IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 9, 2019, accepted April 30, 2019, date of publication May 15, 2019, date of current version May 29, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2916382

Early Warning Method of Transmission Tower Considering Plastic Fatigue Damage Under Typhoon Weather

YI TANG[1], (Senior Member, IEEE), XIANGXIANG XU[1], BIN CHEN[2], AND TAO YI[2]
[1]School of Electrical Engineering, Southeast University, Nanjing 210096, China
[2]State Grid Fujian Electrical Power Research Institute, Fuzhou 350023, China

Corresponding author: Yi Tang (tangyi@seu.edu.cn)

This work was supported by the Science and Technology Project of State Grid Corporation Headquarters–Research on Loss Prediction and Technology Challenge of Typhoon Disaster in Power Grid.

ABSTRACT Strong typhoon can cause low-cycle fatigue damage to transmission towers throughout the impacted area and initiate tower collapse, leading blackout to the power system. As a result, it is necessary to develop an early warning method of transmission towers to help power companies make effective emergency response planning to minimize economic losses in advance of an approaching typhoon. In view of the existing models for predicting component failure probability overly relying on historical data and the lack of early warning methods for transmission towers, a new early warning method based on the failure process of transmission towers under typhoon disasters is proposed in this paper. First, a typhoon warning start point (TWSP) is selected to ensure prediction accuracy of transmission tower failure probability and timeliness of personnel and materials deployment for power companies, then mesh generation is applied to determine the risky tower affected by typhoon at the TWSP. Second, the duration time and changing wind speed of the typhoon on the risky tower are calculated according to typhoon short-time forecast information at the TWSP, and the wind speed is revised in the light of microtopography. Finally, the low-cycle fatigue damage mathematical model based on fatigue damage theory is combined with the improved Poisson formula to attain the failure probability of the transmission towers. In addition, since typhoon develops and dissipates with time, the typhoon path is tracked to correct the low-cycle fatigue damage value on the basis of typhoon nowcasting information, and the failure probability of transmission towers are constantly updated until typhoon departs from the risky zone. The proposed method is applied to the modified IEEE 30 system. The numerical results verify the proposed method is reasonable and effective.

INDEX TERMS Typhoon, transmission tower, fatigue damage, early warning method, short-time forecast, nowcasting, microtopography.

I. INTRODUCTION

Under the background of global climate warming, the frequency and intensity of typhoon disasters have risen obviously, and its enormous destructive force will pose a huge threat to the security of power grids in coastal areas [1], [2]. Compared with conventional power grid accident, the widespread and prolonged power outages caused by typhoon extend the time of repairing and resuming power supply, let alone interruption of communication, health care, water distribution, traffic signaling and other lifeline systems that depend on electricity [3]–[5]. In order to avoid the passive post-disaster rush repair of power companies, it is especially necessary to develop a reasonable and effective early warning method to predict power system reliability before a typhoon makes landfall.

At present, domestic and foreign scholars make lots of research about the operation reliability of power system under typhoon weather, mainly include prediction of failure rate of power grid components and proposal of early warning methods. In the aspect of component failure prediction, various statistical methods such as regression model, generalized linear model and generalized additive model were presented to model failure rates [6]–[11]. Avoiding the mechanism analysis of typhoon disaster that affect the power system, these models are simple and easy to implement, but the validity of

The associate editor coordinating the review of this manuscript and approving it for publication was Zhiyi Li.

results depends on a large amount of historical data, and the requirements for data accuracy are relatively high. In view of uncertainty about meteorological forecast data, fuzzy theory was introduced to establish the relationship between external environmental parameters and failure rate of transmission line [12], [13], the formulation of fuzzy rules has certain subjectivity, which makes the accuracy of the method in dispute. In terms of early warning methods, reference [14] proposed a method considering differential time interval selection to predict the failure probability of transmission lines based on the stress-strength interference model. The power system early-warning defense schemes was extended from traditional fault to group-occurring faults during typhoon disasters in [15]. The above warning objects are mainly transmission lines, ignoring the loss that the collapsed tower will bring to the grid.

According to the analysis of actual disaster damage, the impact of the strong typhoon on the coastal power grid is more concentrated in the structural destruction such as collapsed tower and broken rod. Considering preparedness and restoration efforts of transmission line and transmission tower are completely different before, during and after disasters, it is necessary to carry out research on warning and defending method for transmission towers to resist damage caused by strong typhoon [16].

A reasonable and effective early warning method of transmission towers should closely track the changes of typhoon, and the typhoon forecast information is basically derived from meteorological forecast. Forecasts of disaster weather are mainly divided into three categories by forecast time scale, namely short-term forecast, short-time forecast and nowcasting. The short-term forecast focuses on the weather changing trend in the next 3 days. The short-time forecast refers to the description of weather parameters in the coming 12 hours, the time resolution of the scale is less than or equal to 6 hours, of which 0 to 2 hours is nowcasting. In general, forecast time scale is an important reference factor for the accuracy of weather forecast. Compared with short-term forecast, ‘Capture the wind and rain’ characteristics of short-time and nowcasting forecast determines its important position in severe weather forecast. Short-time forecast can provide the direction of personnel and materials deployment while nowcasting forecast is helpful to improve the accuracy of prediction result. Making full use of the short-time and nowcasting forecast information about the forthcoming typhoon is conducive to guiding power companies to adopt effective measures to mitigate severe consequences of typhoon disasters.

Due to the lack of early warning methods of transmission towers under typhoon disasters, this paper proposes a method to predict the failure probability of transmission tower under typhoon weather. The main contributions of this paper are as follows:

1) Since typhoon path has a great influence on towers, the short-time and nowcasting forecast information of the approaching typhoon can be fully utilized to compute the wind speed and duration time, and particular geographic features of tower are also considered to revise the wind speed.
2) Considering plastic damage process of transmission towers under strong typhoon weather, the low-cycle fatigue damage mathematical model and the improved Poisson formula are built instead of directly mapping the relationship between typhoon parameters and failure probability with historical data.
3) The early warning methods can provide power companies initial warning result and constantly updated warning result of transmission towers, moreover, the most possible failure time of tower can be obtained.

