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Full-time scale resilience enhancement framework for power transmission system under ice disasters

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ABSTRACT

A full-time scale resilience enhancement framework is proposed for power transmission system to improve its resistance against ice disasters. First, system resilience indices are developed to quantify the impacts of ice disasters on the transmission system. Next, the system resilience indices are broken down into each component, so as to locate the weak links of the system under ice disasters. On this basis, a full-time scale resilience enhancement framework is proposed involving pre-failure, during disaster and post-failure period of the ice disaster. In the pre-failure period, prevention strategies can be applied to avoid severe losses. In the during disaster period, deicing sequence can be optimal determined to delay the outage. In the post-failure period, maintenance measures of failed components can be optimized to recover the power supply as effective as possible. Case studies on the IEEE RTS-79 test system have been used to validate the effectiveness and practicality of the proposed approach.

1. Introduction

Driven by the needs of modern society, the power transmission systems have already met certain reliability standards. This achievement has enabled them to maintain a relatively stable operation under conventional disruptions. Recently, however, a few events have led to increased concern regarding the adequacy of the traditional transmission systems in withstanding high impact, low probability events.

One of such events is the ice disaster. This is a high hazard level weather disaster that, together with other disasters, has brought plenty of challenges to the normal and stable operation of power system globally. For example, the ice storm that happened in January 1998 severely affected 1.4 million households in a region stretching from Eastern Canada to Northeastern United States [1]. A more recent example is the 2008 ice disaster that happened in southern China. This was a severe catastrophic event that damaged 36,000 transmission lines of 10 kV. 27.06 million households were directly affected in the form of economic losses of over 110 billion [2–3]. These events show the need to evaluate the performance of systems in the face of such disasters. The concept of "resilience" is proposed to solve this problem.

Currently, there is no consistent definition of "resilience." One of the pioneering and most popular definitions of this concept was brought up by C.S.Colling in 1973 [4]. According to Colling, resilience is the persistence of a system and its ability to absorb changes or disturbances and still maintain the same relationships between population or state variables [4]. It should be noted that the concept of resilience has wide-ranging definitions catering for different purposes and scenarios [5–8].

Considering the presence of different definitions of resilience by using various approaches to quantify system resilience, Panteli M took the influence of severe weather and climate change on power system components into account and a state-of-the-art techniques assessment of power systems resilience is proposed in [9]. Later, Panteli M went further and put forward a conceptual framework for power systems resilience quantification where the critical power infrastructure is modelled, and human response is included [10]. Bruneau M also presented a conceptual framework to define the seismic resilience of communities and quantitative measures of resilience with a focus on enhancement [11]. Additionally, Lu J proposed a dynamic methodology for assessing the impact of ice disasters on the resilience of power transmission systems, which consider the temporal and spatial effects of ice disasters on the system [12].

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Nomenclature

R_{eq}	ice thickness
T	freezing rain hours
r	freezing rain rate
ρ_I	freezing ice density
ρ_W	freezing rain density
W	liquid water content in the air
L_I	ice load
D	conductor diameter
L_W	wind load
S	crossover factor
v	wind speed
L_{WI}	ice-wind load
P_f	fault probability of unit line
a_{WI}	the first threshold value
b_{WI}	the second threshold value
L_i	the length of the ith line
$E[\cdot]$	the expected system resilience
M	number of transmission lines
A	the set of all transmission lines
p_i	failure probability of ith transmission line
$\Omega^k{}_A$	the k order subset of A
s	failure scenario of the corresponding failed lines
P_s	probability of failure scenario s
I_s	impact of failure scenario s
R_{sys}	the system resilience index
ΔI_s	impact-increment of failure scenario s
p_m	failure probability of mth transmission line
$R_{sys}\|p_m = 1$	system resilience index when $p_m = 1$
$R_{sys}\|p_m = 0$	system resilience index when $p_m = 0$
s_m	failure scenario including the failed mth line
s_0	failure scenario without the failed mth line
$R_{cm,pre}$	pre-failure component resilience index of mth line
$R_{cm,post}$	post-failure component resilience index of mth line
ΔIs_m	impact-increment of failure scenario s_m
ΔIs_0	impact-increment of failure scenario s_0
p_j	failure probability of jth transmission line

Acronyms

IISE	impact-increment-based state enumeration method

Importantly, the key challenge concerns how to develop effective strategies to improve system resilience so that more resilient power systems can be built. So far, there already a lot of proposals in some literature. For example, an integrated resilience response framework was proposed in [13] to combine the situational awareness with resilience enhancement as well as provide efficient responses in both preventive and emergency states. Also, an operational enhancement approach was proposed in [14]. This operational enhancement method considered the impact of severe weather on power systems with a procedure for a novel risk-based defensive islanding algorithm. In another proposal made in [15], the key idea was undertaking a proactive operation strategy. This was meant to enhance the system resilience for an extreme unfolding event where the uncertain sequential transition of system states is modelled as a Markov process. One common theme with the above-mentioned proposals and most literature to that effect, is their relatively little recognition for specific weather events such as ice disasters as major threats to power system resilience. In the previous work of our team, some research was conducted on the resilience quantification of the power system under typhoon disaster [1617]. On this basis, this article makes the following innovations:

1) A series of resilience quantification indices, including both system and component level for ice disasters, have been proposed. One upside to these indices concerns the flexibility in their use. They cannot only be used to quantify the overall resilience of the system, but also locate the weak links of the power transmission systems.

2) A full-time scale resilience enhancement framework involving pre-failure, during disaster, and post-failure period of ice disasters was proposed for resilience enhancement in different periods of ice disaster process.

The rest of the paper is organized as follows. Section 2 introduced the probability model of transmission lines under ice disasters. Section 3 presents a series of practical resilience indices, in both system level and component level. A full-time scale resilience enhancement strategy framework is proposed in Section 4. Section 5 conducts case studies, and conclusions are drawn in Section 6.

2. The failure model of transmission lines under ice disasters

Typically, power systems are set to be reliability-oriented. As a result, most of the existing indices only apply to the known threats with a constant component availability rate. However, when the power systems are faced with some extreme, but relatively uncommon disasters such as ice disasters, the failure probability of the transmission line often change with the severity of the disasters. The failure of transmission lines during the ice disaster is mainly due to the vertical force caused by icing and the horizontal force caused by wind. Therefore, both ice load and wind load should be considered when developing the probability model of transmission lines. The practical experience shows that the underground cables in the transmission system are generally not affected in the ice disaster, so the transmission lines mentioned in the research process refer to the overhead lines on the ground. In this article, only the fault of the transmission line is considered, the fault of the transformer is not considered for the time being.

