Power system resilience assessment considering the impact of ice disaster

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Abstract—With the increasingly obvious global climate change and the frequent occurrence of extreme weather events, the normal operation of the power system has a serious impact on the power system, once the extreme weather is bound to cause great harm to the distribution network system, causing large-scale paralysis of the power system, resulting in serious economic losses. Therefore, the study of power system toughness has attracted attention. In order to improve the toughness of the power system under ice disaster conditions, this study proposes a power system toughness assessment method considering the impact of ice disaster. First, the impact of ice disaster on transmission lines is analyzed and a transmission line fault model is established. Second, based on the quantitative index of power system toughness, the quantification of extreme disturbance events is transformed into the quantification of different line faults, and system-level toughness indexes are proposed in order to assess the toughness of the power system in a more specific and accurate way. Finally, the feasibility of the toughness assessment method is verified in the IEEE RTS-79 test system.

Keywords—ice disaster, power system, resilience assessment

I. Introduction

With the continued development of globalization and the acceleration of industrialization, climate change has become a global problem that cannot be ignored by countries around the world. The rise in global temperature has triggered a series of environmental problems, among which the frequent occurrence of extreme climate events has caused a great impact on the socio-economic and human production and life [1]. Among all the affected infrastructures, the stable operation of the power system is particularly critical, which is directly related to the energy security and economic stability of the country.

Extreme weather events such as ice disaster, hurricanes and high temperatures occur frequently, posing serious challenges to the normal operation of power systems. Once the power system is hit hard, it will not only lead to interruption of power supply, but may also trigger a cross-regional chain reaction, which in turn causes huge economic losses and social impacts. For example, the freezing rain in Quebec, Canada in 1998 affected an area of 1.5×105km^2, damaged 600 ultra-high-voltage towers, and caused 1.5 million households to be without power [2].The snowstorm in southern China in 2008 directly affected thousands of transmission lines, more than 36,000 transmission lines of 10 kV and above, and more than 2,000 substations of 35 kV and above in a cluster of shutdowns, resulting in a It caused a historic power supply crisis. The economic losses caused were about 151.6 billion dollars [3]. The consequences of the ice disaster reminded us that the vulnerability of power systems to extreme weather events is a cause for concern. In order to meet the challenges posed by extreme weather events, there is a need to strengthen the resilience and toughness of the power system.

With the frequent occurrence of large-scale power outages around the world, how to improve the resilience of the power system after a perturbation event is a concern for many scholars. In this context, many scholars have introduced the concept of resilience into the power system.1973 Canadian ecologist Holling introduced the concept of resilience into the field of ecology [4]. Since then, the concept of resilience has been introduced into psychology, economics, etc. Ouyang et al.[5] introduced the definition of resilience for earthquake disaster management into the power system, defining that resilience consists of four attributes (referred to as the 4R

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attributes), namely, robustness, redundancy, reactivity and rapidity, and at the same time each of these attributes consists of four dimensions, namely, technological, organizational, social, and economic; in the context of the power system, resilience is defined as a systematic prevention under low-probability high-impact events, with a low probability and a high impact of the event. In the context of power systems, resilience is defined as the ability of the system to prevent resistance, absorb response, and recover quickly under low probability high-impact events [6].

Different definitions of resilience have given rise to different assessment metrics as well as assessment systems. Reference [7] proposes a new region-based resilience indicator that takes into account the criteria of policy makers to measure the resilience of the power system. Reference [8] proposed a resilience assessment metric in terms of the amount of load restored by the system after an extreme disaster by considering the flexible allocation between different resources within the grid. Reference [9] used a complex network model for simulation and utilized the probability of system failure under certain circumstances for resilience assessment. Reference [10] proposed an assessment framework for power system resilience under typhoon disasters, centered around typhoon weather. Reference [11] proposed a new methodology for assessing the resilience of distribution networks to heat waves, proposing the resilience assessment metric as the ratio between the number of customers expected to be affected by the fault and the recovery from the fault. Reference [12] proposed a resilience assessment expression that includes three metrics, namely, system active power deficit, average load recovery speed, and average recovery time to achieve a comprehensive quantification of the distribution network. Reference [13] uses the missing area of the system load curve under extreme hill fire disasters to reflect the transmission system resilience, which can take into account both the time taken by the system to return to normal and the loss of faults during the disaster.