The remaining sections are as follows. Section II describes basic information needed for tower failure forecast. Section III introduces the plastic fatigue damage process of transmission towers under typhoon hazards. Section IV presents the early-warning system of transmission towers. The typhoon path in short-time and nowcasting forecast are utilized to predict the duration time and wind speed of typhoon on transmission tower in Section V. The low-cycle fatigue damage mathematical model and the improved Poisson formula are established to attain failure probability of transmission tower in Section VI. In Section VII, the proposed method is applied to the modified IEEE 30 system with Super Typhoon Maria in 2018, and conclusions are drawn in Section VIII.

II. INFORMATION BASE

Basic information acquisition is an important premise for improving the accuracy of early warning results of transmission towers under typhoon weather. The early warning method of this paper involves many influencing factors. In addition to the basic information of transmission towers, natural environment information such as meteorology and terrain are all required.

A. TYPHOON FORECASE INFORMATION

Generally, the weather bureau will locate hourly to report actual typhoon information when the typhoon center enters the 24-hour warning line, including the current typhoon center position, air pressure, typhoon moving speed, moving direction, maximum wind speed and intensity information, etc. Moreover, the weather condition in the future will be released according to the time resolution of short-time forecast, and the nowcasting information will be updated when positioning typhoon center each time. A fold line typhoon path is represented by point-by-point extrapolation method, the forecast information generally only includes the typhoon center position, the maximum wind speed and the center air pressure.

B. MICROTOPOGRAPHY INFORMATION

The failure of the transmission tower is not only related to the macroscopic weather conditions, but microtopography also plays an important role. Microtopography is a partial narrow

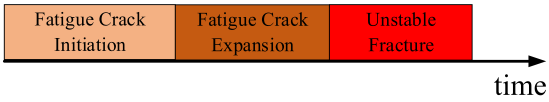

FIGURE 1. Fatigue damage process of transmission towers.

range of conventional terrain, including mountain peak, hillsides, valleys, and so on. In this small area, the weather is prone to comprehensive changes and certain meteorological factors are enhanced [17], [18], jeopardizing the safety of transmission towers. At present, the advanced Geographic Information System (GIS) and mesh generation method can accurately provide the geographical location and microtopography information of transmission tower in the risky area.

C. TOWER INFORMATION

In the strong typhoon environment, the materials (Q345 steel, Q420 steel, Q460 steel, etc.) of transmission tower determine their ability to withstand severe weather. Furthermore, the basic condition of the tower, service time and health information are also an indispensable part to assess the failure rate of transmission tower.

III. FATIGUE DAMAGE PROCESS OF TRANSMISSION TOWER

It generally maintains strong wind for about two days after the landing of typhoon. During this period, the transmission tower will enter a plastic state to dissipate the energy generated by wind loading, and the failure of transmission tower is taken as a cumulative process of plastic fatigue damage (known as low cycle fatigue damage) caused by the repeated strong wind action. Fatigue is an insidious failure mechanism. As shown in Figure 1, The whole process can be divided into three stages: crack initiation, crack expansion and unstable fracture [19]–[21].

When the tower is located in the risky wind circle corresponding to a certain critical wind speed, it starts to enter the plastic state which represents the crack initiation. The fatigue crack expansion is the accumulation process of damage, which related to duration time of wind speed acting on tower. As the final stage of fatigue failure, the occurrence of instability fracture is instantaneous, but from the whole process of fatigue, it is caused by the cumulative fatigue damage, instability fracture is just a manifestation that damage increases to critical value.

It is clear that the damage value is directly related to wind speed. As shown in Figure 2, when the wind speed exceeds critical wind speed V_{cr}, the plastic fatigue damage will increase gradually with time passing, the larger the wind speed, the shorter duration time that the damage accumulates to critical value and tower get failure from normal.

IV. EARLY-WARNING SYSTEM OF TRANSMISSION TOWERS UNDER TYPHOON ENVIRONMENT

During typhoon period, the failure probability prediction of transmission towers is closely related to the typhoon forecast information. The early-warning process of tower should be a renew process with updating of typhoon forecast information. In this paper, the early warning system based on typhoon short-time and nowcasting forecast is described by the flow chart in Figure 3.

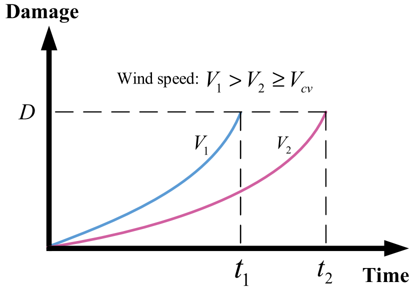

FIGURE 2. Schematic of plastic fatigue damage accumulation under different wind speed.

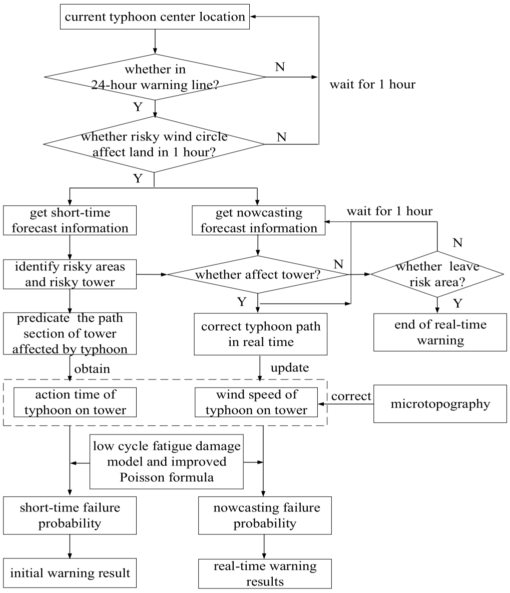

FIGURE 3. Early-warning system of transmission towers.

