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A QUANTITATIVE RESILIENCE INDEX OF POWER SYSTEMS UNDER EXTREME ICE DISASTERS

Ningyuan Zhao[1], Kai Hou [1*], Hongjie Jia[1], Xiaonan Liu[1], Lewei Zhu[2], Dan Wang[1], Yunfei Mu[1], Xiaodan Yu[1]

1 Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, China.

2 Maritime College, Tianjin University of Technology, Tianjin 300384, China.

ABSTRACT

Extreme ice disasters may lead to a rapid degradation of power system performance. By using a fault probability model of transmission lines with respect to ice-wind loads, the impacts of ice disasters on power systems can be regarded as transmission line outages. To quantify these consequences, a quantitative resilience index is developed in this paper. Finally, the proposed index is testified on the IEEE RTS-79 test system. Results indicate that different enhancement measures can be evaluated based on the obtained resilience indices.

Keywords: ice disasters, power systems, fault probability model, resilience index

1. INTRODUCTION

Extreme disasters, such as ice disaster, have consistently threated the power system security.The ice disasters occurred in Eastern Canada and Northeastern United States in January 1998 caused 1.4 million households to be affected by power outages [1].Another example is the ice disaster occurred China in 2008, which leading to power interruptions in 170 cities [2].This means, a power system that meets the reliability operation criteria may still not able to maintain normal operation in the face of disasters. Therefore, the concept of resilience was proposed to solve this dilemma.

The term resilience was first defined by C.S.Colling [3] in 1973--the persistence of a system and its ability to absorb changes and disturbances and still maintain the same relationships between population or state variables. In 1995, the buffer capacity was added to the definition of a resilient concept [4]. Then the definition of resilience became diversified. For example, in [5], a resilient system is defined to be able to create foresight, recognize, anticipate, and defend against the changing fault scenarios even before adverse consequences occur.

While according to the department of homeland security, resilience can be defined as the ability of a system to prevent and adapt to the changing conditions, as well as to withstand these disturbances and recover rapidly [6].

However, there is still no unified understanding of the concept of resilience. Different literatures, define and understand resilience variously, lead to different resilience assessment approaches. Bruneau proposed a general framework to define and quantify the seismic resilience of communities [7]. After that, S. E. Chang proposed seismic resilience measures that relate expected losses and community performance objectives, and re-framed the measures in a probabilistic context [8]. Panteli assessed the resilience based on quantifying the frequency and duration of customer disconnections due to disruptive events and also the number of customers disconnected [9]-[10]. However, there is still few approaches to evaluate the system resilience of ice disasters in the existing literature.

This paper is organized as follows: a broad system resilience performance function is described in Section II. Section III represents a fault probability model of transmission lines under ice disasters. An index to evaluate the resilience of power systems under extreme ice disasters is proposed in Section IV. This index is testified on IEEE RTS-79 test system in Section V. Conclusions are drawn in Section VI.

2. QUANTIFYING THE RESILIENCE CONCEPT

Different disasters produce different impacts on the systems. Hence, a broad resilience performance function should be able to measure the actual or potential performance of any systems at any given time.

To quantifying the resilience concept. And more importantly, directly or indirectly reflects the "4R" characteristics of the system resilience -- robustness, redundancy, resourcefulness, and rapidity. Based on this, Bruneau proposed the community resilience index [7], which can be applied to assess any systems. Fig 1 quantifies the process of the system performance function during the disaster to assess the resilience of power system.

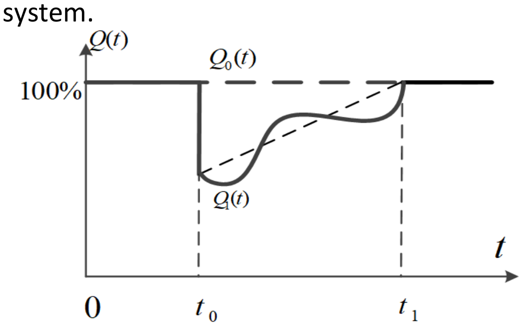

Fig 1 Quantification of resilience concept

$Q_1(t)$ is used to describe the performance of the system, so there is no doubt that the value of $Q_1(t)$ should be 100% when the system is in normal operation. $Q_0(t)$ represents the normal level of this system. However, when a sudden disaster occurs at t_0, the failure scenario begins, and the system performance $Q_1(t)$ will decline rapidly ($0<Q_1(t)<100\%$).