Kathleen f. Jones proposed a simple model for freezing rain ice loads to calculate the ice thickness, which is both practical and easy to implement [18]. The calculation formula of this model is as follows:

$$R_{eq} = \frac{T}{\pi\rho_I}\sqrt{(r\rho_W)^2 + (3.6vW)^2} \tag{1}$$

where R_{eq} is ice thickness (mm), T is freezing rain hours (h), and r is freezing rain rate (mm/h). ρ_I is ice density (g/cm^2);ρ_W is freezing rain density (g/cm^2);v is the wind speed (m/s); W is the liquid water content in the air, which comes from $W = 0.067 \times r^{0.864}$. Based on that, the ice load of per unit of transmission line be concluded by formula (2)

$$L_I = 9.8 \times 10^{-3}\rho_I\pi(D + R_{eq})R_{eq} \tag{2}$$

where L_I is ice load (N/m), D is the conductor diameter (mm).

Similarly, according to [19], the wind load of per unit of transmission line can be determined by the formula (3)

$$L_W = CSv^2(D + 2R_{eq}) \tag{3}$$

where L_W is wind load (N/m); C is a constant coefficient, take 6.964 × 10^{-3}; S is the crossover factor.

A synthetic ice-wind load L_{WI} can be obtained by the force analysis by formula (4):

$$L_{WI} = \sqrt{(L_I)^2 + (L_W)^2} \tag{4}$$

There is a force threshold that transmission lines can withstand. When the force exceeds this threshold, the bearing capacity decreases exponentially with the increase of the generation strain, which leads to the outages of transmission lines. In the light of the metal deformation theory, and assuming that the transmission lines are elliptical. The transmission line failure probability model can be established by formula (5).

$$P_f = \begin{cases} 0 & L_{\mathrm{WI}} \leqslant a_{\mathrm{WI}} \\ \exp\left[\dfrac{0.6931(L_{\mathrm{WI}} - a_{\mathrm{WI}})}{b_{\mathrm{WI}} - a_{\mathrm{WI}}}\right] - 1 & a_{\mathrm{WI}} < L_{\mathrm{WI}} < b_{\mathrm{WI}} \\ 1 & L_{\mathrm{WI}} \geqslant b_{\mathrm{WI}} \end{cases} \tag{5}$$

where P_f is the fault probability of each unit line.a_{WI} is the first threshold value of ice-wind load (N/m),b_{WI} is the second threshold value of ice-wind load (N/m).

According to the definition of the series network, the failure probability of different transmission lines can be obtained by formula (6)

$$p_i = 1 - (1 - P_f)^{L_i} \tag{6}$$

where L_i is the length of the ith line, p_i represents the failure probability of the ith transmission line.

3. Resilience assessment approach of transmission system under ice disasters

3.1. Overall system resilience quantification

Practical experiences show that disruption can happen at any time, causing huge inconveniences to the system. The typical power system performance curve is shown in Fig. 1. Q_0 represents the resilience performance of the initial system. $Q(t)$ shows the system performance curve of the real process under a disruption.

Fig. 1. reveal that the system resilience loss can be expressed as the shadow area of the performance curve. Indeed, Bruneau defined the system performance as the load supply at any time t [20]. Going by this line of thinking, following the occurrence of a disaster, the resilience of the system can be expressed by formula (7):

$$R = \int_{t_0}^{t_1} [Q_0 - Q(t)]dt \tag{7}$$

Because of the typical uncertainty associated with the occurrence of such disasters. To this end, a practical resilience index should not only be used to quantify the disasters that have occurred but also be able to evaluate and quantify the possible resilience losses of the system and the severity the disasters. To achieve this goal, this paper refers to a general resilience quantification index in [17]. This index utilizes a careful consideration of multiple failures of the transmission lines and the system performance degradations of all possible failure scenarios brought by the disasters. In this paper, this index will be especially applied to quantify the transmission system resilience under ice disaster.

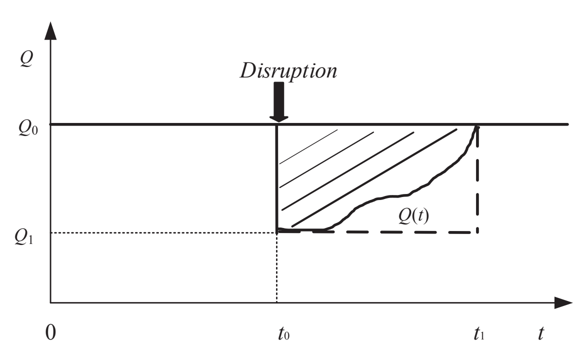

Fig. 1. Resilience curve.

It is worth noting that the system resilience indices can be expressed as the expected impact of potential failure scenarios that may occur under a particular disaster. This is achievable when the index is combined with the probability model of transmission line failure in the last section. The result is the formula for system resilience shown below.

$$R_{sys} = E[R] = \sum_{k=0}^{M} \sum_{s\in\Omega_A^k} (P_s I_s) \tag{8}$$

where R_{sys} represents the system resilience index; $E[\cdot]$ represents the expected value of system resilience, M represents the number of transmission lines, A represents the set of all transmission lines, and $\Omega^k{}_A$ represents the k order subset of A. Additionally, s represents a failure scenario denoted by a set of the corresponding failed transmission lines induced by the extreme ice disaster, P_s represents the probability of failure scenario s at some time and I_s represents load shedding of failure scenario s.

When faced with extreme ice disasters, multiple lines can easily fail, resulting in higher-order failure scenarios. To help reduce the error caused by ignoring the high-order scenarios and maintain the rapidity of the calculation, the IISE method [21] is introduced into the calculation process of system resilience assessment. Therefore, the formula (8) presented above can be translated to formula (9)

$$R_{sys} = \sum_{k=0}^{M} \sum_{s\in\Omega_A^k} \left(\prod_{i\in s} p_i \prod_{i\notin s} (1 - p_i)\right) I_s = \sum_{k=0}^{M} \sum_{s\in\Omega_A^k} \left(\prod_{i\in s} p_i\right) \Delta I_s \tag{9}$$

where p_i can be obtained by formula (6); ΔI_s represents the impact-increment of load shedding of failure scenario s.

