Resilience Assessment and Enhancement Strategies of Transmission System under Extreme Ice Disaster

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2022 IEEE Sustainable Power and Energy Conference (iSPEC) | 978-1-6654-8522-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/iSPEC54162.2022.10033057

***Abstract*—Ice storm event with high impact and low probability causes a huge challenge to the normal operation of the transmission system. To assess and enhance the resilience of the transmission system under an ice disaster, this paper constructs a resilience assessment and enhancement method for the transmission system. Firstly, the failure rate model of the transmission line is established according to the characteristics of the ice disaster scenario. Then, the resilience assessment metrics are constructed by analyzing the whole process of the system resilience under an ice disaster. On this basis, a resilience enhancement method under the ice disaster is proposed by using the transfer entropy of power flow to screen the lines that need deicing. Finally, the IEEE-30 bus transmission system is utilized to assess the resilience of the transmission system and verify the effectiveness of the proposed resilience enhancement method.**

Keywords—ice disaster, resilience assessment, resilience enhancement method

I. INTRODUCTION

Ice disasters can cause prolonged power outages and even serious damage to system components. Jilin Province was hit by the strongest rain, snow, ice and wind disasters in 2020, and causing power outages for 335,000 customers [1]. The severe winter ice disaster knocked out power to nearly 4.7 million electric customers across the U.S. in 2021. Therefore, it is of great importance to research the resilience enhancement strategies of the transmission system under ice disasters and minimize the load loss of the system.

The resilience assessment and weaknesses identification of the transmission system can reduce the impact of similar events in the future. [2] assesses system resilience to extreme weather events by using generation and load demand during disasters and the number of transmission lines as resilience indicators. [3] models power system resilience in the event of a hurricane and assesses resilience by the loss of generation capacity and the cost of restoring the power system after damage to predict the impact of a hurricane on the power system. Taking the average frequency and average outage time of the system in a storm as resilience indicators, the resilience of energy facilities is analyzed and assessed in [4]. [5] proposes a new approach for resilience assessment of the power system by establishing the resilience metric quantified in a system-wide manner at the system level and the resilience metric before and after disruptions at the individual level to assess individual components, respectively. In[6], the concept of vulnerability curve is used to evaluate the failure probability of components, and the resilience of critical infrastructure of the power system under extreme natural disaster is evaluated in terms of weather and time. The resilience assessment method for power system under typhoon disaster is proposed in [7] by considering the combination of resilience and cyber-physical power system. [8] proposes a resilience assessment model and optimal recovery model to the active distribution network.

Under different types of extreme natural disasters, corresponding resilience enhancement methods of power systems are proposed in [9-12]. The strategies of pre-disaster energy storage scheduling, optimal load cutting in disaster and post-disaster optimization of fault line repair sequence are proposed in [9] to achieve the whole process of resilience improvement of island micro-grid group under typhoon disaster. A resilience and reliability enhancement method of the power system is presented in [10] by combining the power flow, probabilistic risk assessment and adaptive capability analysis. [11] proposes a resilience-oriented planning approach to determine the optimal planning of the urban energy system. [12] improves the resilience of the power system under extreme natural disasters by using the defensive islanding method. However, the above researches do not consider the resilience assessment method and the corresponding enhancement strategies of the transmission system under ice disaster in the severe cold region. The long and widespread nature of the ice disaster may lead to a large-area and long-time power outage in the power system, and the operation of the transmission system is faced with challenges. Therefore, a resilience assessment and enhancement method of the transmission system based on extreme ice disaster is proposed in this paper.

II. MODELS OF ICE DISASTER SCENARIO AND LINE FAILURE RATE

A. The Model of Ice Disaster Scenario

The transmission system spans a wide range of distances, so some lines may be affected in the ice disaster scenario. Considering the spatial and temporal characteristics of the ice disaster, in this paper, the model of the ice disaster scenario is constructed according to the wind speed parameter and the landing location parameter.

