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Method of adapting to grid recovery in extreme weather conditions

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Abstract: A reasonable recovery strategy for power system is important for the rapid recovery of the grid after a large-scale blackout. Based on the idea of timing restoration decision and taking into account the influence of extreme weather, a restoration strategy of power grid is proposed to avoid the affection of extreme weather on selecting transmission paths and generators and minimise the risk of a secondary failure in system recovery. Firstly, the recovery model of power elements in the case of extreme weather is established, and the improved Dijiestra algorithm is used to find the optimal path of the target generator. Secondly, the dynamic ordering of the generators is carried out considering the maximum power generation capacity during the grid recovery time, where the effects of various safety constraints and extreme weather on outputs of generators are taken into account. The validity and practicability of the proposed method are verified by the IEEE30 node system and the actual Guangdong power grid.

1 Introduction

There are many reasons for the large-scale blackout of power grids, such as failure of power system equipment, man-made operation errors, network attacks, but a large part of large-scale blackouts is due to the impact of extreme natural disasters. Due to the cold and snow disasters, a large-area blackout occurred in southern power grid of China in 2008 [1]; lightning and storm caused 40% of the domestic losses in Brazil in November 2009 [2]. In 2012, high temperatures led to overloading of transmission lines followed by cascading failures of power system resulting in nearly half of the country's power cuts in India and affecting more than six million people [3]. Generally speaking, power grid accidents caused by extreme weathers are often accompanied by various degrees of damage to power components in the system, so the recovery strategy formulated in a normal state is no longer fit [4]. Therefore, it is necessary to develop the grid recovery strategy in extreme weather conditions.

According to the physical process and major concerns involved in the system restoration, the restoration is decoupled into three relatively independent stages: the preparation phase (1–2 h), the network recovery phase (3–4 h) and the load recovery phase (8–10 h) [5, 6]. This paper focuses on the network recovery phase including the dynamic ordering of generators and the optimal choice of transmitting paths mainly. A reasonable start-up sequence of generators and optimal transmission path making full use of the starting characteristics of generators in the network and maximising the power generation capacity of the generator has a great impact on the overall system recovery. The importance of generator sequencing is affirmed and a series of principles that need to be followed in the process is given in [7]. The system generating capacity is taken as the maximum objective function and the non-dominance sorting algorithm is used to optimise the start-up sequence of generators in [8, 9]. On these bases, the unit recovery problem is treated hierarchically and a coordination restoration optimisation method is proposed in [10].

When start-up sequence of generators has been determined, the smoothly start-up of generators is also affected by the transmission paths selection and the reliability of transmission elements. At the same time, the starting sequence of generators is affected by the choice of transmission paths, that is the two major concerns are mutually consistent. The route optimisation problem of network recovery stage is studied systematically and the optimisation strategy of 'serial' and 'parallel' transmission stages is given by using polynomial time algorithm in [11]; the recovery time of the line is taken into account and the starting order and path of generators are solved with the shortest recovery time as the target in [12], but transmission line over voltage and recovery success rate are neglected.

On these bases, the robust optimisation model of the optimal restoration path is established in [13] to avoid the risk of excessive transmission components being selected. However, it only considers the effect of overvoltage caused by charging capacitance on the recovery time and ignores effects of extreme weathers and operators.

Can be seen from the above analyses, the current researches on network recovery stage are based on the normal power components mainly, but do not take into account the effects of low temperature, snow, hurricanes and other extreme weathers on the start of generator and transmission component. Aiming at the above problems, this paper considers fully the influence of extreme weathers on the process of start-up of generators and charging of transmission component, and the charging time of the transmission path is taken into account in the optimisation process of order of generators. Therefore, the two problems are well linked, and the timing recovery scheme of grid is more reasonable. This paper is organised as follows: Section 2 introduces the dynamic sorting optimisation model of generators. Section 3 analyses the process of the proposed grid recovery strategy. Section 4 shows the simulation analyses and Section 5 draws the conclusion of this paper.

