy chance constrained optimisation model of the wind farm output power is

$$\begin{cases} \max f \\ \text{st}.\ (4)-(5),\ (12)-(13). \end{cases} \tag{14}$$

3.4 Model solving

The power reference optimisation model of wind farm established in this study is a non-linear optimisation model, which is difficult to solve quickly. The intelligent algorithm is the most common method to solve the non-linear model. Artificial bee colony algorithm is easier to implement than other intelligent algorithms, and it can perform local search efficiently, with the capability of global search and avoid falling into a local optimal situation. Therefore, the artificial bee colony algorithm [24] is employed to solve the problem in this study.

4 Example results and analysis

4.1 Simulation scenario

The IEEE 39-bus system is employed to verify the effectiveness of this method. The topology of the power grid is shown in Fig. 1. Wind farms are located at nodes 16, 26, 27, and 29, and the power plants located at nodes 30–39 are traditional thermal units. The unit at node 30 is the black-start unit with self-start capability. The rest are non-black-start units that do not have a self-starting capability.

Assume that nodes 37, 38, 39, and 33 have been restored after the black-start unit. The blue line in Fig. 1 is the restored path. The output power of the unit at node 37 is 51.2 MW, and units at nodes 38, 39, and 33 have been started but the grid-connected generation has not yet started at this moment. Nodes 25, 26, 29, 39, 27, and 16 have recovered their load whose capacities are 60, 50, 30, 106, 96, and 136 MW, respectively. Wind farms are connected to nodes 26, 29, 27, and 16. The wind turbines in the wind farm are assumed to be the same type of doubly-fed wind generator. In order to simplify the calculation, it is assumed that each wind turbine generator operates in the same state. The predicted active power output of a single wind turbine generator under current wind speed conditions is set to 1.5 MW. The number of four wind farms, the current wind farm output, and the average predicted active power output of wind farms are shown in Table 1.

4.2 Simulation results

In this study, an artificial bee colony algorithm is used to solve the fuzzy chance constrained optimisation model of wind farm active power output. The relevant parameters are set as follows: population number $N = 20$; maximum honey mining rate limit = 5; maximum iteration number (MCN) = 200. Set the confidence level as 0.6, which means $\beta_1 = \beta_2 = \beta_3 = \beta = 0.6$, risk participation coefficient λ is set as 0.4.

In order to verify the validity of the proposed model considering the uncertainties of the power output of the wind farm, the deterministic model and fuzzy chance constrained model are used to solve the problem separately. Assume that the actual power output of the wind farm is nearby the predicted value, and the fluctuation range is [0.7, 1]. Actual wind farm power is randomly generated within the range. The wind power dispatch obtained through these three methods is shown in Table 2.

The total active power output of the wind farm solved by three different methods is shown in Table 2. The output power optimised by the deterministic model is maximum and the output power optimised by the robust model is minimum. The output power optimised by the proposed fuzzy opportunity constraint model is less than the result of the deterministic model, but larger than the result of a robust model. As a result, the result of the robust model cannot make full use of wind power resources effectively and the result of the deterministic model may exceed the security constraint, while the fuzzy chance constrained model can provide more wind power with the security of system restoration.

5 Conclusion

The efficiency of the system recovery can be improved when the wind farm participates in the system restoration. Considering that the probability distribution of the active power output of wind farm is difficult to describe accurately, this study proposed an optimisation model of the power output of wind farm during system restoration based on the fuzzy chance constrained, which is solved by the artificial bee colony algorithm. Simulation results show that the proposed method can provide more output power than the robust method and can ensure the security of the restored system compared with the determinate method.

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