Considering the movement of the ice disaster, the maximum impact range of the ice disaster and the wind speed encountered by the line are calculated based on the typhoon

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model [12, 13]. The formula for calculating the differential pressure at the center of the ice disaster is as follow:

$$H(t) = H_0 - 0.02\left[1 + \sin(\varphi - \delta)\right]t \tag{1}$$

where H_0 is the differential initial central pressure at the time of ice disaster landing, δ and φ is the angle between due north and the direction of ice movement and between the coastline, respectively(positive in the clockwise direction).

The maximum radius of the impact of the ice disaster can be calculated from the differential pressure at the center of the ice disaster:

$$\begin{aligned} r_{\max}(t) = \exp(2.63 - 5.086\times 10^{-5}\left(H(t)\right)^2 \\ + 0.0395 y_h(t)) \end{aligned} \tag{2}$$

where $r_{\max}(t)$ is the maximum radius of the ice disaster at time t and $y_h(t)$ is the location of the ice disaster center at time t.

The wind speed encountered by the transmission line during an ice disaster can be calculated according to (3), (4) and (5).

$$v_{R\max}(t) = 0.865 v_{gx}(t) + 0.5 v_T \tag{3}$$

$$v_g(t) = 6.97\sqrt{H(t)} \tag{4}$$

$$V_r(t) = \begin{cases} V_{R\max}(t) d(t) / r_{\max}(t) & d(t) \le r_{\max} \\ V_{R\max}(t)\left(r_{\max}(t)/d(t)\right)^{0.6} & d(t) > r_{\max} \end{cases} \tag{5}$$

where $v_{R\max}$ is the wind speed at the maximum radius of the ice disaster, $v_g(t)$ is the gradient speed of wind at time t and v_T is the ice disaster's movement speed. $V_r(t)$ is the wind speed at a particular location and $d(t)$ is the radius of the ice disaster at time t.

The growth of ice cover thickness on the transmission line can be calculated by using the model in [14], which is given by:

$$R_{\text{ice}} = \frac{t}{\pi \rho_{\text{I}}}\sqrt{\left(r\rho_{\text{W}}\right)^2 + (3.6vW)^2} \tag{6}$$

where R_{ice} is the thickness of the ice cover on the transmission line. t is the duration of the freezing rain, and r is the rainfall rate. ρ_{I} and ρ_{W} is the density of ice and water, respectively. v is the wind speed and W is the water content in the ambient air (W=$0.067r^{0.864}$).

The ice load L_{I} per unit line length can be calculated based on the thickness of the ice cover on the transmission line:

$$L_{\text{I}} = 9.8\times 10^{-3}\rho_{\text{I}}\pi\left(D + R_{\text{ice}}\right)R_{\text{ice}} \tag{7}$$

where D is the transmission line diameter.

According to the wind speed at the location of the transmission line which is calculated in (5), the wind load L_{W} per unit line length can be calculated as follow:

$$L_{\text{W}} = CSv^2\left(D + 2R_{\text{ice}}\right) \tag{8}$$

where C is the constant factor, which is taken here as 6.964×10^{-3}. S is the span factor.

Based on the ice load L_{I} in the vertical direction and the wind load L_{W} in the horizontal direction, the wind load L_{IW} under the combined effect of wind load and ice load can be obtained:

$$L_{\text{IW}} = \sqrt{L_{\text{I}}^2 + L_{\text{W}}^2} \tag{9}$$

B. The Model of Line Failure Rate

The failure rate P_{f} of the transmission line per unit length is established as follow[15]:

$$P_{\text{f}} = \begin{cases} 0 & L_{\text{IW}} \le a_{\text{IW}} \\ \exp\left[\dfrac{0.6931\left(L_{\text{IW}} - a_{\text{IW}}\right)}{b_{\text{IW}} - a_{\text{IW}}}\right] - 1 & a_{\text{IW}} < L_{\text{IW}} < b_{\text{IW}} \\ 1 & L_{\text{IW}} \ge b_{\text{IW}} \end{cases} \tag{10}$$

where a_{IW} and b_{IW} is the threshold value of the line for ice load and wind load, respectively.