2 Dynamic sorting optimisation model of generators

2.1 Branch model

Whether the transmission line can be put into operation safely is mainly affected by the external meteorological environment,

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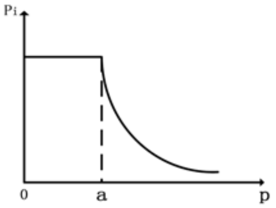

Fig. 1 *Damage probability of transmission element affected by extreme weather*

especially the electrical or physical failure caused by the extreme weather disasters. There has been a deep research foundation for models of outage and damage rate of transmission lines caused by extreme weathers such as low temperature, storm, lightning and other extreme weathers. In [14], fuzzy if-then rule and fuzzy inference system of outage rate are used to analyse the model of the outage rate of the line where climatic conditions are considered to obtain the conditional dependency rate of the line elements affected by the environment. Reliability evaluation index of transmission system is established by combining the reliability model of the line with interval probability theory in [15]. Based on the above researches, the reliability index of transmission elements under weather conditions is calculated by using the connection number theory and the depth optimisation algorithm in [16].

Drop half τ type distribution shown in Fig. 1 is used to describe the damage probability of the transmission element affected by extreme weathers. In Fig. 1, P is the potential damage probability of transmission components subjected to extreme weathers. When the damage probability of transmission elements is less than a given threshold, a, the value of index function of the extreme weather, P_i, is constant 1. When it exceeds the threshold, a, the value of index function of the extreme weather decreases with the increase of damage probability.

The index function of the extreme weather is defined in (1). The inverse of the function value indicates the magnitude of the potential damage probability of the transmission element during the path start time

$$P_{\mathrm{i}} = \begin{cases} 1 & (p < a) \\ \exp[-(p - a)] & (p > a) \end{cases} \tag{1}$$

Where a means selected threshold, and dispatchers can set it according to practical experience. If $a = 0.3$, then when the potential damage probability of the transmission element affected by extreme weather is <0.3, its selection by dispatcher is not affected, but when its probability is >0.3, its selection by dispatcher will be affected.

In addition to the effects of extreme weathers on the recovery of transmission elements, the factors of line capacitance and high-voltage reactor are also considered. When the transmission line is charged, a lot of reactive power will be generated due to the existence of charging capacitor of the line, which will cause voltage rise in some regions of the system, and finally lead to an increase in system recovery time. Therefore, the line with smaller charging power will be selected preferentially during the start-up of the line. Similarly, the line with reactor compensation device will consume reactive power when starting and solves the problem of reactive power surplus. On the other hand, in the actual operation of the power grid, compared to the transmission line, the starting process of the transformer is more complex. Not only inspection of some protective devices is needed but also impact switching test, therefore, the starting time of the transformer will be greater than the transmission line.

According to the above analysis, the proposed branch recovery time model is shown as

$$Wi = \frac{mTi + (QCi - QLi)}{Pi} \tag{2}$$

where W_i is the weight of the start-up time of the branch i in extreme weather conditions; T_i is the start-up time of the branch i under normal conditions; m is a positive integer representing the weighting factor of the time weight and is used to ensure the starting time of the transformer is greater than the transmission line; Q_{ci} is the charging power of the transmission line i; Q_{Li} is the capacity of the high-voltage reactor of the transmission line i; P_i is the impact factor of extreme weathers on transmission components and is obtained by (1).

2.2 Generator model

Extreme weathers not only affect transmission lines but also have a bearing on power plants. Extreme weathers can cause problems such as increased moisture in coal-fired power plants cause the lower calorific value. Heavy rain, typhoons, dust storms and other severe weathers will increase the failure rate of power generation equipment and the difficulty of starting the generator. Therefore, it is necessary to set up the weight index of the impact of adverse weathers on the generator. We analyses the influence of extreme weathers on the starting process of generators by changing the climbing rate of generators.

The general model of generator under extreme weather conditions is shown in Fig. 2. In Fig. 2, C is the unit capacity of a generator indicating power rating that the generator can maintain. R is the starting capacity representing the power to be absorbed by the generator rotor from 0 to synchronous speed. D is the minimum output of a generator.

