# Power System Resilience Assessment Considering the Occurrence of Cascading Failures

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***Abstract*—In recent years, more and larger extreme climate disasters (e.g., typhoons) have occurred, and it is indicating an increasing need for accurate resilience assessment methods to perceive the system's function to respond to climate disasters. This paper presents a resilience assessment method to consider cascading failures prediction on account of extreme climate disasters. In this paper, a cascading failure evolution model considering short and long-time scales is used to analyze the cascading failures that may occur under extreme disasters. Combined with the recovery model, the sequential Monte Carlo simulation method is used to evaluate the power system resilience according to the system function. Applying the IEEE-39-node system as an example, the simulation results show that the proposed method can accurately predict the path of cascading failure and thus can evaluate the resilience of the power system more reasonably.**

***Keywords—Cascading failure, extreme climate disasters, sequential Monte Carlo simulation, power system resilience***

## I. Introduction

At present, affected by global warming, the frequency and intensity of extreme disasters are unprecedented[1]. These extreme weather disasters, such as typhoons, rainstorms ,and heat waves, cause power system failures with low probability and high loss. In recent years, typhoon disasters have had a great impact on the power system. For example, Typhoon 'Lekima' in China's coastal areas of Zhejiang Province in 2019 caused 168 power outages of 110 kV and above lines, resulting in a power outage of 7.5917 million users. China 's typhoon 'Seagull' in Hainan Province in 2014 caused a large number of high-voltage transmission lines to break down, resulting in a blackout of 1.245 million users. The frequent occurrence of extreme disasters has seriously affected the power system operating safely and stably. Power system resilience is the function to prevent, resist, and quickly restore from such low-probability-high-loss extreme events[2]. In the United States, power system resilience is defined as the function of the power system to respond to large-scale, long-term blackouts, and to prepare for accidents, emergency resistance during accidents, rapid recovery after accidents, and long-term learning from accidents. In the UK, the definition of resilience includes but is not limited to the comprehensive characteristics of reliability, robustness, redundancy, rapidity, and resilience. In China, the definition of resilience should include four attributes: robustness, redundancy, agility, and rapidity.

This work was supported by the (Shanxi) Regional Innovation and Development Joint Fund Project (U21A600003).

The resilience assessment framework of the power system does not consider the possibility of cascading failure. Most of the literature only considers the initial disconnection accident under the influence of extreme weather. For example, Ref.[3] proposes a resilience assessment framework under the influence of typhoon disasters with time and space. The spread of blackouts under extreme weather disasters is often the result of a combination of multiple factors. Due to the occurrence of local failures, a cascading reaction is caused. Cascading failures are events in which related components are successively withdrawn from operation after the disturbance occurs. Therefore, only considering the occurrence of extreme climate failures and ignoring potential cascading failures may underestimate the impact of extreme weather. The cascading failure evolution model is also a hot topic in recent research. According to the details of considering the occurrence of different cascading failures, it is divided into Manchester model, hidden failure model, CASCADE model, optimal power allocation model, dynamic model, and so on[4]. Therefore, at this stage, it is urgent to describe the disaster process in more detail and accurately and to study the resilience assessment method of power systems with inevitable cascading failures.

Based on the analysis, this paper presents a power system resilience assessment method considering cascading failure evolution under typhoon disasters. The IEEE-39-bus system simulation analysis is used to verify the effectiveness of the presented method.

The structure of this paper is as follows. After this introduction, section II analyzes the resilience assessment index and model considering cascading failures and gives the specific process, and then analyzes the power system recovery model and overload control model. section III describes the invalid model of a power system under a typhoon in brief. In section IV, the short-time scale cascading failure model based on the electrical stability problem and the long-time scale cascading failure model based on the thermal stability problem is introduced. The short-term and long-term alternating cascading failure model is used to analyze the failure process under typhoons. Section V uses the IEEE-39-bus system to verify the proposed method. Section VI is the conclusion of this paper.

