International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 885

A DISTRIBUTION STRATEGY OF RELIEF AND REPAIR MATERIALS FOR DISTRIBUTION NETWORK IN TYPHOON SCENARIOS

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ABSTRACT

A distribution strategy of relief and repair materials for distribution network in typhoon scenarios is proposed in this paper. Firstly, the typhoon process is simulated by Batts model and the failure rate of electric poles is obtained based on the wind load theory. Secondly, the failure rate of overhead lines is obtained by tandem model of poles. Thirdly, a multi-timescale distribution method of relief materials before typhoon landing is proposed as the first step of the distribution strategy, through which wind-proof cables and generator cars are allocated based on the vulnerability index of overhead lines. The failure frequency of lines and the importance of loads are included in the vulnerability index, where the failure frequency of lines is related to the failure rate of lines. The weights of the two factors are determined by the Analytic Hierarchy Process (AHP). Finally, a distribution method of repair materials after typhoon is proposed as the second step of the distribution strategy, which is based on the priority index of lines to allocate the repair materials. The line integrity and load importance are included in the priority index and the weights of the two factors are determined by AHP. Simulation results show that the proposed distribution strategy can allocate the limited materials more effectively in typhoon scenarios.

Keywords: Batts model, failure rate; vulnerability index; multi-time scale; Analytic Hierarchy Process; priority index of lines.

NOMENCLATURE

Abbreviations	
MCS	Monte Carlo Simulation
AHP	Analytic Hierarchy Process
Symbols	
$R_{\max}$	the radius of maximum wind speed
$V_{R\max}$	the average maximum wind speed
μ_p	the mean value of the anti-bending strength of the concrete pole
δ_p	the standard deviation of the anti-bending strength of the concrete pole
M_p	the anti-bending strength of the pole
P_l	the failure rate of the overhead line
L_k	the vulnerability index of line k
P_k	the priority index of line k
a_1、a_2	weight coefficients in L_k

1. INTRODUCTION

The frequency of typhoon landfall has been increasing as one of the impacts of global warming in recent years. China is one of the few countries that has been severely affected by typhoon disasters in the world. According to statistics (1988-2010), the annual average economic loss caused by typhoon in China reaches 30 billion yuan, and the number of deaths comes to several hundred [1-3]. Meanwhile, the typhoon disasters cause great damage to the power system, among which the distribution network faults account for a large proportion [4]. It is critical that electric poles in the medium and low voltage distribution network collapse during a typhoon attacking process [5-6], exposing the problem of insufficient wind-resisting capability in the coastal distribution network.

Typhoon track can be forecasted by the meteorological department before landing [7]. The number of relief materials such as wind-proof cables and generator cars reserved by power company is limited before typhoon, and the lack of repair material increases the difficulty of repairing process. Moreover, the rules for the distribution of relief and repair materials are lack of research. In this context, the problem of finding the weak links of the distribution network and arranging the repair supplies needs to be solved urgently, as to get the limited relief and repair supplies allocated and utilized efficiently.

Relevant studies have been done in this field: Duties of different departments of power company before and after typhoon disaster were proposed in [8], by which different departments are coordinated against the disaster. Ref. [9] utilized historical data to identify and prioritize the important duties of river managers during predicted typhoons, which are arranged into timeline-based disaster prevention action plans. The principles of power grid regulation mode and accident handling during typhoon attacking process were proposed in [10], and the requirements related to ensuring safe production of power grids during typhoon were developed; Anti-accident measures proposed in Ref. [11] aimed to reduce the failure rate of distribution network equipment caused by typhoon disasters.

It is seen that extensive efforts have been done by power company to against typhoon. However, the distribution rules of limited relief materials in a short time before typhoon landing and the plans for the arrangement of manpower after typhoon need to be furtherly developed. To address this issue, a distribution strategy of relief and repair materials for distribution network in typhoon scenarios is proposed in this paper. In the first step of the distribution strategy, a multi-timescale distribution method of relief materials is developed based on weak links identification of the distribution network before typhoon landing; in the second step, the repair materials are allocated to lines with higher priority indexes to restore the lost load.