Unit preparation time T_{pre}: The time required by generator from the ignition to condition of stabilising the output power

$$\mathrm{T}_{\mathrm{pre}} = t_1 - t_0 \tag{3}$$

According to the actual situation, when the unit reaches the minimum output, its output cannot be stabilised at an output value and can only continue to climb. Therefore, the generator starting model used in this paper is:

$$P_{G(\mathrm{t})} = \min\left\{\frac{k}{g_i}\max\left[(t - t_0), 0\right], C\right\} - RU(t - t_0) \tag{4}$$

where $U(T)$ is unit step function and defined as follows:

$$U(T) = \begin{cases} 0 & \mathrm{T} < 0 \\ 1 & \mathrm{T} \geq 0 \end{cases} \tag{5}$$

g_{i} is the value of the indicator function of the generator affected by extreme weathers.

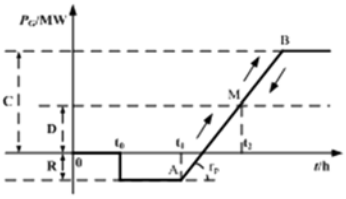

Fig. 2 *General model of generator under extreme weather conditions*

2.3 Objective function and constraint

2.3.1 Objective function of optimal power flow: By using the method proposed in [17], the objective function representing a minimisation of the maximum time for adjustment of all generators is as follows.

Assuming that m generators have been started successfully, then when starting the $m+1$ generator, the objective function is:

$$\min f(x) = \max_{k=1}^{m}\left\{ t_k = \left| \frac{P_k - P_0^k}{r_{pk}} \right| \right\} \tag{6}$$

where P_k is the active power of the kth generator, P_0^k is the current active power of the kth generator, t_k is the adjustment time required for the kth generator, r_{pk} is the climb rate of the kth generator. The optimisation objective is to minimise the climbing time of the generator with the longest climbing time in the process of starting the target generator.

2.3.2 Equality constraint: Equation constraint is the node power balance equations:

$$\begin{cases} P_{Gi} - P_{Di} - \sum_{j=1}^{i=n}\left[e_i\left(G_{ij}e_j - B_{ij}f_j\right) + f_i\left(G_{ij}f_j + B_{ij}e_j\right)\right] = 0 \\ Q_{Gi} - Q_{Di} - \sum_{j=1}^{i=n}\left[f_i\left(G_{ij}e_j - B_{ij}f_j\right) + e\left(G_{ij}f_j + B_{ij}e_j\right)\right] = 0 \end{cases} \tag{7}$$

Where P_{Gi} andQ_{Gi} are active power and reactive power delivered by the generator at node i, respectively; P_{Di} and Q_{Di} are active power and reactive power of the important load at node i, respectively; e_j and f_j are real and imaginary parts at the voltage at node i; G_{ij} and Bij are elements of nodal admittance matrix.

2.3.3 Inequality constraint: Inequality constraints include node voltage constraint and the upper and lower bound of active and reactive power, as shown in

$$\begin{cases} U_{\min} \le U \le U_{\max} \\ P_{\min}(t) \le P_G \le P_{\max}(t) \\ Q_{\min} \le Q_G \le Q_{\max} \end{cases} \tag{8}$$

where $U_{\max}$ and $U_{\min}$ are the upper and lower bound of voltage amplitude of node i, $P_{\max}(t)$ and $P_{\min}(t)$ are the upper and lower limit of the active power output of the generator at node i at t moment, $Q_{\max}$ and $Q_{\min}$ are the upper and lower limit of the reactive power output of the generator at node i,

3 Process of the grid recovery strategy

The grid restoration strategy adapted to extreme weather conditions can be divided into eight steps:

Step 1: Input the basic data needed for the recovery process of the generators, buses, transmission lines, transformers and loads in the grid.
Step 2: Determine the black start units in power grid, including hydropower units or thermal power units with self-starting capability and the remaining thermal power units after the accident.
Step 3: Select thresholds in extreme weather conditions based on the experience of dispatchers and the extent of acceptable risks.
Step 4: Through the Dijkstra algorithm to search for the optimal starting path of all generators, and then calculate the comprehensive index of generators. Then, the starting sequence of generators is obtained by combining the starting parameters of the generator itself. Among them, the weight associated with the performance of the generators:

$$G(i) = \frac{S(i)}{R(i)} \tag{9}$$

where $S(i)$ and $R(i)$ are the starting capacity and the climbing rate of the target generator i, respectively.