2023 International Conference on Power System Technology (PowerCon) | 979-8-3503-0022-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/POWERCON58120.2023.10331511

## II. A Power System Resilience Assessment Method Considering Cascading Failure Evolution under Typhoon Disaster

### A. Power System Resilience Assessment Index Considering Disaster Duration

As a common and general representative, the typhoon has caused great damage to the operation of the power system. In this paper, the system resilience is evaluated by multi-round simulation of a single typhoon. According to the index definition method in[5] , the system resilience is evaluated according to the system function change under the *k*th typhoon disaster. The defined resilience index is:

$$R=\frac{1}{N_{\mathrm{MCS}}}\sum_{k=1}^{N_{\mathrm{MCS}}}\left[\frac{\int_{T_0}^{T_5}S^{(k)}(t)\mathrm{d}t}{\int_{T_0}^{T_5}S_{\mathrm{I}}^{(k)}(t)\mathrm{d}t}\cdot\frac{T_4-T_0}{T_5-T_0}\right] \tag{1}$$

Where $N_{\mathrm{MCS}}$ represent total typhoon simulation rounds; $T_0$ is the time when typhoon begins to interfere with the system; $T_1$ is the time when system function begins to decline; $T_2$ is the time when system function begins to stabilize after declining; $T_3$ is the time when power system restoration model begins to be implemented; $T_4$ is the time when typhoon no longer interferes with the system; $T_5$ is the time when the system function has been restored; $S_{\mathrm{I}}^{(k)}(t)$ is the function curve of the disaster-free system; $S^{(k)}(t)$ is the function curve under disaster.

Fig. 1 is a ladder diagram of power system function change after a typhoon.

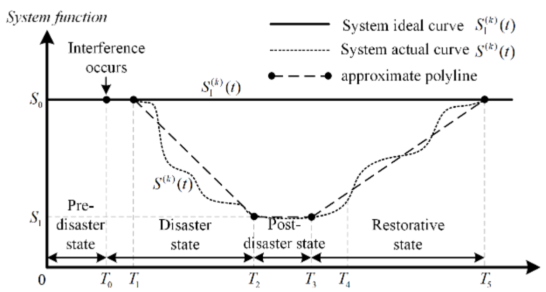


Fig. 1. System Function Curve under a Typhoon

### B. Power System Resilience Assessment Process Integrating Cascading Failure Time Series

In this paper, the occurrence of cascading failure is considered in the process of resilience assessment, and the following flow chart of resilience assessment of power line system with cascading failure evolution under typhoon is obtained as shown in Fig. 2:

1) Input system data and typhoon information, and set the simulation typhoon round as *n*=1, the initial simulation time $t_k$ is the time $T_0$ when the typhoon affects the power system, and the simulation time interval is $\Delta t$ .

2) The typhoon disaster situation and at time $t_k$ are updated, and the failure probability of the affected transmission line in the period time $(t_k, t_k+\Delta t)$ is calculated. The failure set of the transmission line is obtained by random sampling, which is taken as the new failure at time $t_k$ .

3) To determine whether there is a failure in the system, if not directly to 4), if there is a need for cascading failure analysis, and then the system recovery analysis, according to the failure and recovery update system status.

4) Enter the next period time, and repeat 2) -3) until the system function returns to normal.

5) Calculate the resilience index, then simulate the next round of a typhoon, when the convergence coefficient $\beta$ reaches the threshold $\beta_{set}$ .

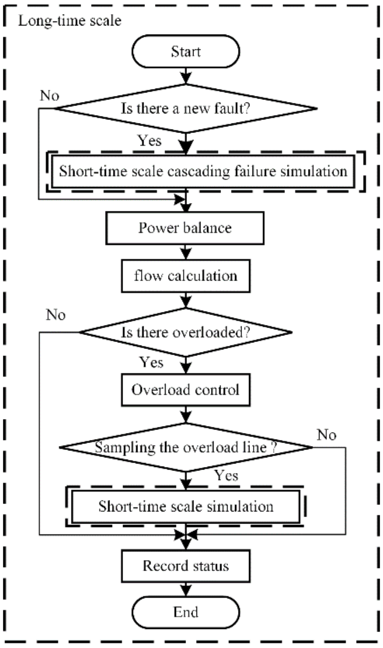


Fig. 2. Resilience Assessment Process of Power System

### C. Power System Recovery Model

Ref.[5] pointed out that the repair time *x* of outage line obeys the normal distribution, and its probability function is:

$$f(x)=\frac{1}{x\sqrt{2\pi}\sigma}\exp\left[\frac{-(\ln x-\mu)^2}{2\sigma^2}\right], x>0 \tag{2}$$