1) Determine the TWSP. If the typhoon risky wind circle will affect land within 1 hour, the short-time and nowcasting forecast information of the typhoon at this moment will be obtained, otherwise continue to wait for the right moment.

2) Publish the initial warning results. The risky area and the risky tower are determined according to the typhoon short-time forecast information, the duration time and the wind speed revised by the microtopography of typhoon on tower are calculated to predict the failure probability of transmission towers with low-cycle fatigue damage model and improved Poisson formula.

3) Continuously renew warning results until the typhoon departs from the risky zone. With the movement of typhoon, the low-cycle fatigue damage value of tower need to be revised due to the replacement of original prediction path by actual typhoon path. Meanwhile, the failure probability of transmission towers need to be updated with latest nowcasting information.

V. PREDICTION OF TYPHOON IMPACT

A. TYPHOON WIND FIELD MODEL

Typhoon is a warm-hearted structure with a particularly low center pressure and center temperature higher than ambient temperature. The typhoon wind field is generally determined by various empirical or semi-empirical and semi-theoretical wind field model with typhoon basic parameters [22]. In terms of disaster warning, the parametric wind field model is widely utilized due to its relatively accurate simulation effect and high computational efficiency. Therefore, the typhoon is represented by the Rankine vortex field model in this paper, and the model is defined as [23]:

$$V_i = \begin{cases} \dfrac{r_i}{R_{\max}} V_{\max}, & r_i \in [0, R_{\max}] \\ \dfrac{R_{\max}}{r_i} V_{\max}, & r_i \in [R_{\max}, \infty) \end{cases} \tag{1}$$

where V_i is wind speed at point i; r_i is the distance from point i to the typhoon center; $V_{\max}$ is the maximum wind speed; and $R_{\max}$ is radius of the maximum wind speed.

The identification model of the radius of maximum wind speed is [24]:

$$R_{\max} = 80 - k(950 - P_c) \tag{2}$$

where P_c is typhoon center pressure, the unit is hPa, k is the model coefficient, the value is 0.769.

B. THE DURATION TIME AND WIND SPEED UNDER SHORT-TIME AND NOWCASTING FORECAST

1) DETERMINATION OF THE TWSP

In order to improve the accuracy of the prediction results, the early warning system of transmission tower will be put into service when the typhoon is hours offshore and its risky wind circle is about to affect the land. As shown in Figure 4, a ∼ d are the hourly actual typhoon positioning information from the weather bureau,f ∼ h are short-time prediction path at typhoon current location *e*. After the typhoon enters the 24-hour warning line, the typhoon information released by the weather bureau each time should be paid close concern so as to determine the TWSP. The specific judgment conditions are as follows:

$$\begin{cases} \begin{cases} V_{di}h + R_{\mathrm{i}} \le S_i \\ R_{\mathrm{i}} > S_i \end{cases} & \text{warning start point } i \\ V_{di}h + R_{\mathrm{i}} > S_i & \text{continue to wait} \end{cases} \tag{3}$$

where V_{di} is the typhoon moving speed at typhoon center position i; h is typhoon positioning time interval, usually 1 hour in 24-hour warning line; R_{i} is the risky wind circle radius at typhoon center position i; S_i is the shortest distance from the coastline to position i.

After determining the TWSP (assuming point e in the figure 4), the risky wind circle radius at this point is taken as the boundary to ensure the risky land area affected by typhoon, and the risky land area is divided into several grids by GIS to obtain the latitude and longitude of risky transmission towers.

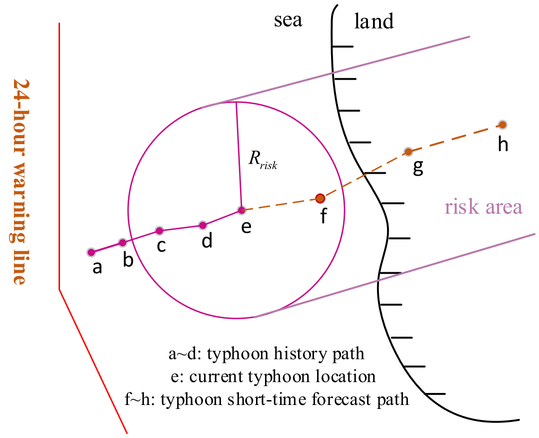

FIGURE 4. Schematic of typhoon moving path.

Then, the duration time and wind speed could be predicted from the TWSP.

2) PREDICTION UNDER SHORT-TIME FORECAST

The main steps of prediction process under short-time forecast are as follows:

(1) Determine the influence state of typhoon on the tower in each short-time forecasting fold line path. The different geographical position of transmission towers determines the variation of duration time from typhoon. For a fold line short-time prediction path, the relationship between the distance from the tower to the predicted typhoon center point and the typhoon risky wind circle radius should be judged as equation (4). If two adjacent typhoon prediction center points are both inside or outside the risky wind circle, it is believed that the typhoon center will maintain the influence state of the front path section on the tower during this path section. Otherwise, the typhoon will start or end to influence tower in this path.

$$\begin{cases} d_i - R_i > 0 \ and \\ \quad d_{i+1} - R_{i+1} < 0, & \text{start to influence tower} \\ d_i - R_i < 0 \ and \\ \quad d_{i+1} - R_{i+1} > 0, & \text{end to influence tower} \\ (d_i - R_i) \\ \quad (d_{i+1} - R_{i+1}) > 0, & \text{keep influence state of front} \\ & \quad \text{path section} \end{cases} \tag{4}$$

where d_i is the distance from the tower to the predicted typhoon center position i.

