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THE IMPACT-INCREMENT STATE ENUMERATION METHOD BASED RESILIENCE ASSESSMENT APPROACH OF POWER SYSTEM UNDER WINDSTORMS

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ABSTRACT

Overhead transmission line is an important part of power system, it is easy to be affected by natural disasters. In order to enhance the ability of power system to resist those disasters, the resilience assessment indices should be established to provide decision support for power grid dispatchers and operators in advance, which has become one of the economical and efficient technical routes to improve the power system resistance ability. In this paper, windstorm is taken as an example, the wind speed related fragility model of overhead transmission line and impact-increment state enumeration method based resilience indices are proposed. The resilience indices are proposed form the perspective of system and component respectively. The system resilience indices can reflect the resilience from a holistic perspective and the component resilience indices are expected to determine the weak points of the whole system. The system resilience and weak points of the IEEE RTS-79 system are analyzed under one certain windstorm and the numerical results verify the effectiveness of the proposed resilience assessment indices.

Keywords: windstorm, wind speed related fragility model, impact-increment state enumeration method, system resilience indices, component resilience indices.

1. INTRODUCTION

With the expansion of power systems, many overhead transmission lines are exposed to external meteorological environment. Windstorm becomes the most serious one among the natural disasters which may result in failures of overhead transmission lines and further result in power outages. This will not only bring great harm to the safe operation of the entire power system, but also have a serious impact on the national economy and the normal life of residents. In order to enhance the resist ability of power system to windstorm, many scholars attempted to introduce the concept of resilience into power system [1]-[6]. A resilient power system can maintain as high operation level as possible under natural disasters. Therefore, how to effectively enhance the resist ability on windstorm and establish a resilient power grid is the common goal that the operators are constantly working on. It is generally known, the failure of some overhead transmission lines may not affect the system operation, while the failure of other overhead transmission lines may cause the system failure which lead to significant load shedding. Thus, the resilience assessment indices while integrating the meteorological environmental information should be established to determine the most influential overhead transmission lines that is the weak points of the system. Those assessment results can provide decision support for dispatchers and operators in advance. Regarding this fact, this paper develops a wind speed related fragility model of transmission line and impact-increment state enumeration method based resilience indices to analyze the impacts of windstorm. Two resilience indices are developed from the perspectives of the system and individual component levels, respectively. Firstly, the wind speed related fragility model is utilized to determine the operation reliability of each overhead transmission line, which is reflected by the transmission line failure probability as a function of the wind speed. According to the wind speed prediction during one certain windstorm, the failure probability of each line can be obtained. Thus, the potential impact of the system and the contribution of each overhead transmission line failure to the total impact caused by windstorm can be

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evaluated quantitatively by the proposed system and component resilience indices respectively. The load shedding is recognized as the impact of windstorm in this paper. Meanwhile, the impact-increment state enumeration method is utilized to quickly compute the proposed indices. The system resilience indices can quantify the total expected value of load shedding under one specific windstorm in advance. The component resilience indices can help determining the most influential overhead transmission lines and informing the dispatchers and operators which lines need to focus on in advance in order to enhance the resistance capability.

2. THE WIND SPEED RELATED FRAGILITY MODEL

In reliability assessment, the failure probabilities of overhead transmission line are obtained from historical data and treated as constants. In resilience assessment, due to the extreme meteorological environment, the failure probability of overhead transmission line is rapidly increased. The wind speed related fragility model of overhead transmission lines are proposed to predict the wind speed at the locations of different overhead transmission line. In this paper, the Batts windstorm model is utilized to simulation the movement and attenuation of windstorm [7]. Before the windstorm landing, the meteorological department can provide the related data, including the landing coordinates of the windstorm center, original pressure difference of the windstorm center, translational speed and the motion direction.

The wind speed at distance r from the windstorm center at t hour can be obtained by

$$v_r = \begin{cases} V_{\max} r / R_{\max} & , r \le R_{\max} \\ V_{\max} (R_{\max} / r)^{0.6} & , r > R_{\max} \end{cases} \tag{1}$$

The radius of maximum wind speed $R_{\max}$ can be obtained by

$$R_{\max} = 1.119 \times 10^3 \times \Delta P_0^{-0.805} \tag{2}$$

The maximum wind speed $V_{\max}$ can be expressed as

$$V_{\max} = 5.712\sqrt{\Delta P_0 - 0.675(1+\sin\phi)t} + 0.5V_T \tag{3}$$

Where $\triangle P_0$ represents the original central pressure difference, V_T represents the translational speed of typhoon, ϕ represents the angle between typhoon motion direction and landing coastline, t represents the duration hour of typhoon.

According to the obtained wind speed based on Batts model, the failure probability of each transmission line during the t hour can be obtained as follow [8]:

$$p_m(t) = 1 - \exp(-\int_t^{t+\Delta t} (\exp((a_m \frac{v_m(t)}{v_m} + b_m) \bullet l_m) dt) \tag{4}$$

where $v_m(t)$ represents the wind speed at the t hour, v_m represents the design wind speed of overhead transmission line m, a_m and b_m represent the model parameters, which can be obtained by statistical analysis of historical data, l_m represents the length of overhead transmission line m. Δt represents the time interval and it is assumed that the wind speed stays the same in Δt.