Existing literature found for the current system toughness assessment methods under the ice disaster is not perfect, this paper will be centered on the snow and ice disaster, research affected by its power system toughness assessment, the contribution of this paper can be summarized as follows:

1. Analyzing the impact of ice storm on transmission lines and establishing a fault model: In view of the impact of ice storm on the power system, this paper analyzes in detail the mechanism of ice storm on transmission lines, and then establishes a transmission line fault model. The model can be used to more accurately describe the fault state of transmission lines under ice storm conditions in power system resilience assessment.
2. On the basis of the quantitative index of power system resilience, this paper combines the quantification of extreme disturbance events with the quantification of different line faults to propose a system-level resilience index. This index can more specifically and accurately assess the toughness of the power system under ice disaster conditions, and help power system operators and maintainers to optimize and improve the system.

In order to better present my work, this paper is organized as follows. Section II develops a fault model for transmission lines under ice disaster. Section III proposes a system-level resilience index under ice disaster. Section IV validates the feasibility of the resilience assessment method in the IEEE RTS-79 test system. Section V summarizes the paper.

II. Analysis of the Impact of Ice Disaster on Transmission Lines

A. Types of transmission line ice cover

Ice damage can cause ice to accumulate on transmission lines, leading to icing of transmission lines, a phenomenon known as ice overlay. Ice cover can lead to tower collapse, transmission line breakage and insulator rupture [14], so it is very important to study the effect of ice cover on transmission lines. There are five common types of ice cover on transmission lines as follows:

1. Freezing rain: density 0.5-0.9g/cm^3, characterized by compactness and transparency. Formed when super-cooled precipitation touches a transmission line with a temperature equal to or lower than 0℃。
2. Freezing fog: density of 0.3~0.6g/cm^3, a milky white opaque body of variable shape. Crystalline freezing fog is over-cooled droplets in the temperature below 0 ℃ transmission line windward side of the collision of frozen and formed.
3. Wet snow: density of 0.1 ~ 0.3g/cm^3, characterized by white, crystal shape and size varies. The temperature at high altitude is below 0℃, but when it approaches the transmission line, it encounters a layer of air that is not very thick and slightly higher than 0℃, and the snowflakes fall into the transmission line before all of them are melted.
4. Mixed Song: density of 0.6 ~ 0.9 g/cm^3, in the lowlands, from the clouds to the ice crystals or raindrops on the ground fog formation.
5. Frost: density 0.05～0.3g/cm^3, white or translucent, fine and dense. Water vapor condenses directly from the air, occurs in cold and calm weather, temperature

Freezing rain has the greatest impact on transmission lines among various types of ice cover, because its structure is close and density is relatively large, which is very easy to cause the collapse of the tower as well as the fracture of the transmission line, so it produces a great threat to the normal operation of the transmission line, resulting in serious consequences, so this paper mainly focuses on the development of this type of ice cover.

B. Transmission line fault modeling

Although field measurements are the most accurate way to measure ice cover data during ice storms, the harsh environmental conditions and the need for preventive strategies make it necessary to model the ice cover growth based on weather forecast data. Considering the ease of data collection and the accuracy of the model, this paper chooses a model for ice cover calculation proposed by Jones [15]. The model makes three assumptions:

1. The collision efficiency of the raindrops with the line is 1;
2. All raindrops impacting on the line condense into ice;
3. Ice cover grows uniformly distributed over the cable surface; the formula is as follows:

$$R_{eq} = \frac{T}{\pi \rho_1} \sqrt{(r\rho_w)^2 + (3.6vW)^2} \tag{1}$$

where R_{eq} represents the thickness of ice cover (mm), T represents the duration of freezing rain in hours (h), π is taken as 3.14, r represents the rainfall rate (mm/h), ρ_1 and ρ_w represent the densities of ice and water, respectively, v represents the wind speed (m/s), and W represents the water content of the air, which is calculated by the formula $W = 0.067\mathrm{r}^{0.864}$.