Among them, the risky wind circle radius of different prediction points can be obtained by using back calculation of equation (1) on the basis of critical wind speed that cause tower into plastic state and known prediction information. The specific typhoon center position O' and O'', which respectively represent the point starting to affect the tower and ending to affecting the tower, is the intersection point of a circle (the tower position is the center of circle and the radius of risky wind circle is the radius of circle) and a straight line (typhoon short-time predication path section that change the influence state on tower). For the convenience of follow-up expression, this paper assumes that O' and O'' respectively fall in 'ef' section and 'gh' section in Figure 4.

(2) Compute the duration time of typhoon on tower as follows:

$$t_h = (\frac{|O'f|}{|ef|} + m + \frac{|gO''|}{|gh|})\Delta T \tag{5}$$

where $|O'f|$ and $|gO''|$ are effective distances that typhoon influence tower in path section where the tower start and end to be affected; $|ef|$ and $|gh|$ are total distance of typhoon path section where the tower start and end to be affected; m is the number of times that typhoon fully act on the tower for each fold line paths; ΔT is the time resolution of short-time forecast.

(3) Partition the duration time of typhoon acting on tower. During typhoon period, the wind speed will change constantly with the variation of typhoon itself, as well as the change of distance between the tower and typhoon center caused by typhoon movement. According to historical typhoon information, the moving wind speed of the strong typhoon is much smaller than its rotating wind speed, it can be approximated that the typhoon rotating wind speed acting on tower keep constant in 10 minutes, and the duration time can be divided into n time intervals per 10 minutes. Considering typhoon center position of short-time forecast from the weather bureau has important guiding significance for typhoon wind direction. In order to reduce personal error, the typhoon forecasting center should be used as starting point or ending position of each time interval. The time interval of tower affected by typhoon can be calculated using the following equation:

$$n = 6[\mathrm{int}(\Delta T\frac{|O'f|}{|ef|}) + \Delta T m + \mathrm{int}(\Delta T\frac{|gO''|}{|gh|})] \tag{6}$$

Taking the path section where the tower start to be affected as an example, (x_0, y_0) is the latitude and longitude of typhoon center O',(x_e, y_e) and (x_f, y_f) are latitude and longitude of typhoon prediction center e and f. Assuming that typhoon make uniform velocity motion in each fold line path, the latitude and longitude of typhoon center (x_i, y_i) after ith time interval could be given by:

$$\begin{cases} V_0 = \dfrac{|ef|}{\Delta T} \\ \left[(x_i - x_{i-1})\dfrac{\pi R}{180}\cos y_{i-1}\right]^2 + \left[(y_i - y_{i-1})\dfrac{\pi R}{180}\right]^2 = \left(\dfrac{V_0}{6}\right)^2 \\ \dfrac{y_i - y_e}{x_i - x_e} = \dfrac{y_f - y_e}{x_f - x_e} \end{cases} \tag{7}$$

where R is the Earth radius, take the value of 6371km.

According to the Rankine model, the wind speed acting on tower is related to the distance from the tower to typhoon center. The distance in different time intervals can be approximately presented as:

$$d_i^2 = \left[(x_i - x_g)\frac{\pi R}{180}\cos y_g\right]^2 + \left[(y_i - y_g)\frac{\pi R}{180}\right]^2 \tag{8}$$

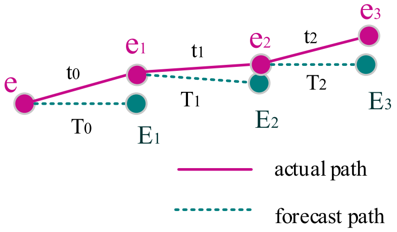

FIGURE 5. Schematic of typhoon nowcasting prediction path.

$$d_{i+1}^2 = \left[(x_{i+1} - x_g)\frac{\pi R}{180}\cos y_g\right]^2 + \left[(y_{i+1} - y_g)\frac{\pi R}{180}\right]^2 \tag{9}$$

$$r_i = \frac{1}{2}(d_i + d_{i+1}) \tag{10}$$

where d_i is the distance from the typhoon center to the risky tower at the beginning of ith time interval, d_{i+1} is the distance from the typhoon center to the risky tower at the ending of ith time interval, r_i is approximate distance from the typhoon center to the risky tower of ith time interval. Therefore, the wind speed acting on tower at different time intervals can be obtained according to equations (10) and (1).

3) PREDICTION UNDERN NOWCASTING FORECAST

Starting from the TWSP, the nowcasting information of typhoon from the weather bureau is hourly tracked. As shown in Figure 5, when the typhoon center locates at point e, the future typhoon position from nowcasting forecast is at point E_1. Considering the prediction error, the actual typhoon position is at point e_1 with future typhoon position E_2, and so on. The weather bureau monitors the latest typhoon data in real time to correct the nowcasting results, so the duration time and wind speed of typhoon on the risky tower also need to be updated in real time.

The influence state of typhoon on the tower is determined in nowcasting prediction path section, and the duration time is updated according to the influence state. The iteration formula is given as follows:

$$\begin{cases} t_{h0} = T_0 \\ t_{hi} = t_{hi-1} + t_{i-1} + T_i - 2T_{i-1} \end{cases} \tag{11}$$

where t_{hi} is the total action time when the typhoon center moves at point i, which contains the predicting action time related to nowcasting path and the actual action time related to existing path. T_i is the predicting action time that typhoon will affect tower in nowcasting path section while t_i is the actual action time. The wind speed prediction of nowcasting is similar to short-time forecast.

