Dynamic Assessment of Resilience of Power Transmission Systems in Ice Disasters

Jiazheng Lu, Jun Guo, Zhou Jian, Yihao Yang and Wenhu Tang*, *Senior Member, IEEE*

Abstract—**This paper presents a dynamic resilience assessment method, which can evaluate the impact of ice disasters on power transmission systems based on their actual location and strength. According to the meteorological law of sleet formation and the mechanical law of transmission lines during breakages and the collapse of towers, power transmission lines and tower outage models are developed through mathematical statistics methods. A fragility curve is used to express the relationship between the failure probability of components of transmission systems and weather intensity. A cell partition method is proposed to analyze the manner in which ice disasters would affect the operation of power transmission systems. The sequential Monte Carlo simulation is applied to calculate resilience indexes. The proposed method is demonstrated using an IEEE 6-bus Reliability Test System under four cases of different resilience enhancement measures. The results highlight the systems' resilience during ice disasters and how resilience enhancement measures would affect the system.**

Index Terms—**Ice disasters, outage models, power transmission systems, resilience, sequential Monte Carlo simulation**

I. Introduction

POWER systems are of particular significance for social production and economic development. As such, they should be not only reliable during normal weather, but also resilient against extreme weather events. Extreme weather events, such as ice storms, have an adverse impact on power system to varying degrees. Despite these events being of low probability, their consequences are so serious that preventive measures must be taken to mitigate them [1]. For example, the ice storm that hit Eastern Canada and Northeastern United States in January 1998 caused 1.4 million households to be affected by power outages [2]. Another example is the 2008 ice disaster in Southern China that wreaked havoc on power grid equipment and interrupted power supplies in certain areas. This event also damaged more than 36,000 transmission lines and affected approximately 27 million households [3], [4]. Therefore, methodologies should be developed for evaluating the resilience of power systems in ice storms in order to apply resilience enhancement measures for mitigating severe consequences of future ice storms.

Various methods have been proposed to evaluate the impact of weather on power systems. A two-state weather model [5] and a multi-state weather model [6] were developed to assess the impact of weather on the reliability of a transmission system. A method for estimating a typhoon's impact on transmission lines based on a tropical cyclone wind model was described in [7]. [8] developed an ice storm weather model and applied the reliability evaluation of a Swedish transmission network. Another model in [9] used a learning machine network to predict the generalized extreme value distribution of ice and wind loads. In addition, the Markov process in [6], [10] was adopted to describe system behavior under different weather conditions, and the Monte Carlo simulations in [11], [12] were applied to assess the stochastic and space- and time-dependent nature of weather events.

The concept of power system resilience was defined in [13]-[15] as the ability of a power system to face extreme events. Various methodologies and indexes were developed recently for evaluating the resilience of power grids. [16] quantified the resilience in a communication network protocol by radar plot. A load restoration framework based on distribution automation technologies was presented in [17] and a probabilistic methodology to assess resilience in transmission systems was described in [18].

In this paper, a method for assessing the resilience of power transmission systems in ice disasters is presented. A simple model for freezing rain ice loads is adopted to calculate the ice thickness by meteorological data. To determine the impact of ice disasters on power transmission systems, both the intensity and duration of an ice storm are considered, along with the state of such ice storm, its track, and the location of the affected power transmission system. A fragility curve illustrates the relationship between failure probability and weather intensity.

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Taking into account fault locations, weather intensity, repair crew ability, and any emergency response plan, a transmission system restoration model is developed. Unlike the reliability evaluation of a power system, the power transmission system response model considers power system splitting. A cell partition method and sequential Monte Carlo simulation are used to evaluate the spatial and temporal impacts of an ice disaster.

This paper is organized as follows: Section II describes the proposed dynamic resilience assessment methodology, which includes ice disaster modeling, power system modeling, and a resilience assessment. In Section III, the proposed method is implemented and verified through a numerical example with four cases. Finally, the conclusion of this paper is given in Section IV.

