

# Research on the influences of location selection and permeability of wind power generation on cascading failure

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**Abstract:** The main cause for cascading failure is large-scale overload caused by localised abnormal flows. With the increase of wind power penetration, the complexity of flow distribution is strengthened. Therefore, it is necessary to study influences of site selection and permeability of wind power generation on cascading failure. An analysis method based on electric betweenness of nodes was put forward, and influences of permeability change on cascading failure on different location selection for wind power generation were researched. According to the study, it was found that when the electric betweenness was low, the overload of wind power led to declining uniformity of power flow distribution, resulting in transfer of flows to other lines. As a result, the heavy load of lines was further aggravated to promote the development of cascading failure. Simulation results of the IEEE30 system showed that with the increase of wind power penetration, the cascading failure was aggravated; and under the same permeability, the lower the electric betweenness of location selection was, the severer cascading failure would be.

## 1 Introduction

As power system develops continuously, load demand and supply ability mutually influence and promote, and they form spiral escalation pattern. Thus, the grid structure and the flow distribution also become increasingly complex. When a circuit or an element breaks because of overload or natural disasters, it will cause flow transfer in the network, and then make other circuit flow increase and become heavy load circuit, and eventually result in a cascading failure. In fact, despite of tiny possibility, such failure may cause considerable loss [1–4]. The increasing complexity of the electric power system, especially the power generation permeability of renewable energy sources such as wind power and photovoltaic power generation inevitably enhances the complexity and uncertainty of power grid flow distribution. Therefore, it is quite significant to study the effect of renewable energy generation grid integration on cascading failure of power grid.

At present, the majority of related researches focus on the influence of intermittency and randomness of wind power generation and their influence on the stable operation of system [4], but they often ignore the influence of locations and permeability of the wind power grid integration on the system. The key to the study of power grid cascading failure lies in the analysis of the flow distribution. Different nodes of wind turbine location have different effects on the flow distribution because of their different transmission capacity for load. Such ‘capability’ is directly proportional to the power transmission capacity margin of the node, and the network topology structure and load distribution of circuit connected to the nodes directly determine the transmission capacity of the nodes [5]. If the wind power generation load is at the nodes with smaller power transmission ability, it tends to trigger circuit overload, result in flow transfer, and cause a new round of overload with the increase of permeability [6]. Therefore, the location and permeability of wind power load directly change the distribution of the initial flow of the system, and inevitably influence the occurrence and development of cascading failure.

Electric betweenness can be used to show the functions of node and circuit in the flow transmission of the whole network. Besides, the transmission capacity of nodes is directly proportional to electric betweenness. As an indicator of measuring transmission

capacity, electric betweenness has been extensively applied in the identification of key circuit and other fields [7].

In order to effectively study the influence of wind power node location and permeability on the occurrence and development of system cascading failure, a kind of analysis method based on electric betweenness was put forward. First of all, a cascading failure model is established to simulate the redistribution of flow after circuit outage. When the power flow after redistribution exceeds the threshold, it is likely to cause another circuit outage, and then trigger a new round of flow redistribution and circuit outage, and eventually trigger a cascading failure. Besides, the severity of cascading failure is measured with quantifiable indicator. The wind power generation model is established and is connected to the nodes with different betweenness. Moreover, the scale of failure under different permeability is calculated through the cascading failure model. Next, the effect of location of the wind power generation on the failure scale of the nodes with different betweenness is analysed, and the influence of location and permeability of the wind power generation node on the scale of cascading failure is evaluated. Finally, with IEEE30 nodes system as a simulation example, the effectiveness of the method is verified.

## 2 Cascading failure model and evaluation index

### 2.1 Cascading failure model

Power grid cascading failure model is a kind of dynamic simulation of the critical state of the system. The calculation processes of the model are given in Fig. 1.

The principle of the model is as follows: to calculate the redistribution of flow by randomly opening and breaking a certain circuit in the grid; when the circuit load exceeds the threshold, it will produce new overload outage, causing a new round of flow distribution and circuit outage, with the process being repeated until the grid network splits. In the actual operation, circuit outage does not necessarily occur when circuit load exceeds normal and stable operation level. When the load exceeds a certain threshold, overload, over current protection device in the circuit can act, and such action is related to circuit flow, so it also increases the