C. WIND SPEED REVISED BY MICROTOPOGRAPHY

Wind pressure height coefficient should be corrected by terrain conditions according to Chinese architectural structure load standards (GB50009-2012). Considering the wind pressure is proportional to the square of the wind speed. For many regular mountain peaks and hillsides as shown in Figure 6,

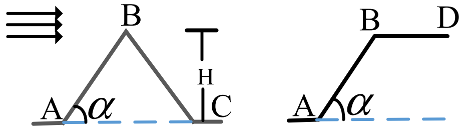

FIGURE 6. Schematic of mountain peak and hillsides.

the wind speed correction factor of top B is given as follows:

$$\gamma = 1 + k\tan\alpha\left(1 - \frac{z}{2.5H}\right) \tag{12}$$

where $\tan\alpha$ is the gradient of windward slope for mountain peak or hillside, take it as 0.3 when the value is greater than 0.3; k is the coefficient, the value is 2.2 for mountain peak while the value is 1.4 for hillside; H is the total height of mountain peak or hillside, the unit for H is m; z is the nominal height of tower, the unit is m, take $z = 2.5\,H$ when $z > 2.5\,H$.

Take the correction coefficient of A as 1.0, and the correction coefficient of peak C and hillside D are 0.707 and 1 respectively, the other places can be determined by linear interpolation. The correction coefficient can be selected between 0.87 and 0.92 when it comes to occlusive terrain such as valley and basin.

VI. FAILURE PROBABILITY OF TRANSMISSION TOWERS

A. FATIGUE DAMAGE THEORY

Damage is an abstract concept that cannot be measured directly by physical quantities, it is usually represented by a dimensionless parameter. According to Palmgren-Miner linear fatigue damage criterion [25], the total fatigue cumulative damage D of tower can be superimposed by a single fatigue damage. When it is equal to 0, the tower is considered to be safe. When it is equal to 1, the tower is considered to get collapsed.

B. LOW CYCLE FATIGUE DAMAGE MODEL

It is inevitable that strong typhoon will pose certain plastic damage on transmission tower within a short time period. According to the test data and finite-element analyses, the damage function related to plastic strain can be expressed in the form of exponent in [26], considering the linear relationship between applied stresses and strain, the fatigue damage model of the tower under strong typhoon can be postulated as follows:

$$D_i = \begin{cases} 0, & V_i \in [0, V_0) \\ ae^{bV_i^2}, & V_i \in [V_0, V_m) \\ 1, & V_i \in [V_m, \infty] \end{cases} \tag{13}$$

where a and b are model coefficients which are related to the material of the tower. V_i is the wind speed acting on tower at time interval i; V_0 is critical wind speed which start to pose low-cycle fatigue damage on the tower, different critical wind speed value for different material; V_m is limited wind speed which directly causing tower collapse without time accumulation, the value is also determined by material; D_i is the low-cycle fatigue damage posing on tower per minute.

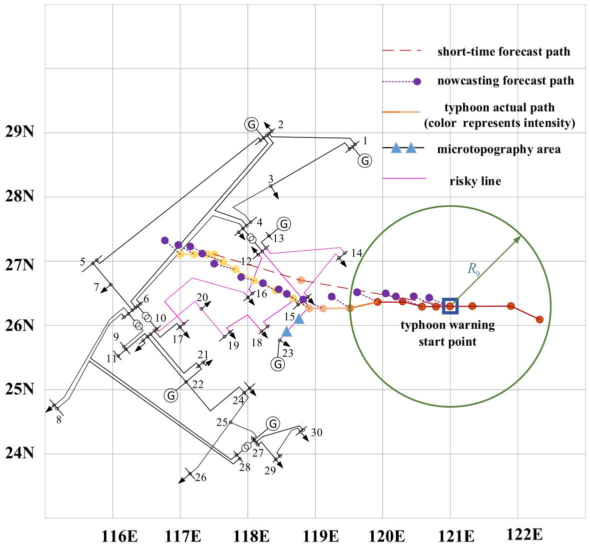

FIGURE 7. Typhoon path and IEEE30 node topology.

C. FAILURE PROBABILITY PREDICTION MODEL OF TRANSMISSION TOWERS

The failure probability of the transmission tower under strong typhoon weather is related to the time accumulation of fatigue damage. Considering that the Poisson model can effectively predict the failure rate of components in a short time [27], the probability model that tower does not collapse in previous i time interval can be corrected as:

$$P_{toi} = e^{\left[\sum_{j=1}^{i}\left(-\frac{D_j}{1-\Delta t(\sum_{k=1}^{j-1} D_k)-D_j}\Delta t\right)\right]} \tag{14}$$

Then the failure probability of the transmission tower in previous i time intervals is

$$P_{towerlossi} = 1 - P_{toi} \tag{15}$$

where Δt is the length of time interval, $\Delta t(\sum_{k=1}^{j-1} D_k)$ is existing cumulative damage of tower from the previous $j - 1$ time interval. when $\Delta t(\sum_{k=1}^{j-1} D_k) < 1$ and $D_j = 0$, namely the tower keep operation in the previous $j - 1$ time interval, and there is no new fatigue damage in time interval j, no matter how long the typhoon acts on the tower, the tower collapse is an impossible event. While $\Delta t(\sum_{k=1}^{j-1} D_k) + D_j = 1$, tower collapse is an inevitable event without considering time accumulation effect.

VII. CASE STUDY

Based on the meteorological information of No. 8 Super Typhoon Maria in 2018, the proposed early warning method is applied to the IEEE 30-node system modified by the actual topology. As shown in Figure. 7, the system includes 30 nodes and 41 transmission lines. The position (121E, 26.3N) is selected as TWSP using the preceding judgment method,

TABLE 1. Lines and towers affected by typhoons.

Line	Line length(km)	Number of towers	Number of equivalent towers
14-15	98.02	98	19
12-14	119.25	119	23
12-15	107.05	107	21
15-23	73.13	73	14
15-18	81.72	81	16
18-19	40.01	40	8
12-16	80.33	80	16
19-20	66.87	66	13
10-20	82.85	82	16
17-16	114.18	114	22

TABLE 2. Wind speed correction coefficient of tower in 15-23 line.