3.2. The component resilience index(pre/post)

So far, the potential loss of system resilience under a specific ice disaster can be quantified by the system resilience indices. However, in the practical, real-life situation, relying on overall system resilience indices only is far from enough to locate the weak links of the system. Therefore, the resilience quantification of each transmission line is needed to increase further understanding of the situation within the system. Considering the particularity of ice disaster, the quantification of the component level resilience index can be done through two aspects: prevention and maintenance. In this regard, pre-, and post-failure components of resilience indices are proposed.

A. The pre-failure component resilience index

According to the transmission line failure probability model, the failure probability of different transmission lines is different. As a result, the contribution of different components to the resilience of the system may also be diverse. In general, the greater the probability of a transmission line failure during the ice disaster, or the greater the load shedding caused by this transmission line, the more critical this transmission is. Combining these, two aspects should be considered in defining the component level resilience index to quantify the resilience of each transmission line: (1) the system resilience index increment caused by the outage of each transmission line. (2) The probability of failure of each transmission line in a particular ice disaster.

First of all, the system resilience index increment caused by mth transmission failure can be obtained as formula (10).

$$\Delta R_{cm,pre} = R_{sys}\big|_{p_m=1} - R_{sys}\big|_{p_m=0} = \sum_{k=0}^{M} \left[\sum_{\substack{s_m\in\Omega_A^k \\ m\in s_m}} \left(\prod_{i\in s_m} p_i\right) \Delta I_{s_m} \right] \tag{10}$$

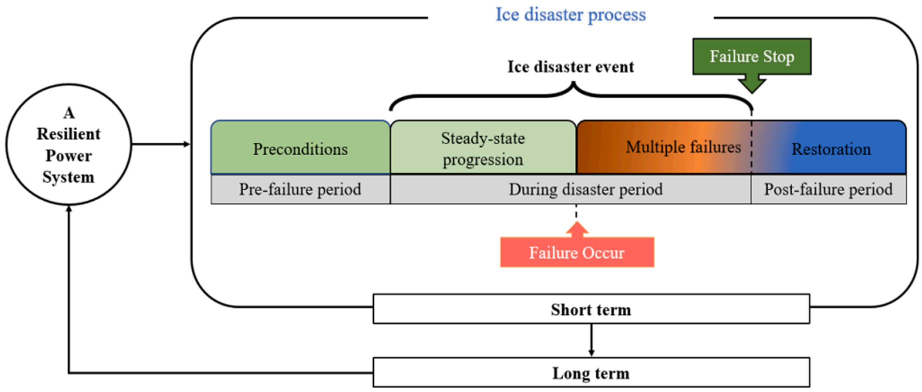

Fig. 2. Stage division of ice disaster.

where

$$R|_{p_m=1} = \sum_{k=0}^{M}\left[\sum_{\substack{s_m\in\Omega_A^k\\ m\in s_m}}\left(\prod_{i\in s_m}p_i\right)\Delta I_{s_m}\right] + \sum_{k=0}^{M}\left[\sum_{\substack{s_0\in\Omega_A^k\\ m\notin s_0}}\left(\prod_{i\in s_0}p_i\right)\Delta I_{s_0}\right] \tag{11}$$

$$R|_{p_m=0} = \sum_{k=0}^{M}\left[\sum_{\substack{s_0\in\Omega_A^k\\ m\notin s_0}}\left(\prod_{i\in s_0}p_i\right)\Delta I_{s_0}\right] \tag{12}$$

where $R_{sys}|p_m = 1$, represents the system resilience when mth transmission line will definitely fail and $R_{sys}|p_m = 0$ represents the system resilience when mth transmission line will never fail induced by ice disaster. s_m represents a failure scenario denoted by a set of corresponding failed transmission lines which including the mth transmission lines, s_0 represents a failure scenario that excludes the mth transmission lines. ΔIs_m represents impact-increment of load shedding of failure scenario s_m, ΔIs_0 represents impact-increment of load shedding of failure scenario s_0.

The pre-failure component resilience index of the mth transmission line can be expressed as in formula (13)

$$R_{cm,pre} = p_m\Delta R_{cm,pre} = p_m\sum_{k=0}^{M}\left[\sum_{\substack{s_m\in\Omega_A^k\\ m\in s_m}}\left(\prod_{i\in s_m}p_i\right)\Delta I_{s_m}\right] \tag{13}$$

where p_m represents the failure probability of mth transmission line.

It should be noted that the impact-increment of each failure scenario has been obtained in the calculation of R_{sys}, and the IISE method is still used in the calculation, so it is not necessary to calculate the ΔIs_m again.

B. The post-failure component resilience index

Although preventive preparations can be taken to avoid the resilience loss of power transmission systems, it is still inevitable that the system will suffer a certain degree of loss in the consideration of the unpredictability of ice disasters. In this case, it is necessary to assess each failed line so that remedial measures can be taken in time to make the system resilience recover as soon as possible. The post-failure component resilience index is proposed to provide theoretical guidance for repair sequences. This index needs to reflect the improvement of the affected system resilience when one specific transmission line is repaired. Based on this goal, the post-failure component resilience index of the mth line can be calculated by formula (14), IISE method is applied to ensure the computational efficiency:

$$R_{cm,post} = R_{sys}\Big|_{\substack{p_i=1,\,i\in\Omega_s;\\ p_j=0,\,j\notin\Omega_s}} - R_{sys}\Big|_{p_i=1,i\neq m\|i\in\Omega_s;\substack{p_m=0;\\ p_j=0,j\notin\Omega_s}} = \sum_{s_m\in\Omega_{m\in s}}\Delta I_{s_m} \tag{14}$$

where p_j represents the failure probability of the jth transmission line; Ω_s is denoted by a set of failed lines under failure scenario s, $\Omega_{m\in s}$ is the subset of Ω_s that contains mth line.

So far, both the component level and the system level of resilience can be quantified by indices. First, an overall picture of power transmission system resilience can be obtained by the system resilience indices. Afterwards, both pre- and post-failure component resilience indices can be used to provide theoretical guidance to the relevant personnel. For instance, the former one can be used to guide the implementation of pre-failure prevention measures before disasters and emergency measures during disaster, while the latter one can be used to provide guidance for repairing and reinforce the damaged facilities after the inevitable loss occurs to help the system back to the normal state as soon as possible.

4. Full-Time scale resilience enhancement framework

A series of practical resilience indices have been proposed in the previous section to quantify the system resilience under ice disaster in both system and component level. In essence, the quantification of resilience should be aimed at improving system resilience, thereby minimize the impact of ice disasters on the transmission system.