In most cases, the repair time of transmission lines is positively correlated with the severity of the ice disaster, and the same can be set in the calculation of the two threshold values. The more severe the ice disaster, the longer the repair time of the transmission line, so the repair time of the transmission line is positively correlated with the severity of the ice disaster. The formula for calculating the line repair time T_{repair} is shown below:

$$T_{\text{repair}} = \begin{cases} T_n & L_{\text{IW}} \le c_{\text{IW}} \\ T_n + \dfrac{L_{\text{IW}} - c_{\text{IW}}}{d_{\text{IW}} - c_{\text{IW}}}\left(T_{\max} - T_n\right) & c_{\text{IW}} < L_{\text{IW}} < d_{\text{IW}} \\ T_{\max} & L_{\text{IW}} \ge d_{\text{IW}} \end{cases} \tag{11}$$

where T_n and $T_{\max}$ is the maintenance time and maximum maintenance time of the line under normal weather condition, respectively. c_{IW} and d_{IW} are the two threshold values set for finding the maintenance time of the transmission line, respectively.

III. Resilience Assessment Metrics Under The Ice Disaster

A. Resilience Assessment Curve

Unlike the other extreme disaster, the ice cover on the transmission line caused by the ice disaster needs some time to accumulate. The transmission system does not fail immediately when an ice disaster occurs. The resilience curve of the power system under the ice disaster scenario is shown in fig.1.

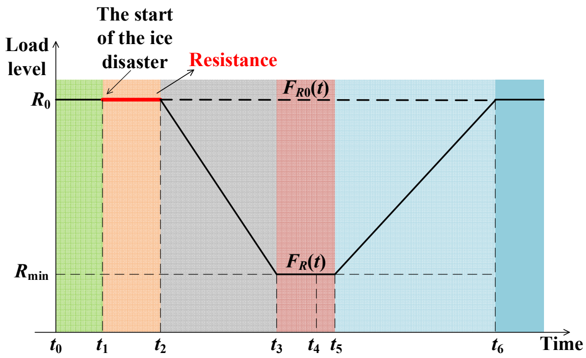

Fig. 1. Resilience curves under ice disaster

As shown in fig.1, $F_{R0}(t)$ is the curve without ice disaster, and $F_R(t)$ is the resilience curve of the system under ice disaster,t_1 is the time when the ice disaster occur, t_2 is the time when the transmission system starts to fail, t_3 is the time when the transmission system enters into a degraded operation state and the system performance does not degrade any further. t_4 is the time when the ice disaster ends, t_5 is the time at which the transmission system recover, and t_6 is the time when the transmission system returns to the initial operating state. Where t_1-t_2 phase is from the beginning time of the ice disaster to the beginning time of the decline of the system performance, which reflects the resistance of the line to the ice disaster in the transmission system, that is, the ice resistance of the line. It is only related to the line's own properties.

B. Resilience Assessment Metric Construction

The resilience assessment curve in fig.1 is used to construct the resilience assessment metric for transmission system to assess the resilience under the ice disaster. The resilience assessment metrics are constructed from three phases: pre-disaster, mid-disaster and post-disaster, reflecting the performance of the transmission system at different phases to measure the resilience of the transmission system under ice disaster. The comprehensive resilience assessment metric is obtained by the weighting method.

1) Pre-Disaster Assessment Metric R_{re}: The metric can reflect the capability of the transmission system to resist the ice disaster. The pre-disaster assessment metric is expressed as follow:

$$R_{\mathrm{re}} = \int_{t_1}^{t_2} F_R(t)\,dt \,/ \int_{t_1}^{t_4} F_R(t)\,dt \tag{12}$$

where $F_R(t)$ represents the resilience curve of the transmission system. The value of the pre-disaster assessment metric is positively correlated with the frost resistance of the transmission line.