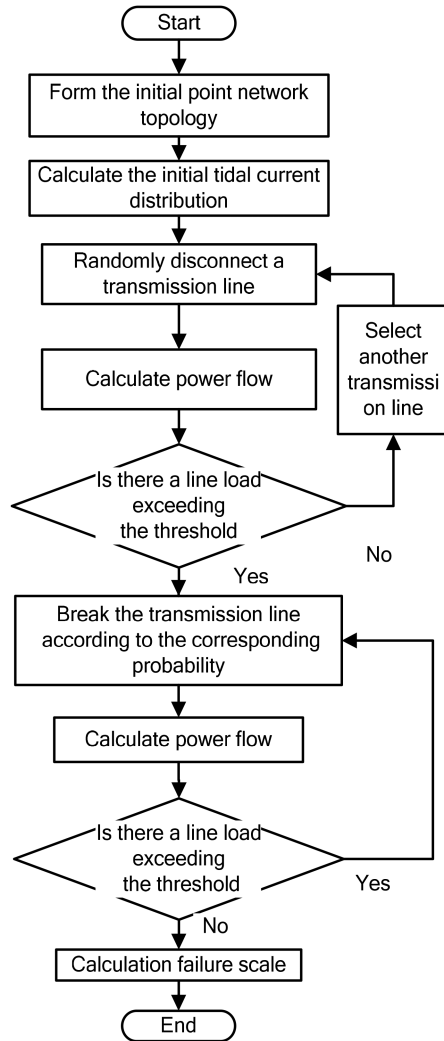


Fig. 1 Flow chart of simulation model

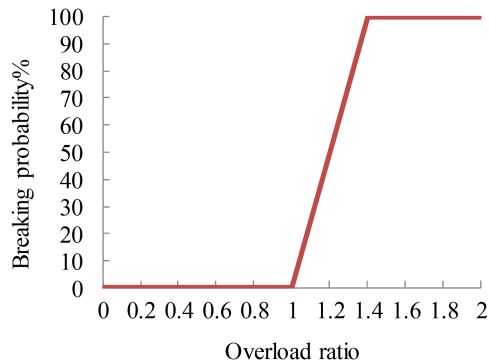


Fig. 2 Curve of breaking probability and overload ratio

probability of circuit outage [8]. Curve of breaking probability and overload ratio are given in Fig. 2.

Here, overload outage is simulated on all circuits through the method of probability: the probability of circuit outage is 0 and 1, respectively, when circuit flow is less than threshold  $C$  and greater than  $1.4C$ .

## 2.2 Cascading failure evaluation index

The basis of the research on the power grid cascading failure is that the severity of the failure can be measured with quantifiable indexes. Here, the loss load ratio and maximum connectivity capability are used as evaluation indicators [9].

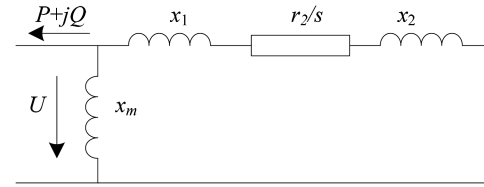


Fig. 3 Equivalent circuit of wind turbine

(a). Load loss ratio: Load loss ratio  $r$  refers to the ratio between the invalid node load after cascading failure and the initial load of the power grid:

$$r = \left( \sum_i^n L_i / L_0 \right) \times 100\% \quad (1)$$

where,  $n$  denotes the number of invalid nodes;  $L_i$  is the load of the invalid node;  $L_0$  is the initial load of the system.

(b). Connectivity: After cascading failure, power grid may be split into several 'isolated islands'. Connectivity  $k$  can be used to evaluate the connectivity of power grid.

$$k = [1 - (N' / N)] \times 100\% \quad (2)$$

where,  $N'$  denotes the maximum number of nodes connecting subgraph after cascading failure, and  $N$  denotes the number of nodes in the network before cascading failure. When  $k$  is larger, the grid has worse connectivity, meaning that higher degree of cracking, higher possibility of grid structure splitting, and worse stability.

## 3 Wind power flow calculation model

### 3.1 Wind turbine model

Currently, wind turbine unit generally adopts the mode of asynchronous generator, which has no excitation device and depends on the reactive power provided by the power grid to establish a magnetic field. Thus, the  $PQ$  node of wind power generation node is usually connected to the system in the calculation of the flow. Wind speed determines the output power  $P$  of the wind turbine and  $P$  is usually characterised by piecewise function.

$$P(v) = \begin{cases} 0 & v < v_{in}, v > v_{out} \\ \frac{v - v_{in}}{v_r - v_{in}} P_r & v_{in} \leq v \leq v_r \\ P_r & v_r < v < v_{out} \end{cases} \quad (3)$$

where,  $v_{in}$ ,  $v_r$ ,  $v_{out}$ , and  $P$  represent cut-in wind speed, rated wind speed, cut-out wind speed, and rated power, respectively. In the process of flow calculation, it can be considered that the output power of the wind turbine at some point is the fixed value determined by the wind speed at that time.