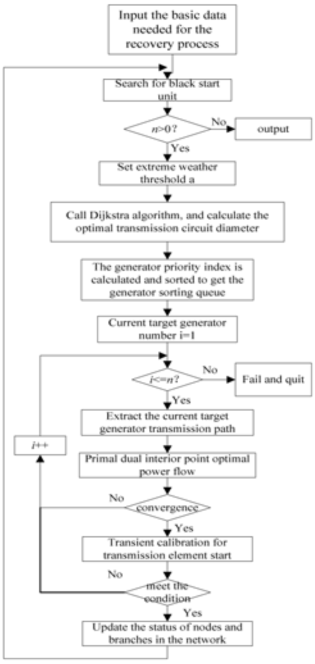

Fig. 3 *Flow chart of the power grid restoration under extreme weather conditions*

Step 5:The primal dual interior point optimal power flow algorithm is used to solve the objective function. If result converges, the target generator can start.
Step 6: Transient verification of the starting path of generators.
Step 7: Modify parameters of generators and value of the line that has been started, then repeat steps 3–8.
Step 8: Choose the final boot programme according to the different optimisation objectives.

The concrete flowchart is shown in Fig. 3.

This method of the power grid restoration under extreme weather conditions includes the following technical characteristics:

(i) Thresholds in extreme weather conditions can be adjusted freely according to the experience of dispatchers.
(ii) The start-up process of each generator is taken as a recovery stage to ensure the shortest recovery time at each stage, and the node and branch state of network are updated when the target generator is started successfully.
(iii) Not only charging time but also charging capacitances and compensation capacities of the high-voltage reactors are taken into account in the time weight of transmission branches.

4 Simulation analyses

4.1 Simulation analysis in the IEEE 30-node standard system

The IEEE 30-node standard system shown in figure is adopted to test the proposed fast recovery method. This system contains 30 nodes, six generators, four transformers and 37 transmission lines. Assuming that the circular area shown in Fig. 4 is affected

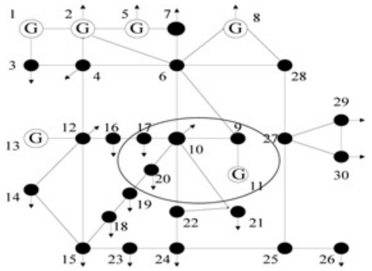

Fig. 4 *Power grid structure of the IEEE 30-node standard system*

by extreme weathers and it consists of one generator, two transformers and eight transmission lines.

The weights of the branch start time of transmission lines and transformers under the normal condition of the IEEE 30-node standard system is shown in Table 1, where capacities of line capacitances and high-voltage reactors have been taken into account.

In cases of extreme weathers, potential damage probabilities of the transmission lines are determined by damage probabilities proposed in [18], and the threshold is set to 0.3. That is, when the potential damage probability is >0.3, the starting time of transmission elements is considered to be affected. Potential damage probabilities of transmission elements affected by extreme weathers are shown in Table 2.

Next, the improved Dijkstra algorithm is used to find the optimal paths for other generators that are not started, as shown in Table 3.

Priority indexes of generators, which take into account characteristics of each generator, are shown in Table 4.

From Table 4, the starting sequence of the target generator is {1, 3, 4, 6, 5} at this stage, and the generator at node 1 has the highest priority.

In Table 2, the shortest weighted path for generator 1 is 1–2.

When the target generator is started, the network status is updated immediately, and the priority index of the target generator is recalculated. Finally, the starting sequence of generators and the corresponding starting time are shown in Table 5.

Table 1 Starting time weights of transmission elements

Start node	Terminal node	Branch weight	Start node	Terminal node	Branch weight
1	2	5.2	18	19	5.2
1	3	5.3	19	20	5.2
2	4	5.3	10	20	5.2
3	4	5.2	10	17	5.1
2	5	5.6	10	21	5.1
2	6	5.2	10	22	5.3
4	6	6	21	22	5.1
5	7	5.4	15	23	5.1
6	7	5.5	22	24	5.2
6	8	6	23	24	5.2
6	28	5.3	24	25	5.3
8	28	5.8	25	26	5.2
9	11	5.3	25	27	5.5
9	10	5.3	27	29	5.4
12	13	5.3	27	30	5.1
12	14	5.5	29	30	5.2
12	15	5.2			
12	16	5.1	4	12	10
14	15	5.3	6	10	10
15	18	5.2	6	9	10
16	17	5.1	28	27	10