2) Mid-Disaster Assessment Metric R_{Loss}: This metric can assess the severity of the loss of system performance under the ice disaster and reflect the robustness of the transmission system. The value of the mid-disaster assessment metric is positively correlated with the resilience of the transmission system. The mid-disaster assessment metric is expressed as follow:

$$R_{\mathrm{Loss}} = \int_{t_2}^{t_3} F_R(t)dt / \int_{t_2}^{t_3} F_{R0}(t)dt \tag{13}$$

3) Post-Disaster Assessment Metric R_{rec}: This metric can assess the recovery rate of the transmission system. The value of the post-disaster assessment metric is positively correlated with the recovery rate of the transmission system, and the expression is shown as follow:

$$R_{\mathrm{rec}} = \frac{\int_{t_5}^{t_6} \left[F_R(t) - R_{\min} \right] dt \,/\, (t_6 - t_5)}{R_0 - R_{\min}} \tag{14}$$

The numerator part of (14) is the base value of the recovery rate of the transmission system, that is, the theoretical fastest recovery rate of the transmission system. The value of the pre-disaster, mid-disaster and post-disaster resilience assessment metrics is between 0 and 1, respectively.

The above three resilience assessment metrics are weighted to obtain a comprehensive resilience assessment metric:

$$R = \omega_{\mathrm{re}} \cdot R_{\mathrm{re}} + \omega_{\mathrm{Loss}} \cdot R_{\mathrm{Loss}} + \omega_{\mathrm{rec}} \cdot R_{\mathrm{rec}} \tag{15}$$

where ω_{re}, ω_{Loss}, and ω_{rec} is the weight coefficients of the pre-disaster, mid-disaster, and post-disaster resilience assessment metric, respectively, which take the values of 0.2, 0.4, and 0.4 in this paper, respectively. The reason for this value is that the main factors affecting the pre-disaster metrics are the frost resistance of the line and the strength of the ice disaster, while the relationship with the self-regulation and emergency response capability of the system is mainly reflected in the part after the system's failure. The value of the weighting factor can be changed for different systems and for different practical conditions.

IV. Resilience Enhancement Method Under Ice Disaster

A. Transfer Entropy of Power Flow of Transmission System

The normal operation of the transmission system may be affected by an extreme ice disaster [16,17]. Therefore, the entropy value is used to represent the operational state of the transmission system and determine the current change and operational state of the transmission system when the line is actively de-icing. In the operational state s of the transmission system, the power flow Δp_{ni}^{s} transferred to line n when line i is out of service can be expressed as:

$$\Delta p_{ni}^{s} = p_{ni}^{s} - p_{n0}^{s} \tag{16}$$

where p_{ni}^{s} is the power flow of line n after line i is disconnected and p_{n0}^{s} is the initial power flow of line n.

After line i is disconnected, the power flow impact ratio of line β_{ni}^{s} assumed by line n is:

$$\beta_{ni}^{s} = \Delta p_{ni}^{s} / \sum_{n=1}^{N_l} \Delta p_{ni}^{s} \tag{17}$$

where N_l is the number of lines in the transmission system.

According to the entropy theory, the power flow transfer entropy H_i^{s} of disconnected line i under the system state s can be defined as follows:

$$H_i^{s} = -\sum_{n=1}^{N_l} \beta_{ni}^{s} \ln \beta_{ni}^{s} \tag{18}$$

When the value of H_i^{s} is large, the power flow impact of the disconnection of line i in the transmission system is relatively small, and the distribution of power flow in other lines is relatively uniform. When the value of H_i^{s} is small, the disconnection of line i has a relatively large impact on the power flow of the transmission system, and the power flow on line i is transferred to one or several lines, and the distribution of power flow is extremely uneven, which is easy to cause line overload and even may lead to cascading faults.