II. Dynamic Resilience Assessment Methodology

The proposed methodology uses sequential Monte Carlo simulation models, which examines the behavior of power transmission systems as a sequence of events organized by time. The impacts of ice disasters over power transmission systems are analyzed based on a cell partition method. The proposed methodology is described by the flow chart shown in Fig. 1, and it is composed of three parts, i.e., ice disaster modeling, power system modeling, and a resilience assessment.

A. Ice Disaster Modeling

There are many models that use meteorological data to calculate the amount of ice accreted on conductors and overhead lines in freezing rain storms [19]-[21]. In this paper, a simple model for freezing rain ice loads [21] is adopted to determine the ice accretion rate based on the weather parameters, which is as follows:

$$R_{\text{eq}} = \frac{N}{\rho_i \pi}\left[\left(P\rho_0\right)^2 + \left(3.6VW\right)^2\right]^{1/2}, \tag{1}$$

where R_{eq} is the ice thickness, N is the number of hours of freezing rain, and P denotes the precipitation rate. In addition, W represents the liquid water content of rain-filled air, which equals $0.067P^{0.846}$, while ρ_{i} and ρ_{o} are the density of ice and water, being 0.9 g/cm^3 and 1 g/cm^3, respectively. V is the wind speed.

The impact of an ice disaster is not only determined by its intensity, but also its duration on a transmission system. The duration of the impact of an ice disaster that is making landfall over a transmission system is shown in Fig. 2. G is the location of the power transmission system. The ice storm centers O_{a} and O_{b} are the boundary locations of the ice storm, which indicate the beginning and end of an ice storm affecting a power transmission system, respectively. The influenced area is considered inside the radius of the impacts R_{a} and R_{b}. Thus, the duration of the impact T_{dur} can be determined by the path of the storm and its moving speed

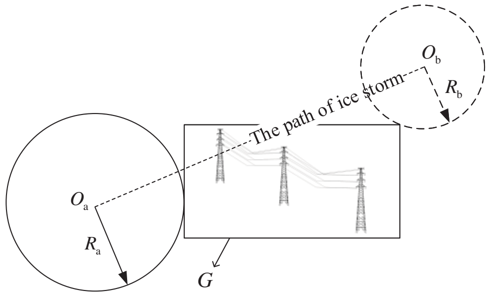

Fig. 2. Duration of impacts of ice storm.

B. Power System Modeling

The power system model in assessment of resilience of

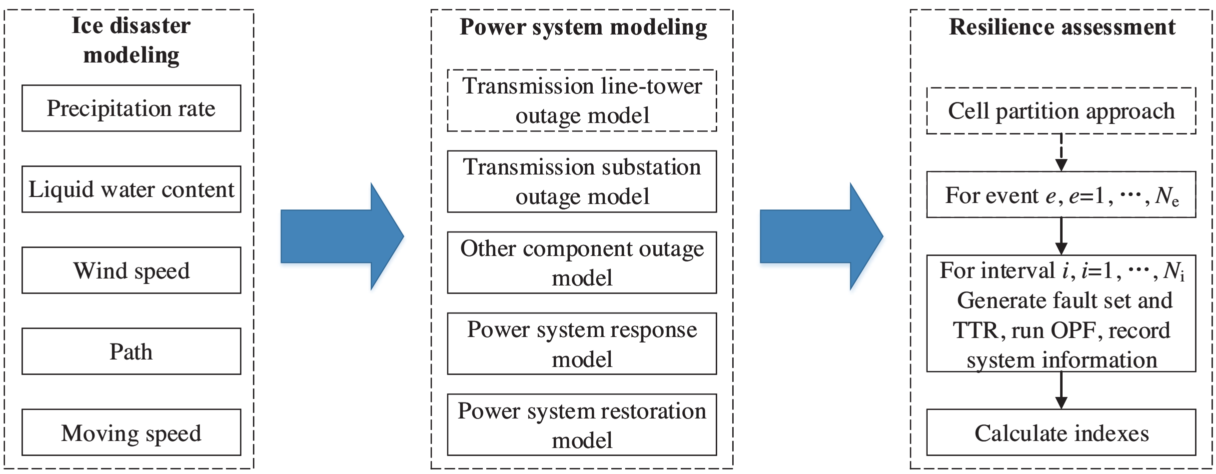

Fig. 1. Framework of the proposed dynamic resilience assessment methodology.

power transmission systems includes an outage model for components, a power system response model, and a restoration model. This paper only considers transmission lines and tower outage due to weather, and substations and generators are assumed to be 100% reliable.