Over time, the performance of the system will fluctuate and return to the normal level at t_1.The whole process can be represented by formula (1).

$$R = \int_{t_0}^{t_1} [Q_0(t) - Q_1(t)]dt \tag{1}$$

According to Fig 1, to quantify the resilience of the system, the most important thing is to evaluate the performance of the system, analyze its severity and make preventive measures or timely emergency strategies. In order to achieve this goal, it is necessary to quantify the changing process of the performance function curve of the system.

The impacts of different fault scenarios on the power system are quite different, which make it difficult to quantify the resilience of the power systems. But for ice disasters, their most direct impacts on the power system are the failures of transmission lines caused by severe weather. Therefore, the system resilience can be evaluated and improved by establishing the transmission lines fault model under the extreme ice disasters and calculating the system load loss caused by the line outages.

3. FAULT PROBABILITY MODEL OF TRANSMISSION LINE UNDER ICE DISASTERS

In order to evaluate the resilience of power system during ice disaster, the fault probability model of transmission lines should be established first. During the ice disaster, the main reason of the transmission lines failure is that the transmission line will be damaged due to the excessive force. There are two main forces work here: the horizontal force due to wind and the longitudinal force due to ice. They can also be considered as wind and ice loads of transmission lines.

3.1 Ice loads

The first step in calculating ice loads is the selection of the forecasting model for ice thickness. Considering the weather condition of ice disaster, the simple model for freezing rain ice loads proposed by Kathleen f. Jones [11] was used to obtain ice thickness. The model assumes that the cables are long cylinders with different diameters suspended horizontally above the ground, so that droplets of water falling on the cables also fall on the cables, and the ice is evenly distributed across the surface of the cylinders. The calculation formula of this model is as follows:

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

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); W is the liquid water content in the air, which comes from W=0.067×$r^{0.864}$.

Thus, the ice loads of transmission lines are:

$$L_I = 2.5\times10^{-4} g\rho_I\pi((D+2R_{eq})^2 - D^2) \tag{3}$$

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

3.2 Wind loads

According to literature [12], it can be concluded that the wind loads of per unit of transmission line are:

$$L_W = 7\times10^{-4}\times gSv^2(D+2R_{eq}) \tag{4}$$

where L_W are wind loads (N/m); g is the value of gravity acceleration, take 9.8 (m/s); S is the crossover factor, v is the wind speed (m/s).

3.3 Fault probability model of transmission line based on ice-wind loads

There is a threshold of the force that transmission line can withstand. When the force exceeds this threshold, the bearing capacity decreases exponentially with the increase of the generation strain, resulting in transmission line outages. According to the deformation theory of metal, the transmission line exponential fault model can be established by formula (5).

$$P_f = \begin{cases} 0 & x \le a \\ \exp\left[\dfrac{0.6931(x-a)}{b-a}\right]-1 & a < x < b \\ 1 & x \ge b \end{cases} \quad (5)$$

where x can be wind speed, ice thickness, ice loads, wind loads, etc ; P_f is transmission line fault probability; a and b are two thresholds.

In the process of ice disaster, transmission lines suffer from the combined force of wind loads and ice loads, as shown in Fig. 2:

$$L_{WI} = \sqrt{(L_I)^2 + (L_W)^2} \quad (6)$$

where L_{WI} are the ice-wind loads.