Table 2 Potential damage probabilities of transmission elements affected by extreme weathers

Start node	Terminal node	Damage probability P_i
6	10	0.15
6	9	0.35
9	10	0.45
10	17	0.50
10	20	0.50
19	20	0.25
9	11	0.55
10	21	0.60

Table 3 Path weight and transmission path of target generator

Generator node number	Path weight D	Power transmission path
2	5.2	1–2
5	10.6	1–2–5
8	35.2	1–2–6–8
11	126.5	1–2–6–9–11
13	35.6	1–2–4–12–13

Table 4 Priority index of generator

Generator node number	Path weight	Generator parameters	Extreme weather impact indicator	Priority score
2	0	0.17	0	0.17
5	0.03	0.16	0	0.19
8	0.22	0.1	0	0.32
11	1	0.2	0.5	2
13	0.22	0.12	0	0.33

Table 5 Starting sequence of generators and the corresponding starting time

Stage	Generator node number	Recovery path	Maximum node voltage	Minimum node voltage	Recovery time
1	2	1–2	0.956	0.952	20.2
2	8	2–6–8	0.957	0.952	46.4
3	5	2–5	0.964	0.952	67
4	13	2–4–12–13	0.967	0.952	102.6
5	11	6–9–11	0.973	0.952	132.9

4.2 *Simulation analysis in simulation system of power grid of Guangzhou, Meizhou*

The feasibility of the proposed method is analysed in the simulation system of power grid of Guangdong, Meizhou, the power grid structure is shown in Fig. 5.

The Qingxi power plant in Meizhou has the capability of black start. The grid restoration scheme for Meizhou area without considering extreme weather conditions is shown in Fig. 6.

The Meizhou area is affected by extreme weathers which is the Jiaying-Meixian line is affected greatly. As a result, the optimal power supply path of generators has changed after being subjected to extreme weathers. The system restoration scheme in extreme weather conditions is shown in Fig. 7. The optimal path to start Meixian power plant removes the Jiaying-Meixian line. Thus, the

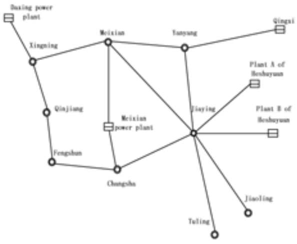

Fig. 5 *Power grid structure of Meizhou area*

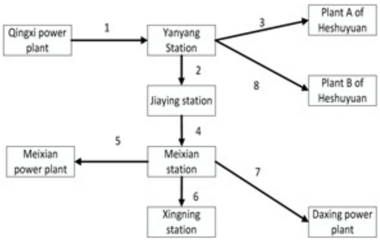

Fig. 6 *Grid restoration scheme for Meizhou area without considering extreme weather conditions*

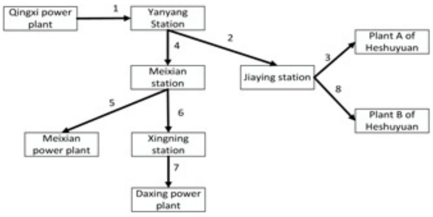

Fig. 7 *Sequence of power grid restoration in extreme weather conditions*

possibility of secondary accident occurring during the start-up of the transmission line is reduced.

5 Conclusion

A decision method of network restoration taking full consideration of the influence of extreme weathers on the starting process of transmission elements and generators is proposed. By analysing the influence of extreme weathers on the starting process of power components, the corresponding model of start-up time is established. Then the improved Dijkstra algorithm is used to get the optimal transmission path of the target generator, and the starting sequence of generators is obtained combining with starting parameters of generators.

In the proposed method, the starting sequence of generators and the optimisation of the transmission path are considered as a unified way to achieve the shortest time of each recovery stage and reduce the outage time of loads.

The simulation analyses in the IEEE 30-node standard system and a simulation system of power grid of Guangdong, Meizhou, show the accuracy and validity of the proposed restoration strategy. Compared with the existing methods, the proposed method takes account of the potential damage probability of the extreme weathers to the power components fully to avoid selecting the transmission element with greater starting risk, which is more suitable to meet the actual requirements.

6 Acknowledgments

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