1) Outage Model for Components: A fragility curve [7], [18] which depicts the relationship between the components' failure probability and weather intensity, is adopted to develop a weather-dependent outage model, as shown in Fig. 3. Empirical data can be used to adjust and develop a more accurate fragility curve for the components of a transmission system. Analytical methods also should be applied in some special situations. This paper only considers permanent failure.

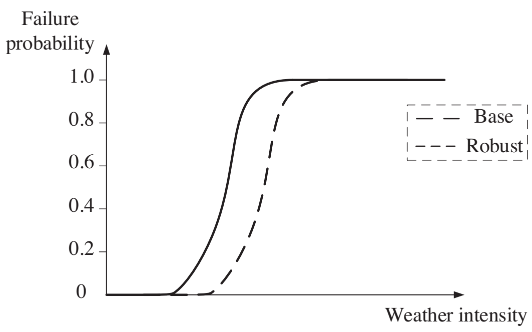

Fig. 3. Fragility curve of a component.

2) Power system Response Model: The power system response model reflects the power system behavior after components fault. In this paper, the power flows are captured by a DC-based model. The dispatch command follows the calculation results of the optimal power flow (OPF), which considers the variations in the available capacity of the transmission lines and generators. During extreme ice disasters, a power grid may be divided into several sub-grids. The model assumed that if there are no generators in the grid, then the nodes will fail. Otherwise, the power will be rescheduled to balance between the total supply and the total demand in each sub-grid and satisfy the line flow constraints.

3) Power System Restoration Model: In the resilience assessment for power systems, the most significant features are response and recovery. The highly accurate restoration time is essential in resilience studies. In contrast to conventional reliability, the restoration time of the component of the permanent failure (TTR_{com}) is determined by weather intensity, the location of the fault, the size of the repair crew, and the emergency response plan as below.

$$TTR_{\text{com}} = \left(TTR_{\text{dis}} + TTR_{\text{rep}}\right) \times k_{\text{w}} + TTR_{\text{wait}}. \tag{2}$$

where TTR_{dis} is the time that the repair crew starts traveling from the department to the site of the breakdown, TTR_{rep} represents the repair time of the components, and k_{w} is a coefficient determined by weather intensity. In addition, TTR_{wait} denotes the waiting time when restoration resources are in short supply.

C. Resilience Assessment

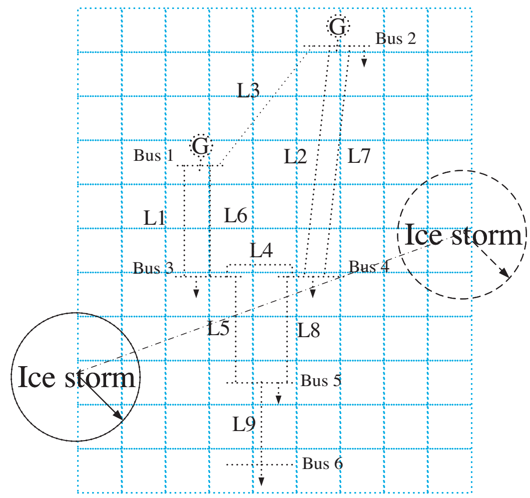

Fig. 4. Cell partition view of the IEEE 6-bus Reliability Test System.

To investigate the temporal impacts of an ice storm, the ice storm duration (T_{dur}) is divided into intervals, and for spatial effect, the studied geographical area is divided into several regions based on the cell partition method, as shown in Fig. 4. Let the number of intervals be i and the total number of intervals be N_{i}. By getting the weather intensity in each region and using an outage model, the weather-affected failure probabilities of components can be obtained.