Most extreme natural disasters, such as typhoons and earthquakes, occur quickly and last for short periods, making it difficult to take pre-failure preventive actions and corrective actions during the disaster. Ice disasters are among the very few exceptions. They are mostly caused by icing and often last from days to weeks owing to the characteristics of the slow growth of icing. Another characteristic of ice disaster is that, unlike earthquakes, meteorological data can be obtained by the weather forecast, which makes the preventive measures possible before such disasters significantly affect the system.

On this premise, a full-time scale resilience enhancement strategy, especially for ice disaster, is proposed in this section to provide guidance for related personnel to carry out corresponding measures.

4.1. Stage division of ice disaster

In order to better improve the system resilience of ice disaster, different actions should be taken in different periods of ice disaster, which requires a detailed division of different periods of ice disaster.

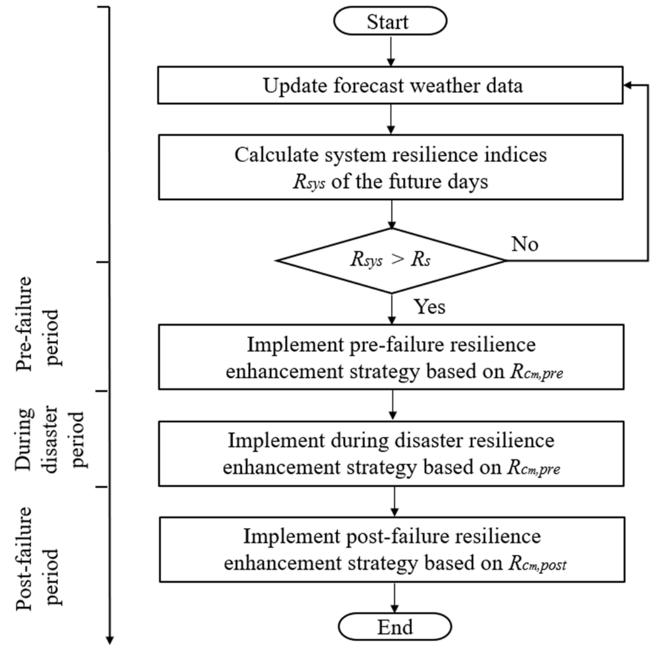

Fig. 3. The full-time scale resilience enhancement framework.

Generally, system resilience can be divided into short and long-term [22]. Fig. 2 depicts this.

A. The short-term

From Fig. 2, the short-term time scale can be divided into three periods: the pre-failure, during disaster, and post-failure periods. The pre-failure period consists of the precondition stage, while the during disaster period consists of steady-state progression stage, and multiple failures stage. The post-failure period consists of the restoration stage.

Pre-failure period: This period is also referred to as the precondition stage because icing requires certain climatic conditions. That is, the occurrence of ice disasters often has a brewing period. During this period, there is no ice on any transmission line and, therefore, the transmission lines have not failed yet. The whole system is still composed of normal components.

During disaster period: including (1) steady-state progression stage: icing on transmission lines begins to occur, and the thickness of icing increases with the severity of ice disaster. In view of the transmission line has a specific resistance to ice disasters, even though there may be a certain degree of ice on each transmission line, it does not cause any line failures. All components are still in healthy condition. (2) Multiple failures stage: this is the stage that causes the most considerable reductions in system resilience. In this stage, transmission lines will start to fail due to previous icing accumulation. The system resilience and performance will also decrease rapidly at this stage.

Post-failure period: also known as the restoration stage. This stage starts with the occurrence of failures until the ice disaster stops and all failed lines are repaired. Restoration stage mainly focuses on the repair of failed components.

B. The long-term

The long term includes the time beyond the short term. The long-term resilience refers to the adaptation ability of the system to changing conditions and new threats [10]. Its realization is mainly through taking long-term planning and the upgrading of equipment measures such as planning redundant circuits, increasing the ice design thickness of the transmission lines to improve the resistance of system to similar disasters. Long-term resilience enhancement often consumes a lot of financial resources. Therefore, this paper mainly focus on short-term resilience enhancement strategy; long-term scenario will be discussed in the future study.

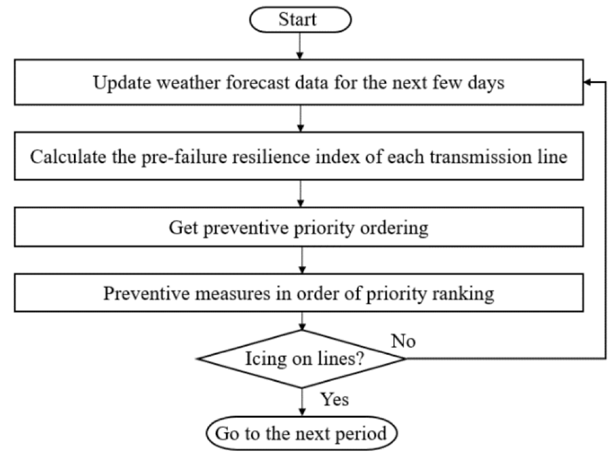

Fig. 4. Pre-failure resilience enhancement.

4.2. The system resilience enhancement strategies

According to the division of the ice disaster period proposed previously, different resilience enhancement strategies are adopted for different periods of ice disaster. The overall resilience enhancement process can be briefly described as Fig. 3:

Step 1: Update the forecast weather data.
Step 2: Calculate the system resilience indices R_{sys} of the next few days.
Step 3: If the value of R_{sys} less than the defined threshold R_s, go back to step 1, otherwise go to the next step.
Step 4: When the value of R_{sys} excess the value of threshold R_s, implement the pre-failure resilience enhancement strategy based on $R_{cm,pre}$ indices. Details of this strategy can be found in the following pre-failure resilience enhancement strategy.
Step 5: Check if there is the icing on transmission lines. If so, go to Step 6, otherwise, go back to Step 5.
Step 6: Implement during disaster resilience enhancement strategy based on the $R_{cm,pre}$ indices. Details of this strategy can be found in the following during the disaster resilience enhancement strategy.
Step 7: Implement a post-disaster resilience enhancement strategy based on the $R_{cm,post}$ indices. Details of this strategy can be found in the following post-failure resilience enhancement strategy.

Overall, before the failure occurs, the framework can be applied to locate the weak links of the system, take appropriate protection for the most critical lines or prepare for deicing. During the disaster, the emergency deicing work can be guided by daily updating the priority ranking. After all the failures stop, selective and targeted maintenance work is carried out so as to achieve the optimal repair efficiency. The detailed introductions to the resilience enhancement strategies of each period are as following:

A. Pre-failure resilience enhancement strategy

Pre-failure resilience enhancement strategy means resilience enhancement measures especially for the pre-failure period. According to the division of ice disaster process, this period consists of the precondition stage.