Fig. 3 shows the simplified equivalent circuit diagram of wind turbine.  $U$  denotes the voltage amplitude of wind power generator node;  $x_m$  denotes excitation reactance;  $x_\sigma$  denotes the leakage reactance of the stator;  $r_2$  denotes the rotor resistance;  $s$  denotes the slip. The formulas (4) and (5) can be derived from the circuit in the diagram.

$$U = \sqrt{-P(s^2 x^2 + r_2^2) / r_2 s} \quad (4)$$

$$Q = - \left( \frac{V^2}{x_m} + \frac{Px}{r_2 s} \right) \quad (5)$$

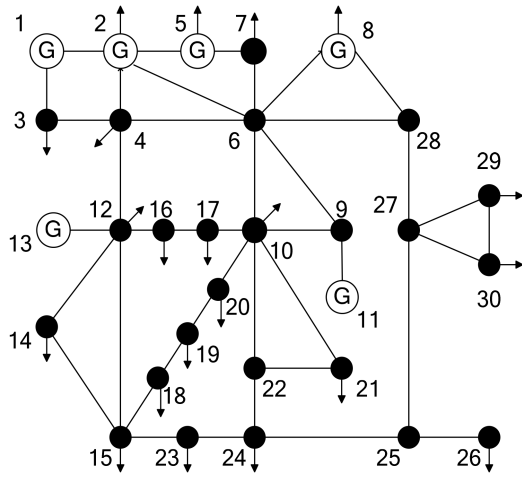


Fig. 4 IEEE30 system

### 3.2 Wind turbine model

In the flow calculation, the following initial conditions are needed: voltage amplitude of node, active output power of wind turbine, stator reactance, rotor reactance, excitation reactance, rotor resistance etc. Then, the wind turbine generator is connected to the system as PQ node, and the system flow equation and the mathematical model of the wind turbine are used for the iterative solution; the flow process including the wind generator forms.

- (i) Calculate initial voltage  $U_0$ ;
- (ii) Calculate the initial slip rates with formula (4);
- (iii) Obtain  $Q$  on the basis of formula (5), calculate the flow distribution by regarded the node as PQ node, and solve new terminal voltage  $U_1$ ;
- (iv) Calculate power factor, and end the calculation if it satisfies convergence condition; otherwise, modify the reactive power after  $U$  change, and return step (ii) to continue iteration until the convergence accuracy is satisfied [10].

## 4 Analysis method based on electric betweenness

### 4.1 Node electric betweenness

The transmission capacity of the power grid can be considered as the capacity of a bucket of water. The flow level can be regarded as the water inside the bucket, and overload can be thought that the volume of water exceeds the capacity of the bucket. 'Short board' determines the capacity of the bucket, but the bucket can hold more water after a reasonable adjustment, such as avoiding the short board by tilting the bucket. The nodes with smaller transmission capacity in the power system is the 'short board'. In order to avoid overload, the nodes with larger transmission capacity should be preferred in wind power grid integration node location. Therefore, the transmission capacity of all nodes should be analysed [11].

Here, electric betweenness is used as the index to quantify the transmission capacity of nodes. As for electric betweenness, the concept of betweenness in complex network theory is referred to [12]. The utilisation share of each branch for 'flow element' produced by 'generation-load' nodes is calculated through flow equation. Moreover, the function of each branch in the transmission of the entire network is measured, and the results are more aligned with actual power system [8].

Electric betweenness is divided into circuit electric betweenness and node electric betweenness. The calculation method of circuit electric betweenness is as follows:

- (i) Select a power generation node and load node randomly, and inject the active power with equal size yet opposite direction, respectively;
- (ii) Calculate the active power of the circuit after injection of power;

- (iii) The sum of the active power generated on a certain circuit by 'generation-load' nodes is the electric betweenness of the circuit, and it can represent the importance in the flow transmission.