The loads capacities of lines are different in the horizontal and vertical directions, so assuming when only considering the wind speed, the threshold values of the wind speed are 1 time and 2 times the design values of the wind speed. Considering only the ice thickness, the threshold values are 1 time and 5 times the design values of ice thickness. On the vertical plane of the conductor, the trajectories of the thresholds of the ice-wind loads can be considered as ellipse, as shown in Fig 2.

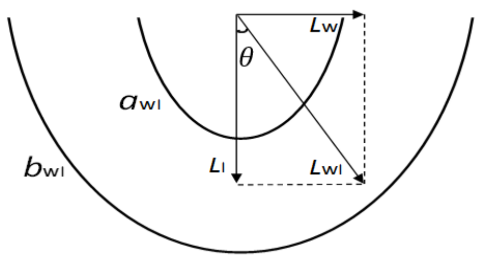

Fig 2 Ice-wind loads and threshold diagram

According to the designed wind speed and ice thickness of the transmission line, two threshold values can be obtained, as shown in formula (7).

$$a_{WI} = \frac{a_W a_I}{\sqrt{(a_W \cos\theta)^2 + (a_I \sin\theta)^2}}$$
$$b_{WI} = \frac{b_W b_I}{\sqrt{(b_W \cos\theta)^2 + (b_I \sin\theta)^2}} \quad (7)$$

where a_I, b_I, a_W, b_W are the thresholds when only considering the ice thickness or the wind speed; a_{WI} is the first threshold value of ice and wind load (N/m), b_{WI} is the second threshold value of ice and wind loads (N/m). θ is the angle between L_I and L_W.

The transmission line fault probability based on ice and wind loads is obtained by formula (8).

$$P_f = \begin{cases} 0 & L_{WI} \le a_{WI} \\ \exp\left[\dfrac{0.6931(L_{WI}-a_{WI})}{b_{WI}-a_{WI}}\right]-1 & a_{WI} < L_{WI} < b_{WI} \\ 1 & L_{WI} \ge b_{WI} \end{cases} \quad (8)$$

Where P_f is the fault probability of unit line.

Different lengths of lines lead to different probability of failure. According to the definition of the series network, the failure probability of each line can be obtained:

$$P_L = 1-(1-P_f)^L \quad (9)$$

where L is the length of different lines.

4. A RESILIENCE INDEX UNDER EXTREME ICE DISASTERS

On the basis of the above sections, this paper proposes an approach to quantify the resilience of system under ice disaster. The proposed system resilience index can not only reflect the resilience of the system in the face of ice disaster but also provide a theoretical basis for the maintenance personnel to predict and enhance the system resilience. The proposed index can be shown in formula (10).

$$R = \sum_{i \in s} P_i \cdot Q_i \cdot t_i \quad (10)$$

where s is a set of scenarios composed of different failure scenarios. i is a failure scenario of set s. t_i represents the duration of the ice disaster, Q_i represents the selected performance function, and this article chooses to use the system's load loss. P_i is the probability of failure scenario i , calculated from the formula (11).

$$P_i = \prod_{i=1}^{N_f} A_{Lm} \cdot \prod_{i=1}^{N-N_f} P_{Lm} \quad (11)$$

where A_{Lm} and P_{Lm} are the normal probability and fault probability of line m, (m=0,1,2,3,...,M). N_f is the number of lines in the system that are under normal operation situation.

Considering the number of components in large-scale power systems, the amount of high order failure states often has a considerable quantity. In view of the state enumeration often ignores this higher-order state, an impact-increment state enumeration method [13] is utilized to improve this problem, which can be expressed as：

$$P_i \cdot Q_i = \Delta P_i \cdot \Delta Q_i \quad (12)$$

It eliminates the normal probability Replace it with the unavailability, that is, the probability of failure. Formula (11) can be changed into formula (13).

$$\Delta P_i = \prod_{i=1}^{N_f}(1-P_{Lm}) \cdot \prod_{i=1}^{N-N_f} P_{Lm} \tag{13}$$

where ΔP_i is the probability of failure scenario i based on impact-increment method.