This is the period that the icing gradually formed. At this time, meteorological departments have already been able to obtain weather data for the next few days through weather forecasts. Therefore, based

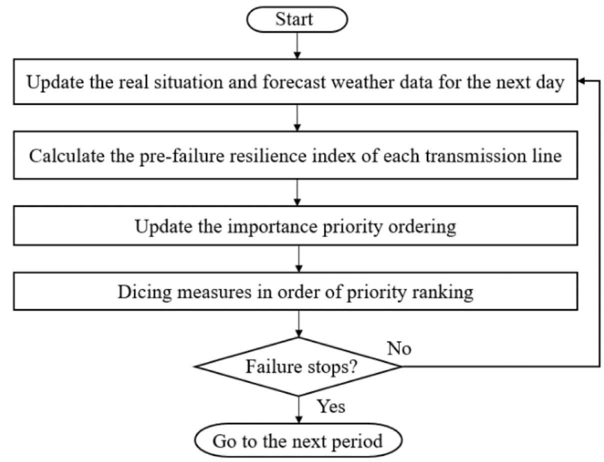

Fig. 5. During disaster resilience enhancement.

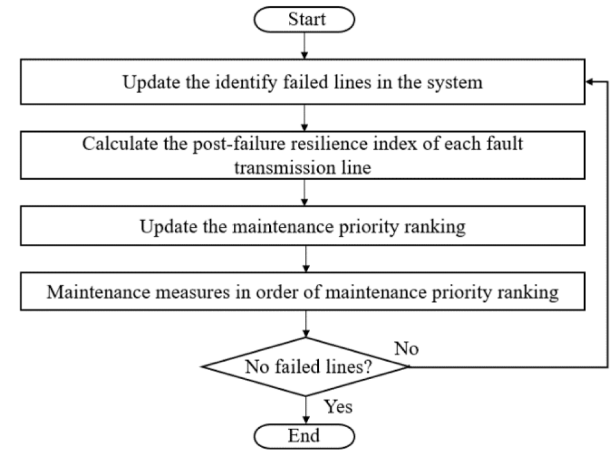

Fig. 6. Post-failure resilience enhancement.

on the pre-failure component resilience index mentioned in the previous section, the index of each transmission line, that is, the potential resilience loss of each transmission line failure can be obtained. According to the definition of the pre-failure component resilience index, the higher the index value is, the more important the line is. In order to minimize potential losses, effective preventive measures should be taken on those key lines, and this is the core of the resilience enhancement strategy during this period, the detailed enhancement strategy steps are shown in the Fig. 4.:

First, update the forecast data. Second, calculate the pre-failure component resilience index of each transmission line in the future period. Third, these indices are sorted to determine the preventive priority of each transmission line. Fourth, according to the priority order, the preventive measures are taken for the key lines, such as applying antifreeze materials to the transmission lines in advance to reduce the possibility of icing. Finally, after all these measures are done, identify whether there is ice on the transmission line, if no, go back to the first step, otherwise, the pre-failure period end, the next period begins.

B. During disaster resilience enhancement strategy

During disaster resilience enhancement strategy means resilience enhancement measures especially for the during disaster period. According to the division of the ice disaster period, the during disaster period includes two parts: the steady-state progression stage and multiple failures stage.

This period begins when the icing occurs on transmission lines until no new transmission line fails. As mentioned above, the formation of an ice disaster is a slow process. Therefore, emergency measures can be implemented during this period to reduce the resilience loss as much as possible. However, due to the extreme cold weather and the severe environment caused by the ice disaster, it is difficult for relevant personnel to carry out the repair work of failed transmission lines. Clearly, deicing measures to some potential key lines before icing lead to any consequences to the transmission lines are comparatively easier to implement.

On the same note, potential resilience loss of each transmission line can be obtained by means of pre-failure component resilience index. The importance priority ranking can also be obtained based on that, which can be used to guide the preventive deicing measures. It is worth noting that the potential resilience loss of each transmission line will change with the change of real-time weather and the implementation of deicing measures. Therefore, this ranking needs to be updated after every day deicing measures for the most realistic guidance. The detailed enhancement strategy steps are shown in the Fig. 5.

First, update the real situation and forecast weather for the next day.

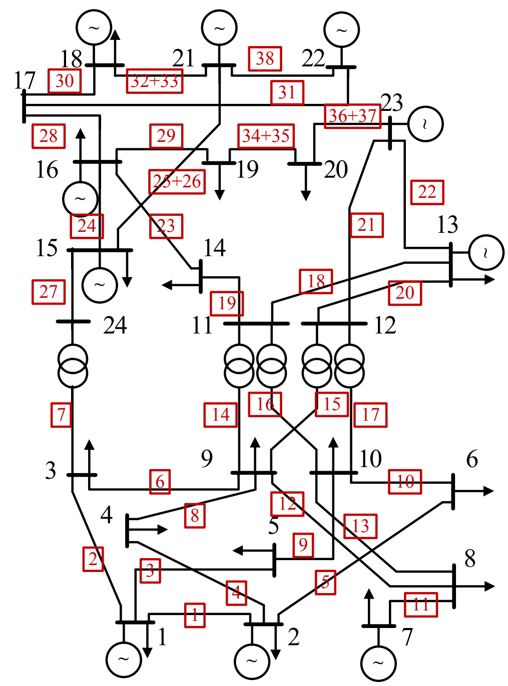

Fig. 7. The topology diagram of IEEE RTS-79 test system.

Second, the pre-failure component resilience index of each transmission line of the next day is obtained based on the first step. Third, on the basis of these indices, update the critical priority. Afterwards, the relevant personnel are arranged to carry out the deicing measures according to the important priority. After all these measures are done, confirm that all failures have been addressed. If no, go back to the first step. Otherwise, the during disaster period end, the next period begins.

C. Post-failure resilience enhancement strategy

Post-failure resilience enhancement strategy means resilience enhancement measures especially for the post-failure period. In the post-failure period, all the failed transmission lines have been identified. In this circumstance, maintenance measures need to be carried out effectively to make the system return to the resilient state as soon as possible. To achieve this goal, the failed transmission lines that have the most significant resilience improvement after each maintenance need to be found out. This can be easily achieved based on the post-failure component resilience index presented in Section 3.