B. Resilience Enhancement Methods for Transmission Systems

To enhance the resilience of the transmission system under an extreme ice disaster, this paper selects key lines for de-icing by predicting the movement path of the ice and calculating the growth of ice cover on the line. DC ice melting method is adopted for the active outage and de-icing. The specific process is shown in Table I.

TABLE I. RESILIENCE ENHANCEMENT METHOD UNDER ICE DISASTER

Algorithm 1: Resilience enhancement method under ice disaster

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Step 1: The actual data of the ice disaster and weather data are entered and the movement path of the ice disaster is determined.
Step 2: The line set L_{ice} that may be affected by the ice disaster is selected based on the ice disaster movement paths and the weather data.
Step 3: The ice thickness growth of the selected lines is predicted, and the reduction quantity of system load by deicing is calculated. (The load shedding model can be found in [18].)
Step 4: The transfer entropy of power flow is obtained according to (16)-(18) and the set of L_{ice} obtained in Step 2 is selected to derive the key line for de-icing.
Step 5: The ice thickness of key lines is determined. If the icing thickness of the selected key line is close to the design value, proceed to Step 6. Otherwise, return to Step 3 and re-predict the icing thickness growth of the line and select the key line for de-icing again.
Step 6: The selected key line is disconnected for de-icing.
Step 7: The variation of system load is obtained by the load shedding model.
Step 8: Resilience assessment metrics of the transmission system are calculated and the enhancement of the resilience extent of the transmission system is estimated.

V. CASE STUDY

To verify the rationality of the resilience assessment method and the effectiveness of the resilience enhancement method under the ice disaster mentioned, the geographic location map of the IEEE-30 bus transmission system is used in this paper. The ice disaster scenario is given in [13]. The geographic location map of the nodes of transmission system and the approximate movement path of the ice disaster are shown in fig.2. Assuming that the ice disaster lands from the right margin of the figure, the geographic location is roughly 37°N/72°W the simulation time interval is 15min.

As can be seen from fig.2, the ice disaster is only likely to affect lines within its movement path, and not all lines have a probability of failure throughout the process.

Fig.3 shows the fault rate of each line in the transmission system. The Monte Carlo method is used to obtain the change of operating state of each line within 48 hours, and then the load reduction model is applied to obtain the load change of the whole process, as shown in fig.4.

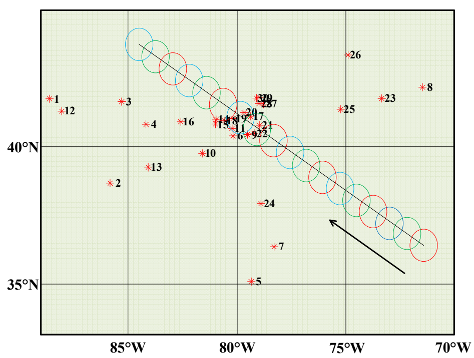

Fig. 2. Geographical location map of the system nodes and the approximate movement path of the ice disaster

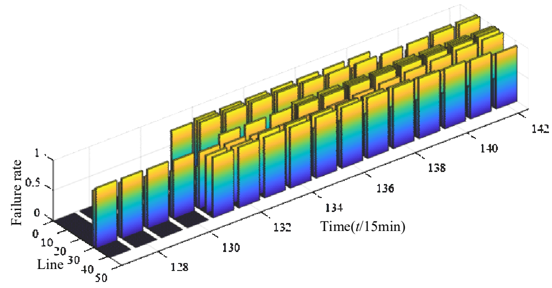

Fig. 3. The failure rate of lines

The ice disaster requires a certain amount of time to reach the fault-prone area, so fig.4 only gives the periods 110-175, the rest of the time in the system without load shedding. According to (12)-(15), the resilience assessment metrics when no resilience enhancement method is taken can be calculated, and the calculation results are shown in Table III. The post-disaster resilience assessment metric of the transmission system is relatively small. It indicates that the transmission system is relatively less resilient.