The formula of node electric betweenness can be obtained through Formula (6):

$$B_e(m, n) = \left| \sum_{i \in G, j \in L} w_{ij} P_{mn}(i, j) \right| \quad (6)$$

In Formula (6),  $m$  and  $n$  are nodes at both ends of the circuit;  $G$  and  $L$  are set of power generation node and load node;  $P_{mn}(i, j)$  denotes the active power-generated circuit  $m-n$  when equal active power is injected to power generation node  $i$  and load node  $j$ , respectively;  $w_{ij}$  is the weight of the power size transmitting from the power generation node  $i$  to the load node  $j$ , and  $w_{ij} = \min(S_i, S_j)$ , where,  $S_i$  is the rated generating capacity of node  $i$ , and  $S_j$  is the maximum load demand of node  $j$ .

The formula of node electric betweenness can be obtained through Formula (6):

$$B_e(k) = \begin{cases} \frac{1}{2} \sum_{l \in F(k)} B_e(k, l) & k \notin L, k \notin G \\ \frac{1}{2} \left( \sum_{l \in F(k)} B_e(k, l) + \sum_{i \in L} w_{ki} \right) & k \in G \\ \frac{1}{2} \left( \sum_{l \in F(k)} B_e(k, l) + \sum_{i \in G} w_{ik} \right) & k \in L \end{cases} \quad (7)$$

In Formula (7),  $G$  is the power generation node, and  $L$  is the load node and connection node set;  $F(k)$  is the set of edges connected with node  $k$ .

### 4.2 Effects of the location and permeability of wind power generation on tidal current distribution

As each node has different electric betweenness, different nodes have different impact on flow distribution even if they are connected to the same amount of wind load; local load rate may increase or decrease, causing non-uniform flow distribution. Flow entropy is a physical index that can measure the uniformity of flow distribution [13, 14]. Here, therefore, the flow entropy is used to measure the influence of node electric betweenness on the flow distribution.

$$H_{Pw} = - \sum_{k=1}^n \bar{\mu}_k p(k) \ln p(k) \quad (8)$$

where,  $\bar{\mu}_k$  denotes the average value of all circuit loads in the interval of  $[(k-1)u, ku]$ ;  $u$  is the length of the load rate interval, and the value is the reciprocal of the interval number  $n$ ;  $P(k)$  is the probability of the circuit load rate in the interval of  $[(k-1)u, ku]$ . Larger flow entropy means the flow distribution of the system tends to be more non-uniform, and that larger scale of cascading failure occurs. Taking the IEEE30 system as an example, Fig. 4 is the topology diagram of IEEE30 system.

The system includes a total of 30 nodes (18 load nodes and six connection nodes). The system has three voltage levels, namely, 132 kV of power transmission network as well as 33 and 11 kV of distribution network. Besides, the system has the initial load peak of 204.3 MVA, and distribution network load of 104.7 MVA. According to Formulas (7) and (8), electric betweenness of nodes in IEEE30 system is calculated and sorted. Table 1 is the result of nodes electric betweenness (EB) in ascending order.

After connecting wind power nodes to each node in Table 2, the flow distribution under the location of different nodes is calculated through the flow calculation method mentioned in Section 2.2. Moreover, the system flow entropy under the condition of different schemes of site selection is calculated through Formula (6), as