1#	2#	3#	4#	5#	6#	7#
1	1	1.264	1.528	1.254	0.98	0.87
8#	**9#**	**10#**	**11#**	**12#**	**13#**	**14#**
1.08	1.161	1.01	0.858	0.92	1.042	1

the time resolution of short-time forecast is 6 hours, and the forecast information of current typhoon position in coming 1 hour is nowcasting. The solid line in this figure shows the typhoon actual path, the lighter the color, the greater intensity of typhoon. It is considered that all transmission towers are made of steel Q345 without obvious defects, and the span distance between towers are 1000m. The nominal height of tower is 20m, the value of a is 1.9249e-7, the value of b is 0.0055, V_m is 53m/s, V_0 is 20m/s. Setting 9-level wind circle as risky wind circle according to critical wind speed of low cycle fatigue damage.

A. RISKY TOWER AND MICROTOPOGRAPHY INFORMATION

Typhoon intensity has obvious attenuation trend after typhoon landing. The transmission line with farther geographical distance will not be considered in this paper, while line 14-15, 12-14, 12-15, 15-23, 15-18, 18-19, 12-16, 19 -20, 10-20 and 17-16 are all listed as risky lines. Since the 1000m span could be ignored relative to the typhoon risky wind circle radius, it is assumed that five towers within 5 km have the same failure probability and five towers could be equivalent to one tower. Under these circumstances, the specific length information of the risky line and the number of equivalent towers are shown in Table 1.

In order to illustrate the impact of microtopography under typhoon environment, it is assumed that the towers of 15-23 line are all in microtopography area. The specific terrain conditions are shown in Figure 8.

Among them, 5#, 6#, 10# and 11# are in the leeward side, 3#, 8#, 13# are in the windward side, and the remaining towers are on the valley, mountaintop and mountain foot. The wind speeds acting on transmission towers will be revised by microtopography as described above, H_1, H_2 and H_3 are set to 40m, 30m and 20m, respectively, $\tan\alpha_1$ is 0.3, $\tan\alpha_2$ is 0.1. The specific wind speed correction factors are as follows:

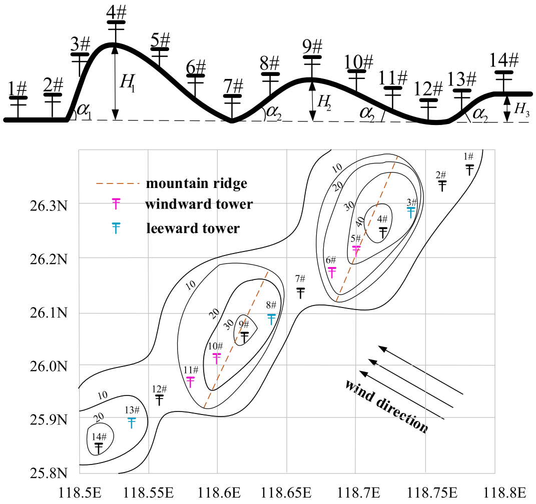

FIGURE 8. Microtopography and contour line of transmission towers in line 15-23.

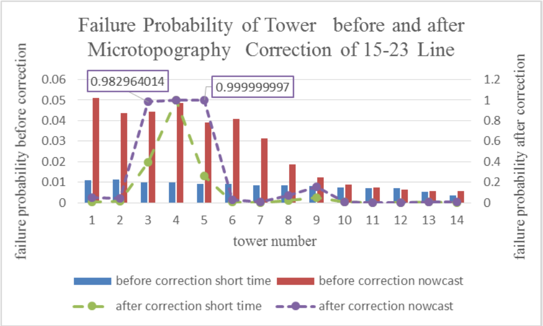

FIGURE 9. Failure probability of equivalent tower in line 15-23.

B. FAILURE PROBABILITY RESULTS OF SHORT-TIME AND NOWCASTING PREDICTION

According to short-time forecast information at the TWSP and continuous updated nowcasting information during typhoon movement, the failure probability of risky towers can be predicted. Lines 15-23 is taken as an example limited by the article space. In order to compare the differences of short-time and nowcasting results at the same prediction time, the nowcasting forecast result after 12 hours from the TWSP is selected. Figure. 9 visualizes the failure probability of each equivalent tower.

Under the same microtopography conditions, short-time prediction result about the failure probability of towers in line 15-23 generally lower than nowcasting prediction, this is due to that short-time prediction path at the TWSP far from line 15-23 compared with the nowcasting prediction path in Figure. 7, the wind speed received by tower is relatively small, as well as the low cycle fatigue damage. The failure probability of tower has close relationship with the typhoon path. Generally, the failure probabilities of tower close to typhoon path is larger, which in line with actual situation, indicating that the proposed method has certain effectiveness.

In addition, the failure probability of tower is quite different pre and post microtopography correction in same forecast scale. The failure probability of 4# towers does not exceed 5%