2. MODEL OF TYPHOON AND LINE FAILURE RATE

2.1 Batts typhoon model

The simulation of typhoon process is the base of distributing relief materials before typhoon landing. Batts model is one of the most widely used wind field models, which includes the calculation of wind speed at different points in the wind field during typhoon process. The wind speeds V_{rin} and V_{rout} in the wind field are shown in (1).

$$\begin{cases} V_{rin} = V_{R_{max}} \dfrac{r}{R_{max}}, & r \le R_{max} \\ V_{rout} = V_{R_{max}} \left(\dfrac{R_{max}}{r}\right)^x, & r > R_{max} \end{cases} \tag{1}$$

where r is the distance from the overhead line to the center of typhoon wind field; $x \in [0.5, 0.7]$. The model is introduced in detail in [12].

2.2 Failure rate of electric poles

The bending moment M_x suffered by section x of the pole in typhoon scenarios is calculated by wind load theory [13] in (2).

$$M_x = (w_{xz}h_1 + 2w_{xz}h_2 + w_{sv}\bar{h}) \times (1 + m_x) \tag{2}$$

$$\bar{h} = \frac{h_1}{3} \cdot \frac{2D_0 + D_x}{D_0 + D_x} \tag{3}$$

where h_1 is the distance from section x to the top of the pole; h_2 is the distance from section x to the crossbar; w_{xz} is the total wind load on the line and insulator; w_{sv} is the wind load on the pole body; D_0 is the diameter on the top of the pole; D_x is the diameter of section x; m_x is the additional bending moment coefficient generated by disturbance.

The poles of the distribution network are mostly made of concrete. The bending strength M_p of the pole obeys a normal distribution, and the probability density function is expressed in (4) [14].

$$f_R(M_p) = \frac{1}{\sqrt{2\pi}\delta_p} e^{-\frac{1}{2}\left(\frac{M_p - \mu_p}{\delta_p}\right)^2} \tag{4}$$

The pole fails once M_x is greater than M_p, and the failure rate of the pole P is depicted in (5).

$$P = P\{(M_p - M_x) < 0\} = \int_0^{M_x} \frac{1}{\sqrt{2\pi}\delta_p} e^{-\frac{1}{2}\left(\frac{M_p - \mu_p}{\delta_p}\right)^2} \mathrm{d}M_p \tag{5}$$

Considering that the failure rate of the pole is related to the failure periods, which include “Infant Mortality” period, “Steady-state” period and “Wearout Failures” period. The failure rate of the pole is modified by the bathtub curve in Fig.1.

The curve is fitted according to the historic failure data of poles. Then P is modified as P_f.

$$P_f = Y^{\beta-1}P \tag{6}$$

where Y is the operating years of the pole; in “Infant Mortality” period ($0<Y<t_1$), $\beta<1$; in “Steady-state” period ($t_1 \leqslant Y \leqslant t_2$), $\beta=1$; in “Wearout Failure” period ($t_2 \leqslant Y$), $\beta>1$.

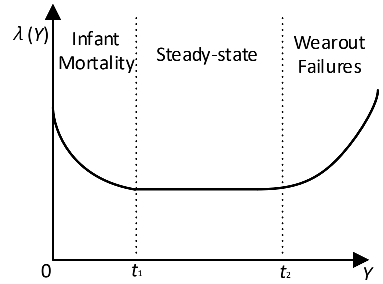

Fig.1 Bathtub curve of pole failure rate.

The failure rate of the overhead line P_l is determined by the tandem model of poles in (7).

$$P_l = 1 - \prod_{i=1}^{r}(1 - P_f(i)) \tag{7}$$

where r is the number of poles in one line.

3. THE DISTRIBUTION METHOD OF RELIEF MATERIALS BEFORE TYPHOON LANDING

The first step of the distribution strategy is the distribution of relief materials including wind-proof cables and generator cars. Considering the limitation of the relief materials, a multi-timescale distribution method of relief materials based on the vulnerability index of overhead lines is proposed aiming at improving the effectiveness of materials.