For each interval i, weather-affected failure probabilities of components are compared with a random number r from a uniform distribution $U(0,1)$. If the failure probability is larger than r, then the component is considered to have broken down. It is important to note that the conditions of adjacent components are not considered in this research study. If the component has broken down, the *TTR* is generated by the power system restoration model. A DC OPF is used here to assess the performance of the system in the power system

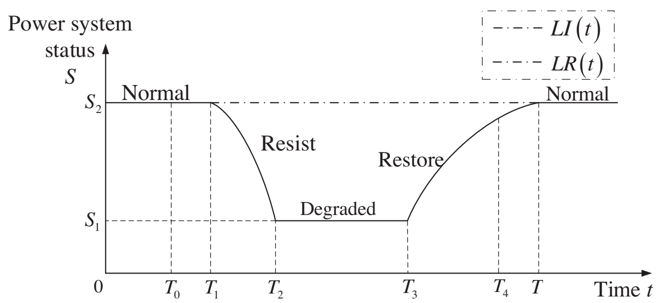

Fig. 5. System status curve of resilience associated with a disruption.

response model.

Repeat the above works at every interval and record the system information (S) of each interval in order to map the system status curves of resilience as shown in Fig. 5. The process in which an ice disaster impacts a transmission system is called an event, which is denoted as e. An event does not stop until the ice disaster leaves the transmission system and the system recovers to its original state. To calculate the resilience indexes, the event is simulated many times, K represents the number of simulations. The resilience index [22] is calculated according to (3) and the system status curve of resilience in Fig. 5.

$$
\begin{aligned}
R_{\mathrm{RICD}} &= E\left[\frac{\int_{T_0}^{T} LR(\mathrm{t})dt}{\int_{T_0}^{T} LI(\mathrm{t})dt}\cdot\frac{T_{\mathrm{dur}}}{T-T_0}\right] \\
&= \sum_{k=1}^{K} P_k\left[\frac{\int_{T_0}^{T} LR(\mathrm{t})dt}{\int_{T_0}^{T} LI(\mathrm{t})dt}\cdot\frac{T_{\mathrm{dur}}}{T-T_0}\right]
\end{aligned}
\tag{3}
$$

where E[•] and R_{RICD} are the expected value and resilience index, respectively. $LR(t)$ is the real performance of a power system and is shown in Fig. 5 with a solid line. $LI(t)$ represents the ideal performance of a power system without any effects and is shown with dash-dotted lines in Fig. 5. T_0 is the beginning time of the effect of an ice disaster on a transmission system, T_1 denotes the time when the transmission system starts to degrade, and T_4 represents the time when the system is no longer under the impact of a disaster. T denotes the time when the restoration is completed. T_{dur} denotes the duration of impact of an ice storm, that is $T_{\mathrm{dur}} = T_4 - T_0$, as defined in Section II-A. P_k represents the probability of an occurrence of a fault scenario (k), and K is the total number of scenarios.

III. Numerical Examples and Discussion

The proposed dynamic resilience assessment methodology is illustrated using the IEEE 6-bus test system [23]. The effect of an ice storm on the power transmission system is used as an illustrative case study to demonstrate the effectiveness of the proposed resilience assessment methodology.

A. Simulation Data

1) IEEE 6-Bus System: The IEEE 6-bus reliability test system includes two generator buses, four load buses, nine transmission lines, and 11 generating units. The system peak load is 198 MW and the total installed generating capacity is 240 MW. To study both the spatial and temporal impacts of an ice storm, the test system in Fig. 6 is partitioned into a number of cells by a cell partition method with 1,200 × 1,400 = 1,680,000. The coordinates of the cell where each bus is located, can be represented by Cell(x, y), which is listed in Table I. The mesh dimensions in both horizontal and vertical directions are presented in the geographic area with 500 m. In each cell, the weather intensity is considered the same.

TABLE I
Location of Buses in The Test System

BUS	Coordinates x	Coordinates y
1	400	800
2	700	1200
3	400	600
4	600	600
5	460	420
6	460	220

2) Ice disaster: The radius of the icing impact is R_{ice} = 100 km. The moving speed of the ice storm is C = 50 km/h. The max precipitation rate is P_{max} = 35 mm/h. The max wind speed is V_{max} = 12 m/s. The attenuation of precipitation rate and wind speed is considered as following the radius direction. The path of the ice storm begins at Cell(230, 440), and ends at Cell(929, 1139), as shown in Fig. 6.