Where $\mu$ is the mean value; $\sigma$ is the variance; typhoon outage line setting parameters: $\mu$ =3.7 and $\sigma$ =2.4; overloaded outage line setting parameters: $\mu$ =3.2 and $\sigma$ =1.4. Considering the safety of maintenance personnel, the typhoon departure is set as the start time of repair.

### D. Transmission Line Overload Control

The overload control of transmission lines is mainly regulated by generator scheduling and load shedding. This article uses DC optimal power flow calculation:

$$\min \sum_{j=1}^{N_D} P_j^C \tag{3}$$

$$\sum_{i=1}^{N_G} P_i^G=\sum_{j=1}^{N_D}\left(P_j^D-P_j^C\right) \tag{4}$$

$$F_l = (\theta_{fl} - \theta_{tl})/x_l, \forall l \in N_L \tag{5}$$

$$P_{\min,i}^{G} \cdot \mu_{G,i} \le P_i^G \le P_{\max,i}^{G} \cdot \mu_{G,i}, \forall i \in N_G \tag{6}$$

$$0 \le P_j^C \le P_j^D, \forall j \in N_D \tag{7}$$

$$-F_{\max,l}^{\text{normal}} \cdot \eta \cdot \mu_{L,l} \le F_l \le F_{\max,l}^{\text{normal}} \cdot \eta \cdot \mu_{L,l}, \forall l \in N_L \tag{8}$$

Where $P_i^G$, $P_j^D$ and $P_j^C$ are the active power output of the $i$th generator, the load demand after the power balance adjustment of the $j$th node , and the load reduction of the $j$th node due to overload control; $P_{\min,i}^{G}$ and $P_{\max,i}^{G}$ are the lower and upper limits of the active power of the $i$th generator respectively; $F_l$ and $F_{\max,l}^{\text{normal}}$ are the upper limits of active power flow and normal power flow of the $l$th line respectively. $x_l$, $\theta_{fl}$ and $\theta_{tl}$ are the reactance of line $l$, and the voltage phase angle of the head and end nodes of the line respectively. $\mu_{G,i}$ and $\mu_{L,l}$ are the state variables of the $i$th generator and the transmission line respectively, 1 is operation and 0 is outage. $N_G$, $N_L$ and $N_D$ are the sets of generators, transmission lines , and load nodes, respectively; $\eta$ is the control coefficient.

## III. TYPHOON-RELATED FAILURE MODEL

In this paper, the modified Rankine model is applied to the simulation of a typhoon wind field. The interaction between a typhoon and transmission lines is shown in Fig. 3. Considering the long span of the transmission line, it is divided into equal-length segments. It can be seen that as the typhoon moves, the location of the fault line is that the wind speed of each segment is different. This means that these factors need to be considered when modeling the failure rate of typhoons on transmission lines.

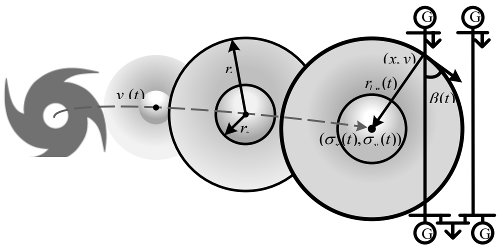

Fig. 3. The Affected Line Interacts with the Typhoon

The failure probability is calculated as follows:

$$p_{L,t,d} = \begin{cases} 0 & 0 < v_{L,t,d} \le v_{\text{des}} \\ \exp\left[\dfrac{0.6931\left(v_{L,t,d} - v_{\text{des}}\right)}{v_{\text{des}}}\right] - 1 & v_{\text{des}} < v_{L,t,d} < 2v_{\text{des}} \\ 1 & 2v_{\text{des}} \le v_{L,t,d} \end{cases} \tag{9}$$