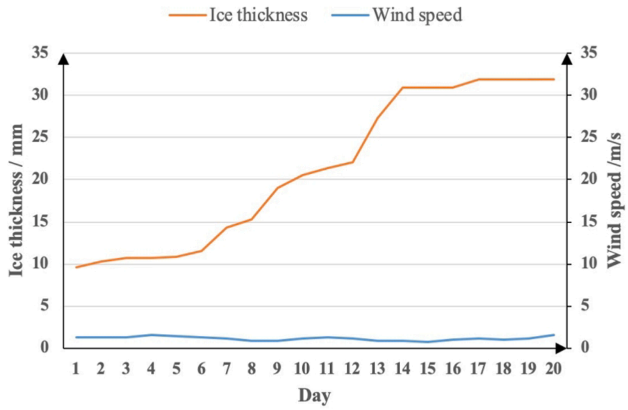

Fig. 8. The trend of wind speed and ice thickness during ice disaster.

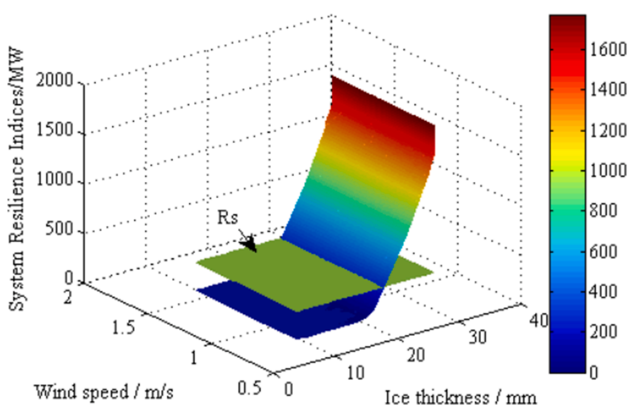

Fig. 9. The predicted system resilience indices.

It should be noted that the maintenance measures will not only change the resilience of the repaired lines but also affect the resilience of other transmission lines in the system. Keeping that in mind, the priority ranking should be updated after everyday maintenance work so as to provide the most reliable guide for the next maintenance work. The detailed enhancement strategy steps are shown in the Fig. 6.:

The process goes as follows: First, update the identify failed transmission lines in the system then calculate the post-failure component resilience index of each transmission line. Afterwards, these indices are sorted to determine the maintenance priority of each transmission line. This is followed by taking the emergency maintenance measures according to the priority order. After each round of maintenance, transmission lines are examined for any presence of failures. If there are, go back to the first step, otherwise output end.

5. Case study

In this section, the IEEE RTS-79 test system [23] is used to prove the effectiveness of resilience indices and resilience enhancement strategies proposed in this paper. Its topology is shown in Fig. 7. The test system consists of 32 overhead transmission lines. According to the requirements of the current design code GB50545-2010 for overhead transmission lines in China, the selection of wind speed and ice thickness for power grid design is based on the ice disaster area, which is 25 *m/s* and 20 mm respectively. The threshold for resilience loss R_s has been set to 10% of total load by experience.

5.1. Case 1:System resilience indices

According to the meteorological data from [24], the predicted wind speed and ice thickness during one ice disaster can be obtained and shown in Fig. 8. Based on this, the predicted overall system resilience indices can be calculated and shown in Fig. 9. The specific values of system resilience indices can be found in Table 1.

Table 1
Predicted daily system resilience indices and priority ranking of components.

Date	R_{sys}(MW)	Priority ordering	Date	R_{sys}(MW)	Priority ordering
1		–	11	43.14	27-23-11-21-19
2		–	12	82.73	27-23-21-11-19
3		–	13	761.736	23-27-21-18-11
4		–	14	1282.20	23-27-21-18-11
5		–	15	1254.50	23-27-21-18-11
6		–	16	1325.48	23-27-21-18-11
7		–	17	1499.39	23-27-21-18-11
8		–	18	1461.26	23-27-21-18-11
9		–	19	1523.64	23-27-21-18-11
10	10.74	27-23-11-19-5	20	1774.25	23-27-21-18-11

It is apparent from Fig. 8 that during ice disasters, the wind speed remains low. As a corollary, the impact of ice thickness on transmission lines will be relatively significant compared to the wind speed. In the process of the actual ice disaster, the change of human intervention on wind speed is minimal. Therefore, the resilience enhancement under ice disaster is mainly achieved by the intervention of icing.

It can be seen from Fig. 9, that the values of system resilience indices increase with the development of ice disaster. That is, the resilience of the system is drastically reduced. This observation, combined with Fig. 8 and the specific values of system resilience indices, the icing on the transmission line increased significantly on day 13, which led to a distinct growth on system resilience indices. It was also the day that the system resilience index exceeded the set threshold, which indicates that the system will show a state of inadequate resilience.

5.2. Case 2: Full-time scale resilience enhancement strategies

A. Pre-failure resilience enhancement strategy

According to the pre-failure resilience enhancement strategy proposed in Section 4, the system resilience indices and preventive priority of next few days should be obtained based on the predicted weather data. In order to facilitate the presentation of the results, only the numbers of transmission lines with the top five priority are listed each day. Results are shown in Table 1.

It is evident from Table 1 that at first, priorities were changing over time. However, with the development of ice disaster, the number of failed transmission lines in the system tended toward a peak value. Hence, as the growing rate of system resilience indices decreases, the priority ranking tended to a fixed order, which suggested that the top five lines may cause more damage to the system resilience compared to other transmission lines. According to the pre-failure resilience enhancement strategy, the optimal strategy is to take preventive measures of Lines 23, 27, 21, 18 and 11. To prove the effectiveness of this strategy, it was compared with 20 other strategies. In this regard, five transmission lines were randomly selected to take preventive measures each time (Except for the transmission lines of 0 lengths). The calculated system and component resilience indices are shown in Fig. 10. The line chart represents the system-level resilience indices obtained under various strategies. The stacked area chart, on the other hand, represents the pre-failure component resilience indices of Lines 23, 27, 21, 18 and 11 under different strategies. Assuming that the transmission lines will have a strong resistance to ice disaster weather after taking preventive measures, the failure probability can be calculated by the availability of ordinary transmission lines under conventional weather.