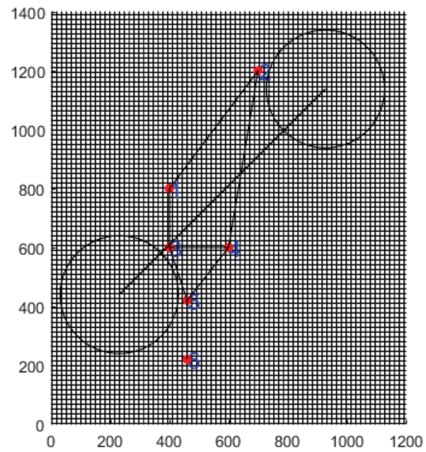

Fig. 6. The results of the cell partition method.

3) Outage Model of Component Considering Icing: The fragility curve of a component is shown in Fig. 3, where the weather intensity is determined by ice thickness. In this example, when the ice thickness (b) is less than the designed ice thickness of the component D = 15 mm, the failure probability f is set as 0; when b is larger than 5D, the failure probability is set at 1; and when the ice thickness is between D and 5D, the failure probability is assumed to increase exponentially. If empirical data were available, the results would achieve greater accuracy. The outage of power transmission corridor is expressed as [24],

$$f=\begin{cases}0 & b\le D\\ \exp\left[\dfrac{0.6931(b-D)}{4D}\right]-1 & D<b<5D\\ 1 & b\ge 5D\end{cases} \tag{4}$$

4) Restoration Model of Component: The department of the repair crew is located at Cell(400, 600). TTR_{rep} of a transmission corridor in a cell is assumed as 1 h, and it can be adjusted by empirical data. When restoration resources are insufficient, the corridor priority level is assumed to be L3 > L1 > L6 > L2 > L7 > L4 > L5 > L8 > L9. Let v_{r} be 60 km/h, and let k_{w} be uniformly and randomly generated based on the ice thickness. Then,

$$k_{\mathrm{w}}=\begin{cases}1 & 0\le d\le 20\ \mathrm{mm}\\ U(1,2) & 20\ \mathrm{mm}<d\le 40\ \mathrm{mm}\\ U(2,3) & 40\ \mathrm{mm}<d\le 60\ \mathrm{mm}\\ U(3,4) & 60\ \mathrm{mm}<d\le 80\ \mathrm{mm}\\ U(4,5) & 80\ \mathrm{mm}<d\le 100\ \mathrm{mm}\\ U(5,6) & 100\ \mathrm{mm}<d\end{cases} \tag{5}$$

where U is the uniform distribution function.

B. Case Study

To assess the impact of an ice disaster and different resilience enhancement measures on the power transmission system, four cases studies are used here:

1) Case 1: Base case, where the simulation data are the same as discussed in the previous assumptions, and only ten teams participate in the repair of the system. No resilience enhancement measures are considered to have been applied.

2) Case 2: Robust case, where the designed ice thickness of the component is increased by 5 mm. The components are made more resistant to icing, and the fragility curves shifts to the right, which is demonstrated in Fig. 3 with dotted lines.

3) Case 3: Rapid repair case, where repair efficiency doubles, i.e., TTR_{com} is reduced by a factor of 1/2 compared with case 1

4) Case 4: Resourceful case, where restoration resources are more abundant than in the base case. There are 20 repair crews participating in the repair of the power transmission system.

In short, the case 1 aims to assess the impact of an ice disaster on the resilience of the target transmission system. The other cases are aimed at enhancing some of the key features of resilience and evaluating their effect on power system resilience.