Where $v_{L,t,d}$ is the central wind speed of the $d$ line segment of $L$ line at time $t$, $v_{\text{des}}$ is the design wind speed of the transmission line, assuming that the design wind speed of all lines is the same. The probability of transmission line failure is :

$$p_{L,t} = 1 - \prod_{d=1}^{q}\left(1 - p_{L,t,d}\right) \tag{10}$$

## IV. CASCADING FAILURE EVOLUTION

Different cascading failures occur at different time scales . This paper considers the short time scale caused by the thermal stability problem and the long time scale caused by the electrical stability problem.

### A. Short-time Scale

The transient module of the short-time scale is mainly to judge whether the protection is correct after the line is removed. In addition to the dynamic process of the system, it also includes the protection judgment such as generator over-limit. The short-time scale cascading failure process simulation flow chart is shown in Fig. 4:

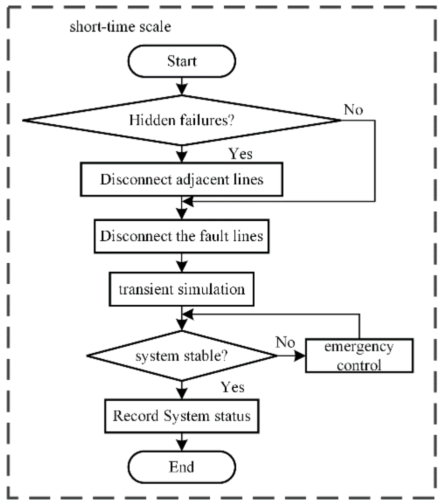


Fig. 4. Short-Time Scale Cascading Failure Process

### B. Long-time scale

The thermal stability problem is mainly caused by overload, and the failure probability is :

$$p_{lf} = \begin{cases} 0 & , 0 < F_l < F_{\max,l}^{\text{normal}} \\ \dfrac{F_l - F_{\max,l}^{\text{normal}}}{F_{\max,l} - F_{\max,l}^{\text{normal}}} & , F_{\max,l}^{\text{normal}} \le F_l \le F_{\max,l} \\ 1 & , F_l > F_{\max,l} \end{cases} \tag{11}$$

Where $F_{\max,l}^{\text{normal}}$ is the normal limit of power flow; $F_{\max,l}$ is the emergency limit of power flow; $F_{\max,l} = \varepsilon F_{\max,l}^{\text{normal}}$, $\varepsilon = 1.4$.

Fig.5 is a long-time scale simulation:

1) Determine whether there is a new fault at time $t$, if there is, execute step 2), if not, execute step 3), to analyze whether there is a new overload line after the load changes.

2) Short-time-scale cascading failure process simulation.

3) Distinguish the state of the system, obtain the subsystem situation by identifying the connectivity of the system, and adjust the power balance to ensure the power balance of each subsystem. When the power imbalance occurs, generator output adjustment, generator tripping , or load shedding are used to deal with it.

4) Calculate the power flow of each subsystem, compare the power flow of each line with the upper limit of the normal value of the power flow, check whether there is an overloaded line, if there is an overload control on the line, if not, record the system state and end the simulation.

5) According to formula (11), the fault probability of the overloaded line is calculated, and the fault set is obtained by sampling method. If the set is non-empty, the fault set is used as a new fault to simulate the short-time scale cascading failure process. If the set is empty, the simulation is completed after recording the system state.

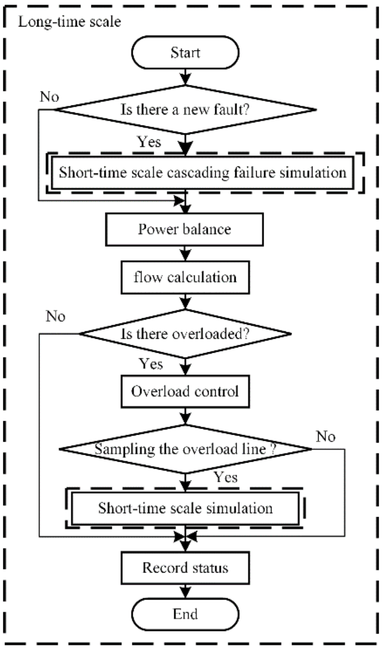


Fig. 5. Long-Time Scale Cascading Failure Process

## V. Case Studies

In this section, the resilience assessment method proposed in this paper is verified in the IEEE-39-node system. The power system geographic topology diagram is shown in Fig. 6.