In the process of ice disaster, the transmission line is mainly subjected to two aspects of the force, on the one hand, the force due to the line ice-covering, the force is vertical; on the other hand, the force is mainly due to the wind, the force is horizontal. Under the premise of known cable diameter and ice thickness, the ice force load per unit length of transmission line can be obtained, and the calculation formula is as follows:

$$L_I = 9.8 \times 10^{-3} \rho_1 \pi \left(D + R_{eq}\right) R_{eq} \tag{2}$$

Where L_I represents the ice force load (N/m) and D is the cable diameter (mm).

Provided that the thickness of the ice cover is known, the wind load per unit length of the transmission line can be obtained [16], which is calculated as follows:

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

Where L_W stands for wind load (N/m), C is the constant coefficient taken as 6.964×10^{-3}, S is the spanning factor, generally S is taken as 1, and v_g is the wind speed.

The effects of ice cover and wind on transmission lines are perpendicular to each other without taking into account the longitudinal component of wind and the occurrence of other small probability events. This is shown in Fig 1.

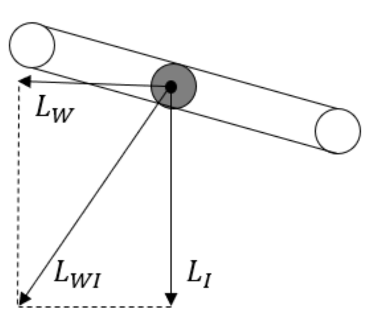

Fig. 1 Force analysis of transmission lines

According to the force synthesis can be obtained transmission line ice wind load, the formula is as follows:

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

Where L_{WI} represents ice wind load (N/m).

Since ice cover will bring certain impacts to transmission lines, transmission lines are often designed with a certain degree of resistance to ice, and when the force applied to the line exceeds its set value, its probability of failure will increase exponentially. The formula for calculating the probability of failure of a transmission line per unit length is as follows:

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

Where λ_f is the probability of failure per unit length of transmission line, and a_{WI} and b_{WI} are the two threshold values of ice and wind loads (N/m).

The probability of failure of a transmission line of length l (m) can be obtained from the definition of series network[17]. The formula is as follows:

$$\lambda = 1 - (1 - \lambda_f)^l \tag{6}$$

III. Evaluation of Transmission Line Resilience Under Ice Disaster

A. *Quantification of power system resilience*

At this phase, many scholars have proposed the quantification of power system resilience, but there is no complete unified standard, the existing power system resilience quantification index is based on the power system performance function is determined. Fig 2 shows a "ladder diagram" reflecting the change of power system performance Q under the perturbation time. Where t_0 is the beginning of the perturbation event, t_1 is the moment when the system performance decreases; t_2 is the moment when the system is derated; t_3 is the moment when the system performance starts to recover; and t_4 is the moment when the system performance returns to normal.

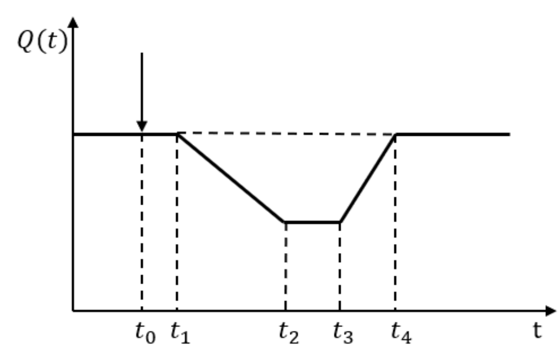

Fig. 2 Performance function change process

Scientific and effective quantification of the abstract concept of distribution grid resilience is the basis for grid resilience assessment. The resilience metric is defined as the area of performance loss in the system. The calculation involves integrating the product of the performance loss and time with the following formula:

$$R = \int_{t_0}^{t_1} [100 - Q_1(t)]dt \qquad (7)$$

At present, ice disaster events are considered low-probability events with unpredictable consequences. However, these events directly increase the failure probability of power transmission lines. Therefore, this study extends the existing quantification indicators of power system resilience by incorporating the quantification of ice disaster event probabilities into the quantification of the probabilities of different line failures and their respective impacts.