It can be concluded from Fig. 10 that:

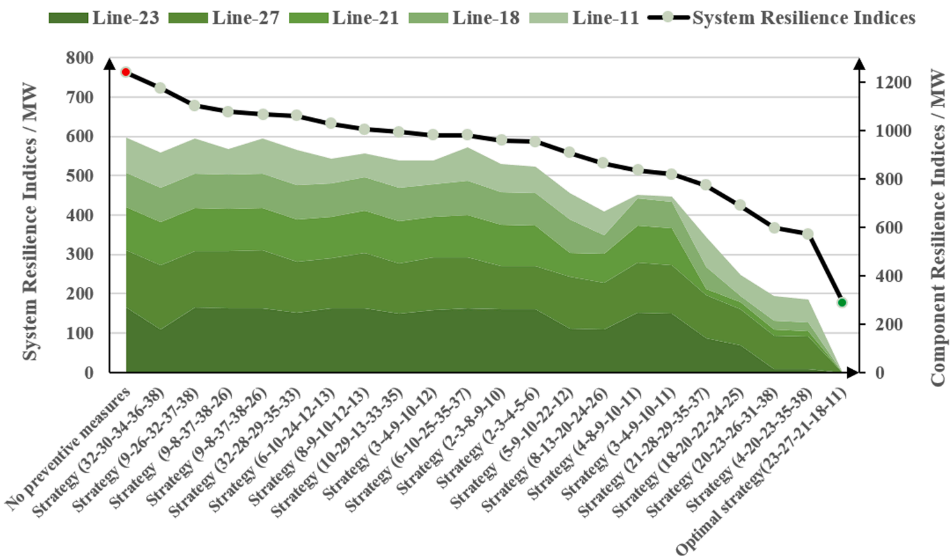

Fig. 10. The pre-failure system & component resilience indices.

Table 2
Resilience enhancement results of Strategy A.

Date	Line NO.	Deicing days	R_{sys}(MW)
1	31	4	–
5	21	4	–
9	22	3	–
12	2	3	76.76
15	5	3	944.86
18	38	3	1092.83

i) When five lines were randomly selected for preventive measures, the amount of resilience loss declined to some extent compared to the situation that no preventive measures were taken. However, the loss of system resilience is mostly minimized when preventive measures are taken according to the optimal strategy.
ii) Generally, the changing trend of pre-failure component resilience indices of these five lines is basically consistent with the trend of system resilience indices. Therefore, the loss of system resilience mainly result from the weak links. Therefore, it is necessary to develop targeted deicing strategies.
iii) The value of pre-failure component resilience indices of these five lines under the optimal strategy is not 0. It is because the transmission lines also have the probability of failure even in normal weather. Also, although the component resilience indices of these five lines are relatively small, the value of system resilience index under optimal strategy cannot be ignored. The reason is despite the preventive measures taken on these five lines, still other transmission lines may lead to resilience loss.

In conclusion, the superiority of the proposed strategy is effectively proved by the results.

B. During disaster resilience enhancement strategy

In this part, several comparative cases were examined to verify results obtained in Section 4. Assuming that the daily deicing capacity of maintenance personnel is 20 km.

Strategy A: Deicing measures start from day 1 according to the descending order of transmission lines length. Results are shown in Table 2.

Evidently, the system resilience indices are a little bit lower than the indices obtained in Table 1. The difference can be attributed to the implementation of deicing, which was absent in the results outlined in Table 1.

Table 3
Resilience enhancement results of Strategy B.

Date	Line NO.	Deicing days	R_{sys}(MW)
1	23	2	–
3	27	2	–
5	21	4	–
9	18	2	–
11	11	1	12.06
13	20	2	13.79
14	19	2	275.23
17	22	3	286.55
19	29	1	341.14
20	25	1	251.37

It is important to note that, owing to the limited deicing ability, the strategy of deicing according to the length descending order may lead to the late deicing of some more important lines and multiple failures occur. This might eventually lead to the rapid growth of the system resilience indices, resulting in an overall plausible outcome.

Strategy B: Deicing measures start from day 1; the deicing sequence is based on the fixed priority sequence obtained in Table 1. Results are shown in Table 3.

Table 3 shows that, although the deicing measures have reduced the system resilience indices compared with the indices of the same period without any dicing measures, the effect is not satisfactory. This outcome can be attributed to the following reasons.

i) According to Table 1, in the early stages of the ice disaster, the priority ranking of transmission lines is not the order chosen by this

Table 4
Resilience enhancement results of Strategy C.

Date	Line NO.	Deicing days	Priority ordering	R_{sys}(MW)
1–9	–	–	–	–
10	27	2	27-23-11-19-5	10.74
12	23	2	23-11-21-19-22	48.85
14	11	1	11-18-20-25-26	536.72
15	29	1	29-25-26-28-20	330.64
16	25	2	25-26-28-20-18	251.77
18	20	2	20-18-21-4-8	166.06
20	4	2	4-8-9-3-13	111.41

Table 5
Resilience enhancement results of Strategy D.

Date	Line NO.	Deicing days	Priority ordering	R_{sys}(MW)
1	23	2	–	–
3	27	2	–	–
5	21	4	–	–
9	18	2	–	–
10	11	1	11-13-4-5-8	12.06
12	4	2	4-8-5-25-26	13.79
14	29	1	29-25-26-28-34	232.26
15	25	1	25-26-28-3-9	133.47
16	3	2	3-9-13-5-12	48.49
18	13	2	13-5-12-9-8	12.36
20	5	2	5	5.68

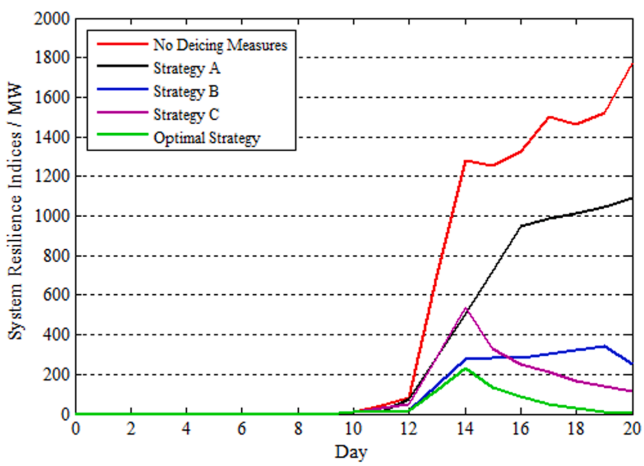

Fig. 11. System resilience indices of ice disaster under various strategies.

strategy. Consequently, this led to some more important lines getting little to no deicing measures at the right time.

ii) In the process of ice disaster occurrence, the priority of each transmission line will constantly change as a result of the changing weather and implementation of deicing measures. This strategy was carried out according to a fixed order, which also causes the late deicing of some important lines. There will still exist the situations that the system resilience indices exceed the set threshold.

Strategy C: Deicing measures start from the system begins to show loss of resilience, and the deicing order is updated every day according to the pre-failure component resilience indices. Results are shown in Table 4.