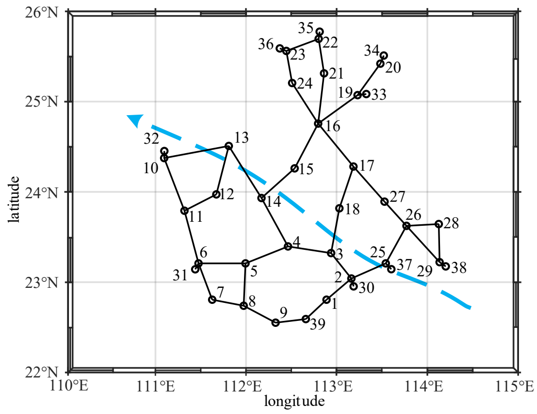


Fig. 6. IEEE39 Geographic Topology Diagram

It is assumed that the typhoon begins to interfere the power system from 0:00 on the first day. The path is shown in Fig. 6. The failure probability of different transmission lines during the typhoon is calculated. The failure probability of the five most seriously affected transmission lines is shown in Fig. 7.

The influence of the typhoon will be a dynamic continuous process. For purpose of measuring the calculation accuracy and efficiency, the simulation time interval is 0.5 h, the typhoon wind speed is 25 km/h, the line design wind speed is 30 m/s, the hidden failure probability is 0.0013, and the convergence variance coefficient $\beta_{set}$ is 0.02.

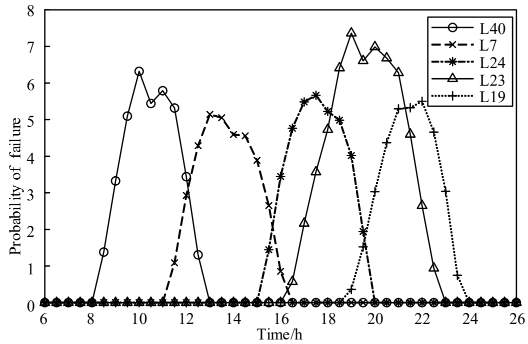


Fig. 7. Partial Transmission Lines Failure Probability

In the *k*th round of typhoon failure prediction, lines L41, L7 , and L25 fail at different times. This paper analyzes the failure conditions in this outage scenario. Table I. is angle generation without considering cascading failure evolution. Table II. is generated from a more comprehensive perspective considering cascading failures.

TABLE I. System Failures without Considering Cascading Failures

| time | system state |
|---|---|
| 8.5 h | Line L41 outage |
| 14 h | Line L7 outage |
| 18.5 h | Line L25 outage |
| 27.5 h | line L41 resumed operation |
| 29 h | line L7 resumed operation |
| 30.5 h | line L25 resumed operation |

TABLE II. System Failure with Considering Cascading Failures

| time | system state |
|---|---|
| 8.5 h | Line L41 outage，Generator G8 outage |
| 14 h | Line L7 outage |
| 18.5 h | Line L41 outage, Transient simulation Low voltage load shedding protection removes 66 MW load |
| 19 h | Load recovery supply due to low voltage load shedding |
| 20h | Line L26 outage |
| 27.5 h | line L7 resumed operation |
| 29 h | line L41 resumed operation |
| 30 h | line L26 resumed operation |
| 30.5 h | line L25 resumed operation |
| 33 h | The generator G8 returned to the grid connection. |

The description of Table II. outage scenario is closer to the actual situation, which verifies the feasibility and rationality of the method in this paper. The method proposed in this paper can not only simulate the initial outage scenario under a typhoon disaster, but also simulate the subsequent possible cascading failure evolution process.