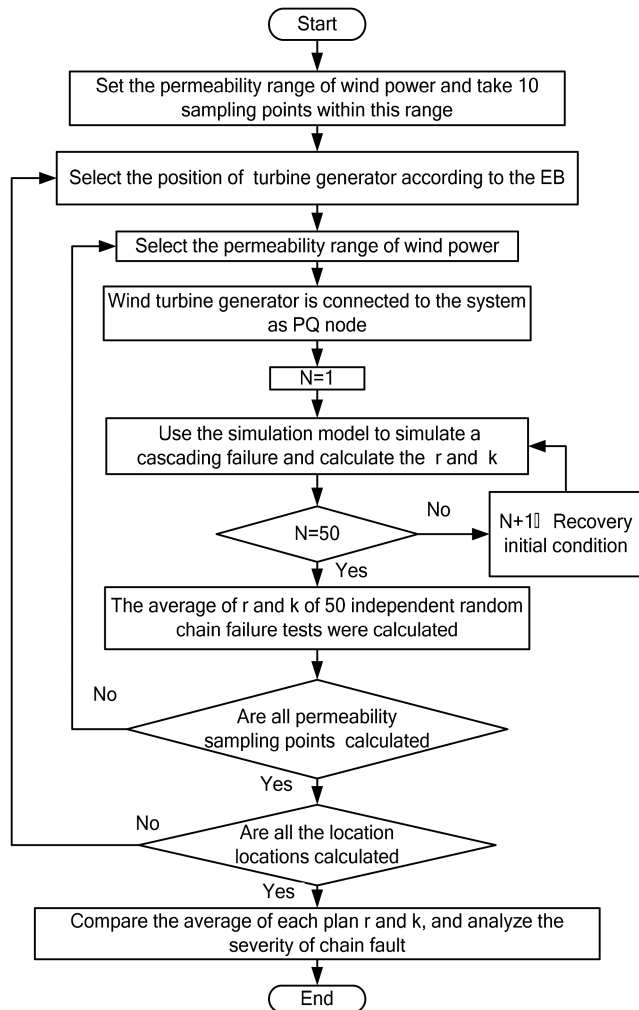


Fig. 5 Flow chart of analysis method

Table 1 Node electric betweenness of IEEE30 system

Node	EB	Node	EB
26	3116.62	24	54,343.5
14	21,443.5	18	64,117.51
7	26,244.8	19	98,054.75
15	33,742.5	20	109,731.1
29	37,219.2	12	201,890.9
30	38,404.3	17	381,823.7
3	43,109.3	4	481,934.9
16	45,433.5	21	2,105,170
23	50,165.5	10	4,629,228

Table 2 Power flow entropy distribution of different wind power penetration

Node	Load entropy under different penetration				
	10%	11%	12%	13%	14%
26	2.4442	2.4446	2.4890	2.4928	2.5584
14	2.4164	2.4164	2.3860	2.5255	2.5394
7	2.4164	2.4164	2.4780	2.5212	2.6008
4	2.3548	2.3548	2.4333	2.5393	2.4945
21	2.2828	2.2828	2.2873	2.3276	2.3499
10	2.2828	2.2828	2.3613	2.4055	2.4164

Table 3 Electrical parameters of wind power generator

$x_1/\text{pu}$	$x_2/\text{pu}$	$r_2/\text{pu}$	$x_m/\text{pu}$	$s_N$
0.09985	0.10906	0.00373	3.54708	-0.004

shown in Table 3. The ordinal number in Table 3 is the node electric betweenness in ascending order.

When the permeability of wind power that is connected to a certain node changes, the power flow distribution, as well as the flow entropy, will change. Table 2 shows the change of the flow entropy with the increase of permeability after the wind power generation node is connected to node 26, 14, 7, 4, 21, and 10 respectively.

According to Table 2, the nodes have different electric betweenness, but flow entropy also rises with the increase of permeability of fans connected to all nodes. In other words, the rise of the load makes the system flow distribution more non-uniform.

#### 4.3 Analysis method

As seen from the results of Tables 2 and 3, the location and permeability of wind power nodes directly influence the uniformity of flow distribution, and they undoubtedly have a direct impact on the occurrence and development of cascading failure. For the above comparison of the change of flow entropy, the qualitative analysis is conducted on the trend of such influence only from the perspective of flow uniformity. In order to more intuitively quantify the degree of influence, this paper proposes a method for the quantitative analysis of the influence: to analyse (1) the influence of the electric betweenness of nodes with equal wind load on the scale of a cascading failure and (2) the influence of the change of wind power permeability on cascading failure in the same position. Fig. 5 is the flow chart of the analysis method.

The core idea of the analysis method is as follows: to connect special PQ node of wind power station to the target grid, change the initial topology structure, and flow distribution of grid, and then calculate load loss ratio and maximum connectivity capability after the initial conditions change through cascading failure simulation model. The cascading failure model adopted here belongs to a random triggered pattern, so the cascading failure process is independently simulated for 50 times. Besides, the average of  $r$  and  $k$  is calculated so as to eliminate the disturbance of random factors.

#### 5 Case study

Here, IEEE30 system is used as the simulation example, and the parameters of wind turbine listed in Table 3 are adopted. According to the analysis method presented in Fig. 5, the wind power node is connected to each load node separately. Furthermore, the load loss ratio and maximum connectivity capacity of the location scheme are calculated. Fig. 6 shows the distribution of load loss ratio  $r$  under the location schemes of different wind power generation nodes.