3.1 Vulnerability index of overhead lines

The vulnerability index of overhead line k is defined to identify the weak links of the distribution network which need to be reinforced with priority. Two factors are contained in L_k as depicted in (8).

$$L_k = a_1 \times F_k + a_2 \times I_k \tag{8}$$

$$a_1 + a_2 = 1 \tag{9}$$

The meaning of F_k and I_k in (8) are as follows. The F_k is defined as the failure frequency of overhead lines, which is determined by the results after M times simulation of typhoon process.

$$F_k = \frac{1}{M}\sum_{i=1}^{M} s_k(i) \tag{10}$$

where $s_k(i)$ is the state of line k after the *i-th* simulation of typhoon process. The *i-th* typhoon process simulated by Batts model is divided into n periods. For each time period, the failure rate of lines is obtained by (1)-(7), then the state of lines is determined by Monte Carlo Simulation (MCS). The final state of line k is represented by $s_k(i)$, in which 0 denotes fault state and 1 denotes normal state. Then the state of all overhead lines in the distribution network is recorded in $\boldsymbol{S}$. The load loss and economic loss are determined by $\boldsymbol{S}$ after this typhoon. What's more, the M is finally fixed when the value of load loss converges to a certain value.

The I_k is defined as the load importance connected with line k.

$$I_k = \frac{C_k \times D_k}{\sum_{i=1}^{m} C_i \times D_i} \tag{11}$$

where m is the total number of load buses in the distribution network; C_i is the amount of load at bus i (MW); D_i is the economic value per MW of bus i (yuan·(MW·h)$^{-1}$).

The weight coefficients in L_k are determined by AHP [15], which consists of three steps. Firstly, a hierarchical model containing goal level, criteria level and alternatives level is built to decompose the problem; secondly, a judgment matrix $\boldsymbol{C}$ about I_k and F_k is built based on the operating experience; finally, a_1 and a_2 are obtained by the normalization of the eigenvector of $\boldsymbol{C}$.

It can be obtained from the definition of L_k that the lines with higher vulnerability values are resulted from higher failure frequency or higher load importance, which are identified as weak links in typhoon scenarios.

3.2 The multi-time scale distribution method of relief materials

The forecast information of 72h and 24h before typhoon landfall provided by meteorological department is used in the distribution method, which includes paths and wind levels of typhoon [16]. The timeline of the multi-timescale distribution method is shown in Fig.2.

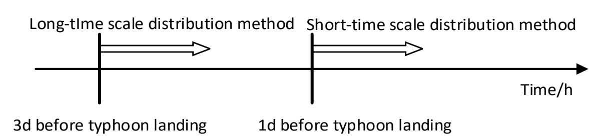

Fig.2 Timeline of the multi-timescale distribution method

The long-timescale distribution method of wind-proof cables: In urban and rural areas, the coverage of windproof cables is far from enough due to the limitations of terrain and cost. The installation of wind-proof cables is an effective means of typhoon prevention. The long-term scale distribution method of wind-proof cables is carried out 72h before typhoon landing. The vulnerability values of lines are obtained according to the typhoon forecast information. Then the wind-proof cables are allocated to the lines with higher vulnerability values, where the number of lines (k_1) is decided by the amount of wind-proof cables. After reinforcement, the wind load on the pole is reduced under the same wind speed. Thus, the failure rate of the pole decreases obviously.

The short-timescale distribution method of generator cars: The large scale of power-off accidents caused by typhoon are always sudden and severe. The prevention work should be accomplished as soon as possible. Generator cars are widely used in the prevention of power off accidents due to good maneuverability. However, the number of generator cars reserved by power department is limited.

The short-time scale distribution method is carried out 24h before typhoon landing. The allocation of windproof cables in the long-time scale distribution method improves the strength of the reinforced poles. The vulnerability values of lines are obtained again according to the real-time typhoon forecast information, and lines with higher vulnerability values (k_2) are allocated with generator cars to guarantee power supply during typhoon process.

4. THE DISTRIBUTION METHOD OF REPAIR MATERIALS AFTER TYPHOON

The lack of manpower and materials resources makes it difficult for power department to repair all failed line at the same time after typhoon, and it is of great significance to arrange the repair order reasonably to restore the power supply as soon as possible.