Through the above multi-rounds typhoon simulation, and according to whether the occurrence of cascading failure is considered, the resilience index is calculated separately. Fig. 8. shows the convergence process of the conventional assessment method and the assessment method in this paper. The variance convergence coefficient of the resilience index is shown in Fig. 9.

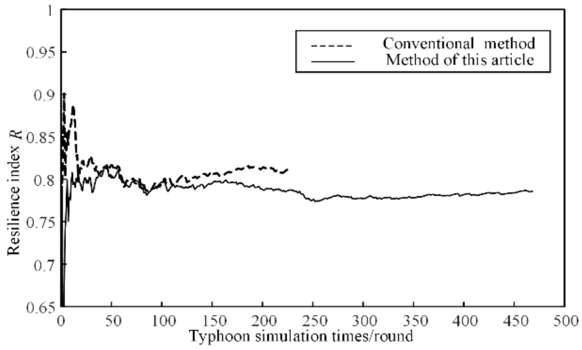


Fig. 8. Simulation Convergence Process of Resilience Index

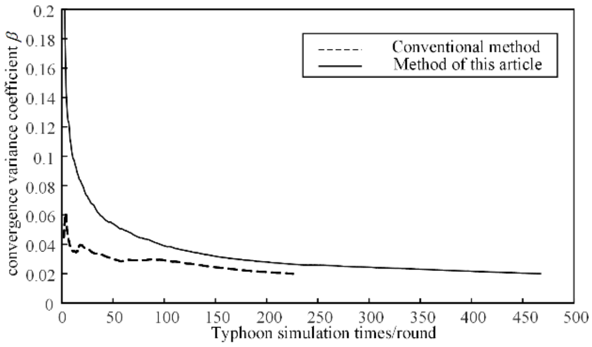


Fig. 9. Variation of Convergence Coefficient of Variance

The assessment results are as shown in Table III. The assessment results of the traditional method are more optimistic, this is because the possible cascading failures are not described. Compared to only considering the initial failures, the comprehensive assessment considering cascading failure in this paper results will be more accurate and objective.

TABLE III. RESILIENCE ASSESSMENT RESULTS

| Method | Conventional method | Method of this article |
|---|---|---|
| $R$ | 0.8151 | 0.7875 |

This article takes into account the grid operator's tolerance of line overload $l$, as shown in Fig. 10, the transmission line operating capacity coefficient is negatively correlated with the resilience index, and the power system resilience index is the largest when the operating capacity coefficient is 1, indicating that strict overload control measures can improve system resilience. Therefore, the power grid operators should take strict control measures for transmission line overload during the typhoon, eliminate the line overload at a small cost of load reduction, avoid the occurrence of cascading failures, and Improve the ability function of the power system to resist failure.

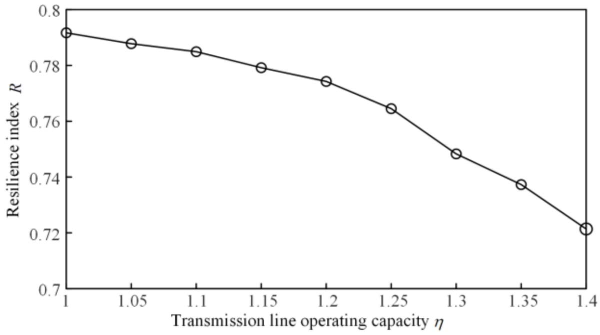


Fig. 10. The Resilience Index Values of Different Overload Control Measures

## VI. CONCLUSION

Based on the conventional resilience assessment, this paper considers the cascading failure prediction process of long and short-time scales and proposes a more perfect resilience assessment method considering cascading failures. This method can simulate the time-varying process of cascading failure under a typhoon, and describe the influence of the typhoon more comprehensively, which conforms to the actual operation of the power system. This can help power grid decision-makers to perceive the power outage range of the typhoon in a more accurate way, so as to adapt to accurate resilience control and recovery strategy. The system with new energy as the main body will be one of the future trends. The next step should focus on the failure evolution model of the power system with a high permeability of new energy and carry out resilience analysis.

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