As seen from Fig. 6, with the continuous increase of permeability, the load loss ratio of each location scheme increases continuously, that is, with the increase of wind power load, the cascading failure causes more serious damage. After wind power is connected to the nodes with different electric betweenness, they have different impact on cascading failure. From the general trend, the larger the electric betweenness of the location node has, the

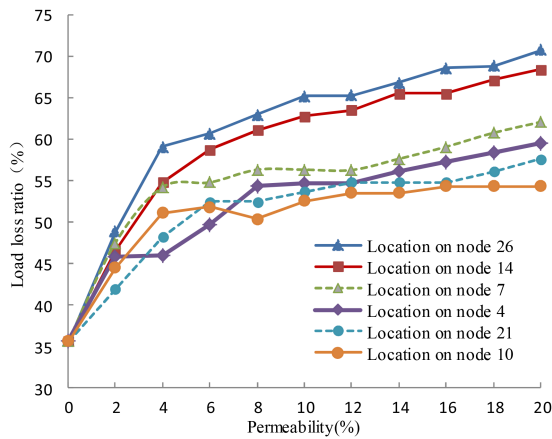


Fig. 6 load loss ratio distribution of different location decisions

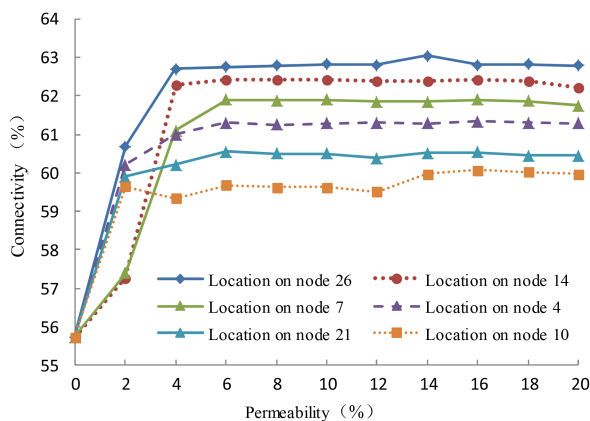


Fig. 7 Connectivity distribution of different location decisions

more serious damage the cascading failure will cause. Fig. 7 shows the distribution of load loss ratio  $r$  under the location schemes of different wind power generation nodes.

According to Fig. 7, with the continuous increase of permeability, cascading failure causes more serious splitting. Compared with load loss ratio, and as seen from the general trend,  $k$  tends to be stable after the permeability reaches a certain range, rather than always increase with permeability mainly because  $k$  is an unweight parameter, and the grid is regarded as the network without the authority, and because the load level of each node is not considered.

As can be found after comparing the distribution of load loss ratio  $r$  and connectivity capability  $k$ , as the permeability of wind power increases constantly, the target system is increasingly demanded after suffering cascading failure. In other words, the increase of permeability makes the cascading failure severer. Especially when the node location of wind power has smaller electric betweenness, it has more obvious influence because the nodes with smaller electric betweenness have weaker power transmission capacity, being the 'short board' of causing overload. Circuit outage will inevitably cause the redistribution of flow. When wind power load is concentrated in the nodes with smaller electric betweenness, the system flow tends to be more uneven, and further enhance the overload of some circuits, intensify the development process of cascading failure, and finally cause larger failure.

Studies have pointed out that the flow near conventional energy will quickly decrease when the wind power has higher permeability [13, 15], and then the flow will present increasingly uneven distribution. Such conclusion is also proved in this paper through computing the change of flow entropy. Moreover, according to the simulation results about the scale of the cascading failure, higher permeability means more non-uniform distribution of the power flow, and bigger scale of cascading failure. If the 'weakness' (namely the nodes with small electric betweenness) in the topology structure can be avoided in wind power location planning, the

robustness of power grid can be effectively improved, and the scale of cascading failure can be reduced.

## 6 Conclusion

Overload caused by flow anomaly distribution is the main reason for cascading failure. With the constant increase of permeability for wind power, the flow distribution becomes more complex. To reduce its potential threat to the power grid stability, it is necessary to study the influence of wind power generation location and permeability on cascading failure.

Here, a method based on node electric betweenness is proposed to study the influence of the change of permeability on the severity of the cascading failure when different nodes are selected as the location of wind generator.

Based on the calculation results of the scale of cascading failure, with the increase of permeability, load loss ratio  $r$  and connectivity capability  $k$  are also rising, suggesting that the increase of the permeability increases the severity of cascading failure. Under the same permeability, the larger the electric betweenness the location node has, the smaller  $r$  and  $k$  are; otherwise, the smaller the electric betweenness is, the larger  $r$  and  $k$  are.

According to the research findings, the system will have larger flow entropy when wind power load is mainly on the nodes with smaller electric betweenness, indicating the flow distribution of the system tends to be uneven; the overload on some circuits, as well as development process of cascading failure will be further intensified, and it will cause larger failure. Therefore, the location of wind power in nodes with larger electric betweenness can help to absorb new power generation and reduce the scale of cascading failure.

## 7 Acknowledgments

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