While the performance function is changed into:

$$\Delta Q_i = \sum_{k=0}^{n_i}(-1)^{n_i-k} \sum_{u \in s_i^k} Q_u \tag{14}$$

where ΔQ_i is the load loss of a system based on impact-increment state enumeration method, n_i is the number of fault components in fault scenario i, and s_i^k is the -order subset of i, defined as follows:

$$s_i^k = \{u \mid u \subset i, Card(u) = k\} \tag{15}$$

where Card(u) is the number of elements in state u, when $k = 0$, s_i^k is an empty set.

Thus, the formula for calculating the system resilience index based on impact-increment state enumeration method under ice disaster can be obtained:

$$\Delta R = \sum_{i \in s} \Delta P_i \cdot \Delta Q_i \cdot \Delta t_i \tag{16}$$

where Δt_i is equal to t_i, Δt_i is used in order to unify the form. According to the above formulas and fault probability model, the resilience index of the extreme ice disaster can be calculated.

5. CASE STUDY

In this section, the IEEE RTS-79 test system is used to illustrate the resilience index. Its total load is 2850MW. The meteorological data used is from [14].

Case 1: Base case

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 are 25m/s and 20mm respectively.

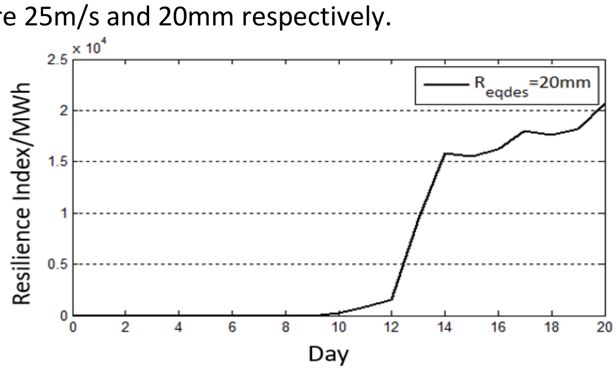

Fig 3 System resilience index

Based on this, the resilience index of this system can be obtained. According to the resilience index curve in Fig 3, the system performance has changed dramatically in 20 days.

Case 2: enhancement case

Two enhancement measures are used to evaluate their impact on the resilience of this system. The resourceful measure assuming the maximum load loss that the system can bear each hour is 10% of its total load. Managers will take deicing measures once the loss of system is beyond this value. While the robust measure increases the design ice thickness value to 30 mm. Simulation results are shown in Fig. 4.

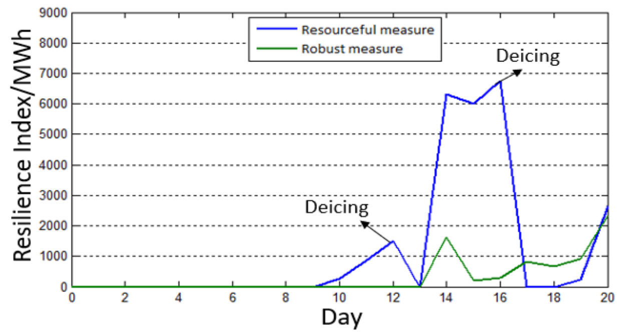

Fig 4 Simulation results of enhancement measures

The resilience index curves of figure 4 indicate that both methods can improve the resilience of the test system to a great extent, but the robust measure is more effective in enhancing the resilience of this test system.

However, the economy of these measures is also an important factor to be considered by power companies. Therefore, the cost of increasing the design ice thickness of the transmission lines should be compared with the cost of deicing. to determine the optimal scheme. That will be expended in our future paper.

6. CONCLUSION

By using a fault probability model of transmission line with respect to ice-wind loads, a quantitative resilience assessment index under extreme ice disasters is proposed. Cases studies show that the proposed approach is effective. Influences of extreme ice disaster on power systems can be quantified by the proposed resilience index. This resilience index can also reflect the effect of different resilience enhancement measures on power systems and provide theoretical basis for them.

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