B. System-level resilience indicators

System-level resilience indicators reflect the impact of various disturbances on resilience from a system perspective. These indicators are widely used and quantify the results and duration of the impacts caused by disruptive events in the power system. They specifically quantify two aspects of the 4R attributes of resilience: robustness and rapidity.

Existing resilience quantification indicators often only consider the impact of specific fault situations. However, over a certain period of time, the system may experience multiple different fault situations. Therefore, the occurrence frequency of different fault situations is also an important aspect to measure system resilience. For disturbances that can cause performance losses in the system, improving the system's resilience indicators can be achieved by reducing the frequency of their occurrence. The calculation formula for system-level resilience indicators is as follows:

$$R = \sum_{i \in s} f_i \Delta t_i \Delta Q_i \qquad (8)$$

Where s is the set of fault situations that have occurred; f_i is the frequency of occurrence for fault situation i; Δt_i is the time it takes for fault situation i to return the system to normal state; and ΔQ_i is the impact of fault situation i on the system performance function.

In power system circuits, most faults that occur are usually transmission line faults. When a transmission line fault occurs, there may be situations where the branch flow exceeds the limit. After a series of scheduling measures, if there are still situations where the branch flow limit is exceeded, load shedding is required. This paper quantifies the frequency of fault situations that cause the branch flow limit to be exceeded as a quantification indicator of frequency, and quantifies the time it takes to restore the branch flow limit to normal state as a quantification indicator of rapidity. The branch flow limit is quantified as a quantification indicator of robustness.

Using the state enumeration method to obtain the system fault situation i, the probability P of the previous possible system state i_0 and the device failure rate λ obtained by the Markov method are used to obtain the probability of the enumerated system state occurrence, resulting in the frequency indicator. The calculation formula is as follows:

$$f_i = P\lambda \qquad (9)$$

In the case of ice disasters, the failure probability λ of transmission lines will also increase. This paper chooses equation (6) to calculate the failure rate of transmission lines. When a transmission line is broken, the output of the generator has not changed, and the active power output of each generator remains at P_{GK0}. At the same time, each load node remains at the original load P_{Ln0}, resulting in a flow limit situation. Through generator scheduling, the active power output of the generator node changes to P_{GK1}, and the flow will not exceed the limit. The scheduling time of the generator is obtained by dividing the change in the active power output of the generator node by the climbing rate of the generator. The maximum scheduling time is selected as the time limit for the branch flow. The specific formula for the system-level resilience index is as follows:

$$R = \sum_{i \in s} f_i \Delta t_i \sum_{l=1}^{L} \Delta Q_{il} \qquad (10)$$

IV. Case Study

The IEEE RTS-79 reliability test system is used in this case study, and its topology is represented in Fig.3.

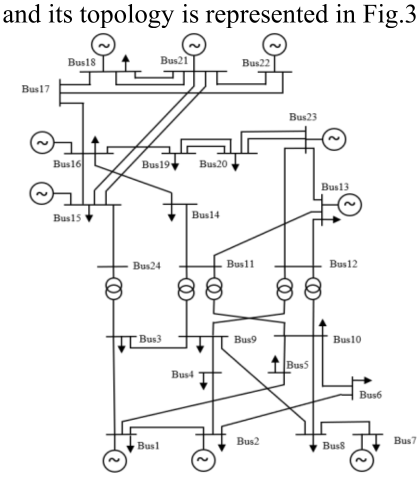

Fig. 3 System topology

Case1: According to reference [18], a resilience metric for assessing the power system is proposed as the maximum lost load ratio, being defined as the ratio of the amount of system load in the worst case of a fault to the amount of system load in the case of no faults, which describes the system resilience of the distribution network in the case of faults suffered from the resultant level.The calculation formula is as follows:

$$R_a = \frac{\sum_{j \in \Omega_N} \Delta P_{load,j}}{\sum_{j \in \Omega_N} P_{load,j}} \qquad (11)$$

Generate line fault states based on Monte Carlo method, select five lines with high probability of failure, disconnect them and generate fault scenarios.