The selection of key lines for de-icing is shown in Table II by the proposed method. The line with the largest transfer entropy of power flow during line outages is line 16-17. The active outage de-icing brings a small amount of system load lift S, as low as 24.7 MWh. The load enhancement of the transmission system is taken as the first criterion for the screening of the key line for deicing, so line 21-22 is selected as the key line for deicing. The change of the load curve before and after de-icing is shown in fig.4.

TABLE II. THE AMOUNT OF SYSTEM LOAD INCREASE AND TRANSFER ENTROPY OF POWER FLOW BY DE-ICING

Line	S(MWh)	H_i	Line	S (MWh)	H_i
6-10	22.05	3.0286	10-22	36.2	2.5043
16-17	24.7	3.0628	21-22	104.95	1.7826
15-18	10.4	2.8839	22-24	-13.1	2.7401
10-17	16.85	2.9868	27-29	18.55	1.7992
10-21	10.08	1.7137	27-30	76.2	1.7336

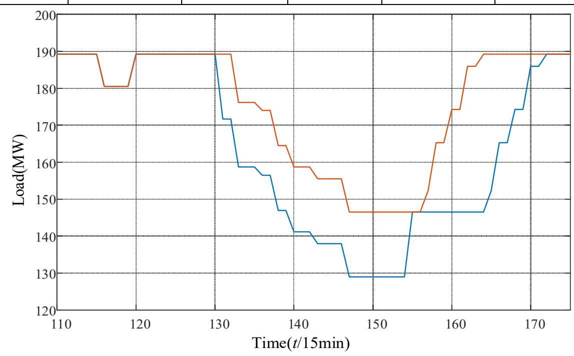

Fig. 4. Comparison of load curves with and without the resilience enhancement method

As shown in fig.4, the selected key line for de-icing is shut down and de-iced at the 114th time interval. The load of the transmission system did not drop because of the redundancy of the transmission system. The load reduction of the transmission system can be significantly reduced by using the proposed resilience enhancement method. The calculated results of the resilience assessment metrics after adopting the resilience enhancement strategy are shown in Table III.

TABLE III. RESILIENCE ASSESSMENT METRICS

Metric	R_{re}	R_{Loss}	R_{rec}	R
Normal situation	0.7312	0.7963	0.4666	0.6514
Enhancement Method	0.7709	0.8709	0.5836	0.7360

As shown in Table III, the total load reduction of the transmission system during the ice disaster is reduced by adopting the resilience enhancement method. By using the proposed resilience enhancement method, all resilience assessment metrics are improved accordingly, and the comprehensive resilience assessment metric R is improved by 12.99%. In the case and ice disaster scenarios described above, this is a relatively significant improvement compared to the resilience assessment metric without the resilience enhancement method.

VI. CONCLUSION

To assess and enhance the ability of the transmission system to resist the ice disaster and the recovery rate of the transmission system, this paper presents a resilience assessment and enhancement method of the transmission system under an extreme ice disaster. Firstly, the ice disaster scenario model and the failure rate of the transmission lines model are constructed. Then, the resilience assessment metrics of pre-disaster, mid-disaster and post-disaster phases are proposed to evaluate the ice resistance, the performance loss and the recovery rate of the transmission system, respectively. In addition, an enhancement resilience method of the transmission system under the ice disaster is proposed by choosing the key line to de-icing. The case study can prove that the proposed method can reduce the load shedding of the transmission system by the de-icing of the key line and effectively enhance the resilience of the transmission system under an extreme ice disaster.

ACKNOWLEDGMENTS

This work was supported by the State Grid Jilin Province Electric Power Co., Ltd – Research and Application of Power Grid Resilience Assessment and Coordinated Emergency Technology of Supply and Network for the Development of New Power System in Alpine Region (Project Number is B32342210001).

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