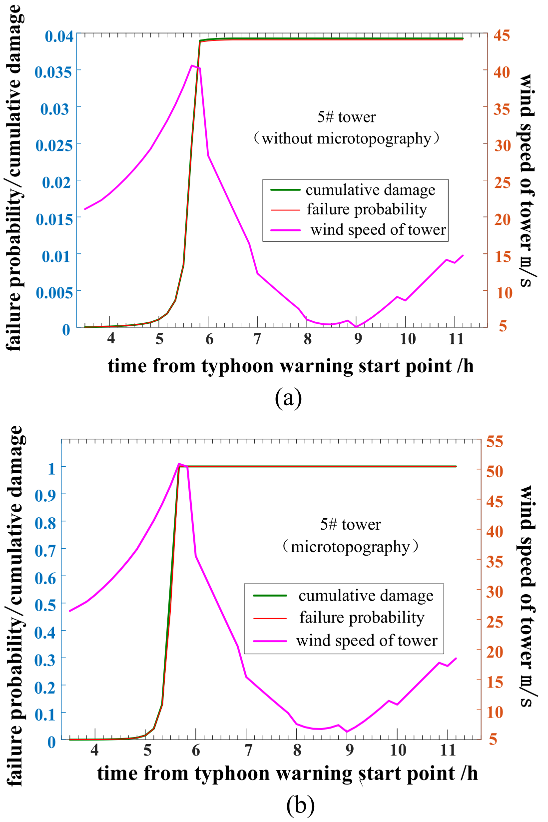

FIGURE 10. **Change of cumulative damage of 5# tower. (a) Before microtopography correction. (b) After microtopography correction.**

both in short-time and nowcasting forecast before correction. After considering the influence of microtopography, the collapse of 4# tower is considered to be an inevitable event. With a concrete analysis of this phenomenon, it is find that 4# tower is located at the top of the highest mountain with small obstacle, the tower is prone to get plastic fatigue damage. Besides, the failure probability of 3# tower and 5# tower located at higher terrain are also high. The results make a good explanation for the fact that towers collapse are not scattered everywhere, but concentrate in a small area. The influence of microtopography cannot be ignored under the typhoon environment.

C. CHANGE OF CUMULATIVE PLASTIC DAMAGE WITH TYPHOON MOVEMENT

During typhoon movement, the internal damage of tower is continuously increasing. When the damage accumulates to a certain value, the tower will collapse at a certain time, which bring a fatal impact to the normal operation of power system. Take 5# tower supporting line 15-23 as an example. As shown in Figure 10, the cumulative damage is close to 0.04 with max wind speed received by tower close to 40m/s before correction, while damage close to 1 with max wind speed close to 50m/s after correction, it is obvious the plastic damage increase most rapidly when the wind speed over 40m/s.

It is also worth noting that the changing tend of cumulative damage pre and post microtopography correction is similar in Figure 10. The tower is subjected to higher wind speed within 5-6 hours after the TWSP, fatigue damage and the failure probability both increase sharply, that is to say at this time segment the tower is most likely to get collapsed. With the decrease of typhoon intensity after landing, the typhoon center gradually departs from the tower, the wind speed acting on the tower no longer poses low-cycle fatigue damage on the tower, and the probability of the tower collapse is no longer increased.

The early warning method can update failure prediction of tower as typhoon moving to the latest position. When the failure probability of tower changes sharply next time, it indicates that the tower is more easily to get collapsed during this period.

VIII. CONCLUSION

Typhoon can cause widespread and prolonged power outages, effecting social production and life through direct loss of power and loss of other lifeline systems dependent on electric power. To improve current forecasting methods and to provide insight into tower collapse under typhoon weather, an early warning method of transmission tower considering plastic fatigue damage is proposed in this paper, and the results of testing numerical example verified that the method is reasonable and effective.

The proposed early warning method has the following characteristics:

1) It pays more attention to the ways and mechanism of typhoons affecting the tower instead of historical data. Tower collapse is an inevitable result when damage accumulation to critical value.
2) An appropriate TWSP is selected according to typhoon's actual information so as to ensure the early warning requirements of efficiency and accuracy.
3) Based on typhoon prediction path, the typhoon intensity, the duration time, the material of towers and the terrain condition are all considered for accurately predicting the failure rate of transmission towers.
4) The low-cycle fatigue damage mathematical model is employed to compute the internal damage caused by wind speed, it combined with the improved Poisson model can describe event occurrences well. The example results show the failure rate is closely related to the typhoon path and microtopography, which matches practical case.
5) The short-time initial early warning results obtained before typhoon landing and the updated nowcasting results obtained during typhoon movement are helpful for power companies to master the dynamic change of typhoon and make effective emergency preparedness.
6) It should be pointed that the implementation of the proposed method is mainly to demonstrate the feasibility of the method. For practical applications, relevant fatigue test data of transmission tower with different materials need to be acquired in advance to ensure the related coefficient.

REFERENCES

[1] R. A. Davidson, H. Liu, I. K. Sarpong, P. Sparks, and D. V. Rosowsky, "Electric power distribution system performance in Carolina hurricanes," *Natural Hazards Rev.*, vol. 4, no. 1, pp. 36–45, 2003.

[2] Y. Wang, C. Chen, J. Wang, and R. Baldick, "Research on resilience of power systems under natural disasters—A review," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1604–1613, Mar. 2016.

[3] J. Winkler, L. Dueñas-Osorio, R. Stein, and D. Subramanian, "Performance assessment of topologically diverse power systems subjected to hurricane events," *Rel. Eng. Syst. Safety*, vol. 95, no. 4, pp. 323–336, Apr. 2010.

[4] Z. Huang, D. V. Rosowsky, and P. R. Sparks, "Long-term hurricane risk assessment and expected damage to residential structures," *Rel. Eng. Syst. Saf.*, vol. 74, no. 3, pp. 239–249, 2001.

[5] E. M. Gil and J. D. McCalley, "A U.S. energy system model for disruption analysis: Evaluating the effects of 2005 hurricanes," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1040–1049, Aug. 2011.

[6] H. Liu, R. A. Davidson, D. V. Rosowsky, and J. R. Stedinger, "Negative binomial regression of electric power outages in hurricanes," *J. Infrastruct. Syst.*, vol. 11, no. 4, pp. 258–267, 2005.

[7] Y. Zhou, A. Pahwa, and S. S. Yang, "Modeling weather-related failures of overhead distribution lines," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1683–1690, Nov. 2006.