Case2:Based on Equation (10), the resilience index of each branch can be calculated. By summing up the results of each branch, the overall resilience index R_{pre} of the entire system can be obtained. The calculation result is:

$$R_{pre} = \sum_{i \in s} f_i \Delta t_i \sum_{l=1}^{L} \Delta Q_{il} = 0.1381$$

The resilience index calculation results of each branch under normal weather conditions are shown in the Fig.4.

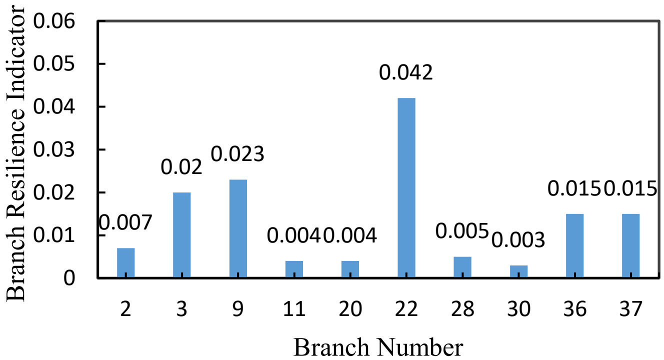

Fig. 4 Branch resilience indicator under normal weather conditions

During an ice disaster, the ice thickness and wind speed during the disaster period can be obtained from weather forecasts. Based on Equation (10), the resilience index of each branch can be calculated. The calculation result is:

$$R_{post} = \sum_{i \in s} f_i \Delta t_i \sum_{l=1}^{L} \Delta Q_{il} = 180$$

The resilience index calculation results of each branch under ice disaster weather conditions are shown in the fig.5.

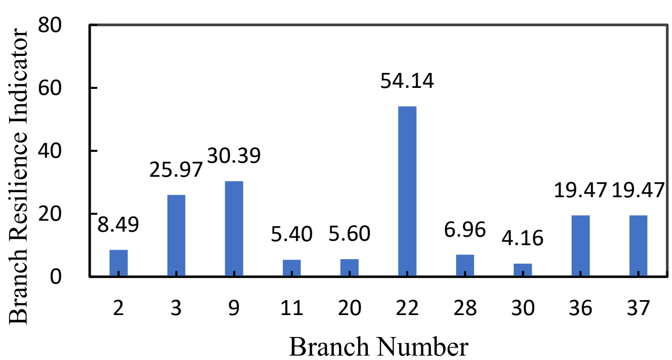

Fig. 5 Branch resilience indicator under ice disaster weather conditions

From the calculation results, it can be seen that compared to normal weather conditions, the overall system resilience will significantly decrease during ice disasters. Based on the resilience index calculation results of each branch, it can be observed that Branch 22 has the highest resilience index, indicating that this line is most susceptible to the impact during ice disasters, leading to a decrease in the overall system resilience.

Table 1 case analysis

Case	Normal weather conditions	Ice disaster weather conditions
Case1	0.98	0.4
Case2	0.1381	180

By Table 2, we can see that both resilience assessment methods aim to describe the resilience performance of the distribution network when facing extreme weather events such as ice disaster. However, the method proposed in this paper has the unique advantage that it is not only able to assess the resilience of the entire distribution network, but more importantly, it is able to refine to the level of each transmission line and quantify the resilience capability of individual lines. This granular approach allows power system operations and maintenance personnel to identify those lines that are most vulnerable to damage during an ice storm. By analysing the resilience metrics of these high-risk lines, targeted resilience enhancement measures can be more precisely developed, such as reinforcing these lines to increase their ability to withstand extreme weather.

V. Conclusions

In order to assess the resilience of the power system under ice disaster, this paper establishes a system-level resilience index, which reflects the system-level resilience strength as a whole, and can identify the weak links of the system, so that a variety of countermeasures can be taken to minimize the impacts on the power grid before an extreme event occurs.

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