It can be concluded from Table 4 that Strategy C did not take deicing measures from the beginning when the icing first occurred on the transmission lines. This caused the accumulation of icing. What is more, the system starts to lose resilience at the same time when multiple failures occur. This occurrence leads to lots of lines needing to be deiced at the same time. Owing to the limited deicing capacity, the loss of resilience in the system is still considerable even if the orders are updated in real time and deicing measures are taken strictly according to the priority order.

Strategy D: Deicing measures start from day 1, and the deicing sequence is updated every day according the pre-failure component resilience indices. Results are shown in Table 5.

Strategy D strictly follow the during disaster resilience enhancement strategy proposed in this paper to take deicing measures. Evidently, the resilience indices of the system remain below the threshold in the whole process, and the indices values of each period under this strategy also showed a significant reduction compared with the indices of the same period without any dicing measures.

Table 6
The post-failure component resilience indices and repair effectiveness.

Indices	Before repair	First Repair	Second Repair	Third Repair	Fourth Repair
$R_{c_{23},post}$(MW)	238.36	–	–	–	–
$R_{c_{27},post}$(MW)	215.13	93.32	–	–	–
$R_{c_{21},post}$(MW)	115.12	24.84	13.79	–	–
$R_{c_{18},post}$(MW)	207.77	40.71	19.84	–	–
$R_{c_{11},post}$(MW)	153.52	66.23	20.71	–	–
Repair Priority	–	Line-23	Line-27	Line-11	Line-18
Repair effectiveness	0%	75.8%	94.2%	100%	100%

A more straightforward comparison of the four strategies involves the use of a line chart of the four strategies, as shown in Fig. 11.

The results in the above tables and the line chart provides clear proof that all the four strategies can reduce the loss of resilience to a certain extent. In this regard, Strategy A demonstrates the importance of deicing by priority. Strategy B illustrates the importance of deicing according to priority updated in real time, while Strategy C illustrates the importance of deicing measures when the first icing was produced. Importantly, they proof the relative superiority of Strategy D.

C. Post-failure resilience enhancement strategy

In the post-failure period, the primary task is to carry out effective repair works for the failed transmission lines. The proposed post-failure component resilience indices can reflect the improvement of system resilience by repairing different transmission lines. On this note, higher index value implies a higher repair priority. That said, in order to validate the post-failure resilience enhancement strategy proposed in this paper, some of the most influential transmission lines calculated by case 2 were selected. These were Line-23, 27, 21, 18 and 11. Assuming that these transmission lines have been identified as failed, the post-failure component resilience indices of these five lines were calculated and maintenance work carried out according to the maintenance priority ranking. The results are as shown in Table 6.

The repair effectiveness in Table 6 represents the resilience recover the degree of the system after each repair. Before repair, the highest priority of the five transmission lines is Line-23. Therefore, Line-23 is selected for the first maintenance. After that, prioritizations of remaining transmission lines were updated following each round of maintenance.

From Table 6, it is apparent that after the first maintenance, the repair effectiveness rose from 0% to 75.8%. The magnitude of the improvement in system resilience decreases gradually in each following round. The reason is, the transmission lines contributing most to the system resilience are repaired preferentially. Such implementation can get the system out of the state of resilience insufficiency as soon as possible. It also reflects the importance of higher priority transmission lines.

Remarkably, after the third maintenance, the post-failure component resilience index of each transmission line changed to 0. The reason is that after the third repair, these transmission lines no longer produce load loss. However, unrepaired transmission lines are still in an abnormal state, and although they may not contribute to the resilience of the system, maintenance work still needs to be done.

In order to further validate the practicability of the proposed post-failure resilience enhancement strategy, three different strategies were carried out for comparison. The specific repair sequence is as follows:

Strategy 1: In ascending order of transmission line numbers (Line 11-18-21-23-27);
Strategy 2: Radom order (Line 18-21-11-23-27);

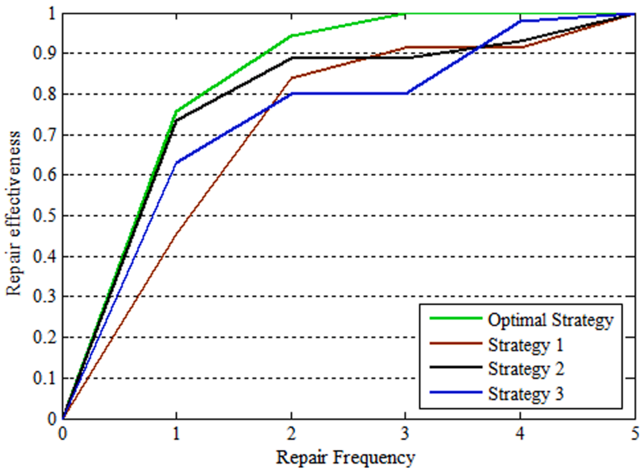

Fig. 12. The repair effectiveness of various repair strategies.

Strategy 3: In descending order of transmission line length (Line 21-27-18-23-11);

It is worth noting that the repair effectiveness of Strategy 2 stayed the same after the second repair. It is due to the transmission line selected by the second maintenance has no effect on the overall system resilience. Similar attribution can be made for Strategy 3.

Another interesting observation is that all strategies in Fig. 12 achieved system resilience enhancement eventually. However, not all of them is optimal. For instance, the proposed approach consistently outdid the other approaches in essential metrics such as recovery speed. It cements the findings from previous tests where the proposed approach was found to be superior.

6. Conclusion

This paper proposed an effective resilience enhancement framework specific to ice disasters. It was based on a series of resilience quantization indices in both system and component level and covered all periods of the ice disaster event process. Case results indicated that the proposed approaches can correctly improve the resilience of the system. For instance, the proposed strategy can help locate the weak links and guide the prevention measures before the failure occurs. During the ice disaster, the proposed strategy can guide the deicing sequence update in real time, thus minimizing the impact of the disaster on the power transmission system. After the disaster, the optimal repair sequence can be worked out by the proposed strategy to make the system back to its resilient state as soon as possible.

CRediT authorship contribution statement

Ningyuan Zhao: Methodology, Software, Validation, Investigation, Writing - original draft. **Xiaodan Yu:** Writing - review & editing, Supervision. **Kai Hou:** Conceptualization, Writing - review & editing, Supervision. **Xiaonan Liu:** Conceptualization, Writing - review & editing. **Yunfei Mu:** Writing - review & editing. **Hongjie Jia:** Supervision, Project administration, Funding acquisition. **Hui Wang:** Writing - review & editing. **Hongmei Wang:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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