The priority index P_k of line k is defined considering the line integrity C_k and the load importance I_k connected with line k as shown in (12).

$$P_k = b_1 \times C_k + b_2 \times I_k \tag{12}$$

$$C_k = 1 - \frac{m}{n} \tag{13}$$

It is assumed that the total collapse number of poles in the distribution network is m and the number in line k is n after typhoon. It can be seen from the definition of P_k that the higher priority index of line k is resulted from higher integrity and higher load importance. Thus, the line with high P_k is easier to recover more load in a short time, which is repaired with priority.

The number of collapsed poles in each line is added up after the attacking process. The limited manpower and material resources are allocated to the lines with higher values of $P_{k.}$

Lines connected with more valuable and important load points are given higher priority to be improved by power department in traditional strategy. It ignored the actual failure condition of poles and overhead lines to some extent. The load loss and economic loss of the distribution network are compared applied with traditional strategy and the distribution strategy proposed in this paper in the following case study.

5. CASE STUDY

The IEEE RBTS BUS6 system is utilized as a test system as shown in Fig.3, in which two voltage levels of 33KV and 11KV are included.

The lengths of feeders are given in Table 1. The load level and economic value of unit load of each load point are shown in Table 2.

Table 1 Feeder lengths of IEEE RBTS BUS6 system.

Length(km)	Feeder Section Numbers
0.6	2 3 8 9 12 13 17 19 20 24 25 28 31 34 41 47
0.75	1 5 6 7 10 14 15 22 23 26 27 30 33 43 61
0.8	4 11 16 18 21 29 32 35 55
0.9	38 44
1.6	37 39 42 49 54 62
2.5	36 40 52 57 60
2.8	34 46 50 56 59 64
3.2	45 51 53 58 63
3.5	48

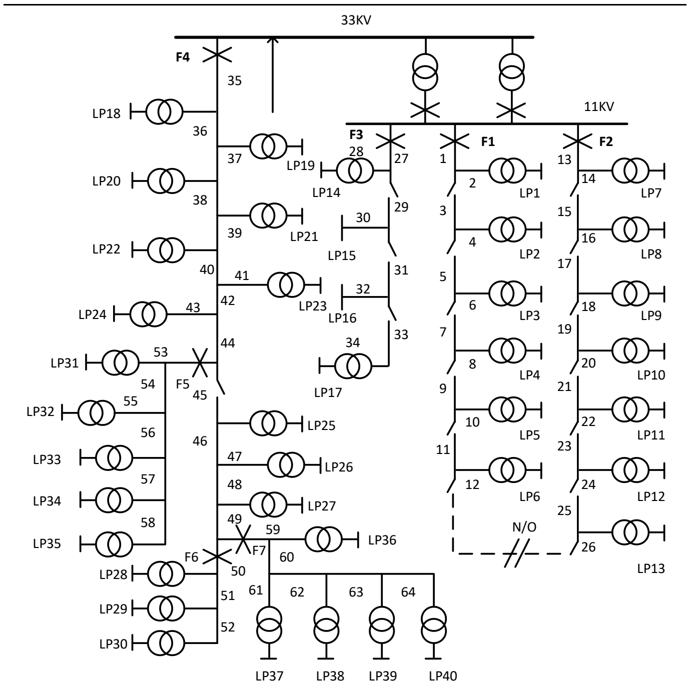

Fig.3 IEEE RBTS BUS6 system

Table 2 Customer data of IEEE RBTS Bus6.

Load Point	Load Level of per Load Point (MW)	Economic Value of Unit Load (yuan·(MW·h)$^{-1}$)
15	1.6391	790
16	0.9025	790
32 37	0.1929	790
20 30 34	0.2501	790
21 35	0.2633	790
24 40	0.3057	790
26 38	0.2831	790
14 17	0.4697	570
5 6	0.2163	570
2 4 11 19	0.1808	570
12 13 22	0.2070	570
1 3 9	0.1775	570
7 8 10 18 23	0.1659	570
27 29 33 39	0.1585	570
25 28 31 36	0.1554	570

The pole with strength class of *G* and height of 12m is used in this study. The mean value of the anti-bending strength (μ_p) is 58.51KN·m. The design wind speed of the concrete pole is about 30m/s under this strength. The landing location of typhoon is marked at ***O*** in Fig.4. The distribution network is represented by the pentagram in Fig.4. P1 is the forecast path and ΔP_0=35hPa, $\theta=\pi/4$ at 72h before typhoon landing; P2 is the more accurate forecast path and ΔP_0=37hPa, $\theta=\pi/4$ at 24h before typhoon landing.