C. Simulation Results

Fig. 7 shows ice thickness for each bus which increases with time. It can be seen that Bus 2 and Bus 6 always equal 0, because both are positioned outside the ice storm's area of influence. There is no consideration about ice-out, with ice

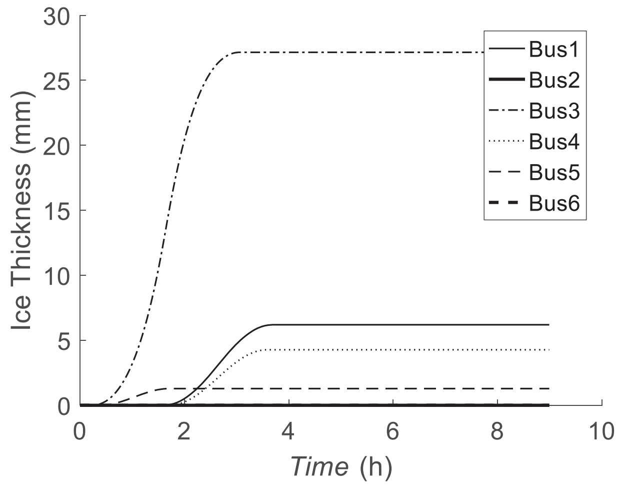

Fig. 7. The results of ice thickness for each bus.

thickness for each bus reaching a maximum and remaining so until the ice storm moves away. The path and density of the ice storm and location of the bus affect the maximum and the start time of icing.

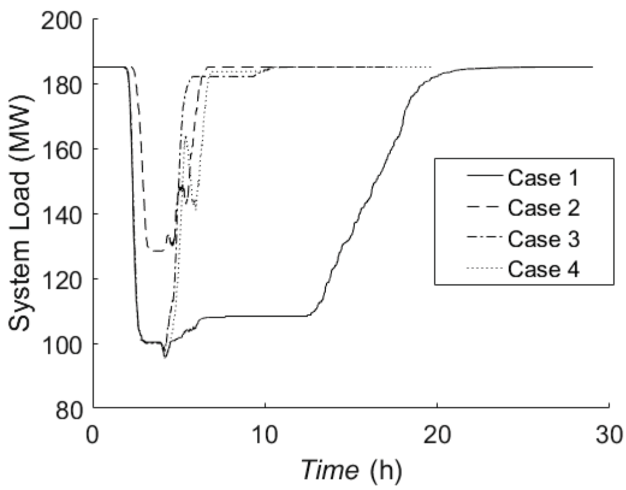

Fig. 8. The results of the resilience curve for all cases.

According to the results, T_{dur} is 6.45 h. T_0 is 0.11 h and T_4 is 6.56 h. Fig. 8 shows the results of the performance curve of the system in all cases. It can be seen that T in Case 1 is larger than those in the other cases, involving improvement measures to enhance the system's resilience.

As there is improvement in system robustness in Case 2 (the designed ice thickness of the component is increased by 5 mm), less components experience outages in an ice disaster and require less time to repair broken components. T_1 in Case 2 is larger than those in other cases obviously, and the minimum of the curve is larger than that in other cases.

Case 3 shows that recovery is faster than in Case 1 due to an improvement in the efficiency of the repair team. Overall, the shape of the curve in Case 3 is the same as that in Case 1; only the recovery time point and ratio of the curve in the later stages are different.

Case 4 involves increasing the number of repair teams to ten, and restoration is more resourceful than in other cases. According Fig. 8, the curve in Case 4 spends has less recovery time.

TABLE II
THE RESULTS OF RESILIENCE INDEXES

Case	1	2	3	4
R_{RICD}	0.2132	0.4578	0.4302	0.3569

The resilience index is calculated by (3) and the results of the resilience index are shown in Table II. R_{RICD} in Case 2, Case 3, and Case 4 is larger than that in Case 1, and R_{RICD} in Case 2 is the largest. This indicates that the measure for improving the designed ice thickness of the component is most effective in enhancing the resilience of the test system. The power company, however, must consider the economic benefit of the robustness improvement measure. Different measures have different effects on the resilience of power transmission system, and the conditions and characteristics of the ice disaster and systems need to be considered in order to determine the most effective measures.

IV. CONCLUSION

This paper has developed a dynamic resilience assessment method to evaluate the impact of ice disasters on power transmission systems. The proposed resilience assessment methodology has been tested with a numerical example, which includes four cases that consider different resilience enhancement measures. The results verify that the proposed methodology is effective and that it can assess the spatial and temporal impact of an ice disaster on the resilience of power transmission systems by considering the track of an ice storm and the location of affected components. At the same time, the proposed methodology can reflect the impact of measures on system resilience. A cost and benefit analysis will be developed in our future work.

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