[8] H. Liu, R. A. Davidson, and T. V. Apanasovich, "Spatial generalized linear mixed models of electric power outages due to hurricanes and ice storms," *Rel. Eng. Syst. Saf.*, vol. 93, no. 6, pp. 897–912, 2008.

[9] S.-R. Han, S. D. Guikema, S. M. Quiring, K.-H. Lee, D. Rosowsky, and R. A. Davidson, "Estimating the spatial distribution of power outages during hurricanes in the Gulf coast region," *Rel. Eng. Syst. Saf.*, vol. 94, no. 2, pp. 199–210, 2009.

[10] S.-R. Han, S. D. Guikema, and S. M. Quiring, "Improving the predictive accuracy of hurricane power outage forecasts using generalized additive models," *Risk Anal.*, vol. 29, no. 10, pp. 1443–1453, 2009.

[11] S. D. Guikema, R. Nateghi, S. M. Quiring, A. Staid, A. C. Reilly, and M. Gao, "Predicting hurricane power outages to support storm response planning," *IEEE Access*, vol. 2, pp. 1364–1373, 2014.

[12] Y. Liu and C. Singh, "Evaluation of hurricane impact on failure rate of transmission lines using fuzzy expert system," in *Proc. 15th Int. Conf. Intell. Syst. Appl. Power Syst. (ISAP)*, Curitiba, Brazil, Nov. 2009, pp. 1–6.

[13] Y. Liu and C. Singh, "A methodology for evaluation of hurricane impact on composite power system reliability," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 145–152, Feb. 2011.

[14] Y. Huang, R. Wei, E. Zhou, Z. Zhang, H. Hou, and H Geng, "Early warning method of transmission line damage under typhoon disaster," *Autom. Electr. Power Syst.*, vol. 42, no. 23, pp. 142–150, Dec. 2018.

[15] Y. J. Wu *et al.*, "Extension of power system early-warning defense schemes by integrating typhoon information," in *Proc. IET Int. Conf. Sustain. Power Gener. Supply (SUPERGEN)*, Hangzhou, China, Sep. 2012, pp. 1–7.

[16] F. Bai *et al.*, "A measurement-based approach for power system instability early warning," *Protection Control Mod. Power Syst.*, vol. 1, no. 4, pp. 1–9, Jun. 2016.

[17] J. L. Walmsley, P. A. Taylor, and J. R. Salmon, "Simple guidelines for estimating windspeed variations due to small-scale topographic features–an update," *Climatolog. Bull.*, vol. 23, no. 1, pp. 3–14, 1989.

[18] W. Weng, P. A. Taylor, and J. L. Walmsley, "Guidelines for airflow over complex Terrain: Model developments," *J. Wind Eng. Ind. Aerodyn.*, vol. 86, nos. 2–3, pp. 169–186, 2000.

[19] X. Yang, N. Li, Z. Jin, and T. Wang, "A continuous low cycle fatigue damage model and its application in engineering materials," *Int. J. Fatigue*, vol. 19, no. 10, pp. 687–692, 1997.

[20] Y. Duyiand and W. Zhenlin, "A new approach to low-cycle fatigue damage based on exhaustion of static toughness and dissipation of cyclic plastic strain energy during fatigue," *Int. J. Fatigue*, vol. 23, no. 8, pp. 679–687, 2001.

[21] Y. Murakami and K. J. Miller, "What is fatigue damage? A view point from the observation of low cycle fatigue process," *Int. J. Fatigue*, vol. 27, no. 8, pp. 991–1005, 2005.

[22] A. W. MacAfee and G. M. Pearson, "Development and testing of tropical cyclone parametric wind models tailored for midlatitude application—Preliminary results," *J. Appl. Meteorol. Climatol.*, vol. 45, no. 9, pp. 1244–1260, 2006.

[23] K. Chen, "A new model of typhoon wind field distribution," *Mar. Sci.*, vol. 14, no. 3, pp. 1–5, May 1990.

[24] F. Kato, "Study on risk assessment of storm surge flood," Nat. Inst. Land Infrastruct. Manage., Tokyo, Japan, Tech. Rep. 275, 2005.

[25] ASCE Committee on Fatigue and Fracture Reliability, "Fatigue reliability: Development of criteria for design," *Struct. Div., ASCE*, vol. 108, no. 1, pp. 71–88, 1982.

[26] A. M. Kanvinde and G. G. Deierlein, "Cyclic void growth model to assess ductile fracture initiation in structural steels due to ultra low cycle fatigue," *J. Eng. Mech.*, vol. 133, no. 6, pp. 701–712, 2007.

[27] F. Xiao, J. D. McCalley, Y. Ou, J. Adams, and S. Myers, "Contingency probability estimation using weather and geographical data for on-line security assessment," in *Proc. 9th Int. Conf. Probabilistic Methods Appl. Power Syst. (PMAPS)*, Stockholm, Sweden, Jun. 2006, pp. 1–7.

YI TANG (M'07–SM'19) received the Ph.D. degree from the Harbin Institute of Technology, Harbin, China, in 2006.

He is currently an Associate Professor with Southeast University, Nanjing, China. His research interests include smart grid, power system security, power system stability analysis, renewable energy systems, and cyber-physical systems.

XIANGXIANG XU is currently pursuing the M.S. degree with Southeast University, Nanjing, China. Her current research interests include power system operation and control, and power system risk analysis.

BIN CHEN received the master's degree from the Harbin Institute of Technology, Harbin, China, in 2007.

He is currently with the State Grid Fujian Economic Research Institute, Fuzhou, China. He is a Senior Engineer. His main research interests include renewable energy systems and power system planning.

TAO YI received the bachelor's degree from the North China Electric Power University, China, in 2007, and the master's degree from Fuzhou University, China, in 2016.

He is currently with the State Grid Fujian Economic Research Institute, Fuzhou, China. His main research interests include renewable energy systems and power system planning.

• • •