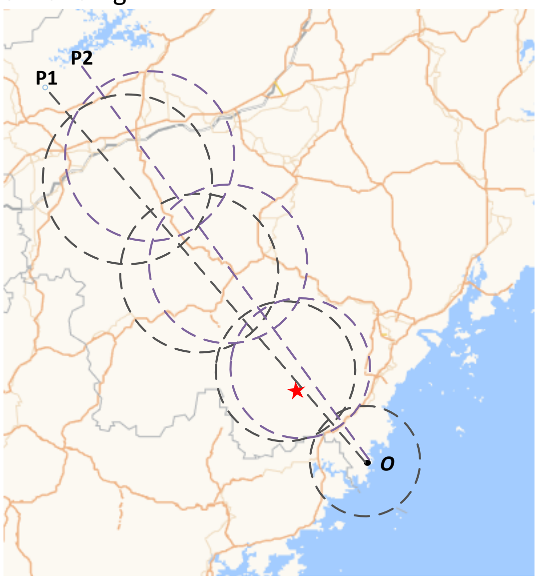

Fig.4 The geographic information of distribution network and forecast paths of typhoon

Under the above setting conditions, the vulnerability values of overhead lines at 72h and 24h before typhoon landing are obtained, respectively. The selected weak links by the proposed distribution method and traditional method are listed in Table 3.

Table 3 Results of weak links.

	Multi-timescale distribution method	Traditional distribution method
72h before Typhoon Landing	30,32,28,34,64	30,32,43,64,47
24h before Typhoon Landing	52,43,62,39	62,39,58,38

Based on the results in Table 3, the wind-proof cables and generator cars are allocated to the weak links 72h and 24h before typhoon landing, respectively. The load loss and economic loss after reinforcement by the multi-timescale distribution method and traditional distribution method are shown in Table 4.

Table 4 Results of load loss and economic loss.

	Multi-timescale distribution method	Traditional distribution method
Load loss (MW)	4.02	4.49
Economic loss (yuan)	6.14×10^4	6.43×10^4

Table 4 shows that the load loss and economic loss applied with the proposed distribution method are lower than applied with traditional distribution method.

After one simulation of typhoon attacking process, the priority indexes P_k of lines are obtained. Assuming that only 20 poles can be repaired at the same time after typhoon, and the first batch of lines which are repaired after typhoon are listed in Table 5.

Table 5 List of the first batch of repaired lines.

	distribution method of repair materials proposed in this paper	Traditional repair method
Feeder Number	47,38,55,58,61,10	52,55,61,28

Table 5 shows that more lines can be repaired in the first batch applied with the proposed strategy, and the restored load reaches 1.399MW after the repair of the 6 lines. While after repairing the lines 52, 55, 61, 28 determined by traditional repair method, the restored load is 1.105MW, which is lower to some extent.

CONCLUSION

A distribution strategy of relief and repair materials for distribution network in typhoon scenarios is proposed. The two steps of the distribution strategy are applied to allocate relief and repair materials before and after typhoon landfall, respectively. The following conclusions are given through the analysis of the test system.

1) The distribution strategy of relief materials before typhoon landing is based on the typhoon forecast, which requires the accuracy of typhoon forecast information.
2) The failure frequency of lines during typhoon process is considered additionally when allocating the relief materials compared with the traditional method, through which materials can be allocated efficiently to reduce the load and economic loss.
3) The line integrity and load importance are both considered in the repair process after typhoon, and the efficiency of restoring the lost load is improved significantly.

ACKNOWLEDGEMENT

This work is financially supported by the Research and demonstration of management and control verification for distribution network dispatching based on battalion coordination information (State Grid Corporation Science and Technology Project).

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