3. THE RESILIENCE ASSESSMENT INDICS

Before the windstorm landing, it usually unable to predict the accurate failure scenario, that is, which transmission lines will fail. Thus, it is necessary to enumerate all possible failure scenarios caused by windstorm in advance and determine which overhead transmission lines are most influential on the supply capability of the system, those lines need to be pay more attention. Thus, the resilience indices are proposed form the perspective of system and component to give the useful information to the dispatchers and operators. The system resilience indices are defined to quantify the expected value of load shedding under all possible failure scenarios by considering potential multiple transmission line outages, which is utilized to assess the entire system resilience in advance. On the basis of system resilience indices, the component resilience indices are proposed to quantify the contribution of each overhead transmission line to the entire system resilience. State enumeration method is a commonly used technique to enumerate the possible failure scenarios and its efficiency goes up exponentially with the increment of overhead transmission line number. In order to quickly compute the proposed indices, the impact-increment state enumeration method is utilized [9]-[10]. Thus, for system with N overhead transmission lines, the impact-increment state enumeration method based system and component resilience indices at the t hour can be obtained as follow.

$$R(t) = \sum_{k=0}^{N} \sum_{s \in \Omega_A^k} \left(\prod_{i \in s} p_i(t) \right) \Delta I_s \tag{5}$$

where s represents a failure scenario denotes by a set of the corresponding faulty transmission lines. A represents the set of all transmission lines and Ω^k_A represents the k order subset of A. $p_i(t)$ represents the failure probability of ith transmission line that related to the sth failure scenario, which can be obtained from (4). ΔI_s represents the impact-increment of load shedding, which can be obtained by the optimal power flow algorithms.

$$
\begin{aligned}
R_m(t) &= R(t) - R(t)\big|_{p_m(t)=0} \\
&= \sum_{k=0}^{N} \sum_{s\in\Omega_A^k} \left(\prod_{i\in s} p_i(t) \right) \Delta I_s \\
&\quad - \sum_{k=0}^{N} \sum_{s\in\Omega_A^k} \left(\prod_{i\in s} p_i(t) \right) \Delta I_s \Big|_{p_m(t)=0} \\
&= p_m(t) \sum_{k=0}^{N} \left[\sum_{\substack{s_m\in\Omega_A^k \\ m\in s_m}} \left(\prod_{i\in s} p_i(t) \right) \Delta I_{s_m} \right] \\
&\quad + \sum_{k=0}^{N} \left[\sum_{\substack{s_0\in\Omega_A^k \\ m\notin s_0}} \left(\prod_{i\in s_0} p_i(t) \right) \Delta I_{s_0} \right] \\
&\quad - \sum_{k=0}^{N} \left[\sum_{\substack{s_0\in\Omega_A^k \\ m\notin s_0}} \left(\prod_{i\in s_0} p_i(t) \right) \Delta I_{s_0} \right] \\
&= p_m(t) \sum_{k=0}^{N} \left[\sum_{\substack{s_m\in\Omega_A^k \\ m\in s_m}} \left(\prod_{i\in s} p_i(t) \right) \Delta I_{s_m} \right]
\end{aligned} \tag{6}
$$

where $R(t)\,|_{Pm(t)=0}$ represents the system resilience under the assumption that the failure probability of overhead transmission line m is 0, which means that this line will never fail under windstorm. It's worth mentioning that the impact-increment of load shedding ΔI_s has been obtained during the computation process of system resilience index, only the failure probability of each overhead transmission line at each time need to update by (4).

4. CASE STUDY

The IEEE RTS-79 system [11] is implement to testify the efficiency of the proposed resilience assessment indices. This system consists of 38 lines and 24 buses, including 10 PV buses and 17 PQ buses. The annual maximum load is 2850MW. The geographical schematic diagram of IEEE RTS-79 system is shown in Fig. 1, and the latitude and longitude of each overhead transmission line the number of each bus has been marked in this figure [12]. According to the prediction information of windstorm from [12], the landing position is 111.7411°E, 21.1343°N, the pressure difference is 23.24hPa, the translational speed is 18.14 km/h. The windstorm is assumed to move in the northwest direction, and the angle with the west direction is 46.46°.

The results of the proposed system resilience indices are shown in Fig 2. Due to the movement and attenuation of windstorm, the wind speed decreases with time. Thus the failure probability of each overhead transmission line decreases according to (4), so the system resilience also decreases according to (5).

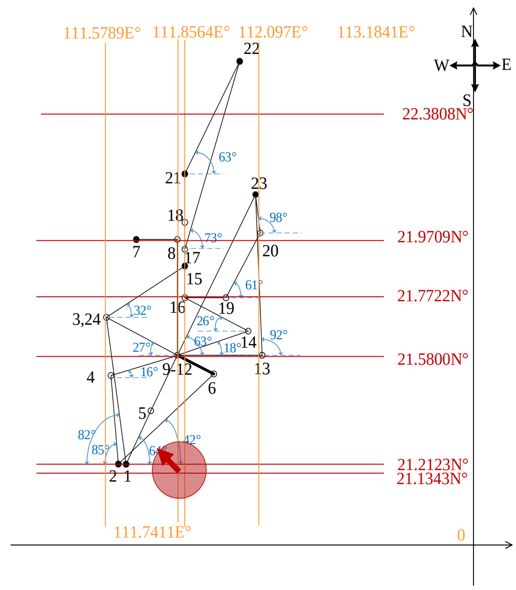

Fig 1 The geographical schematic diagram

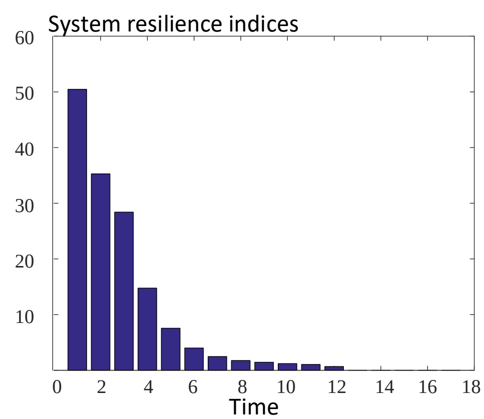

Fig 2 The system resilience indices

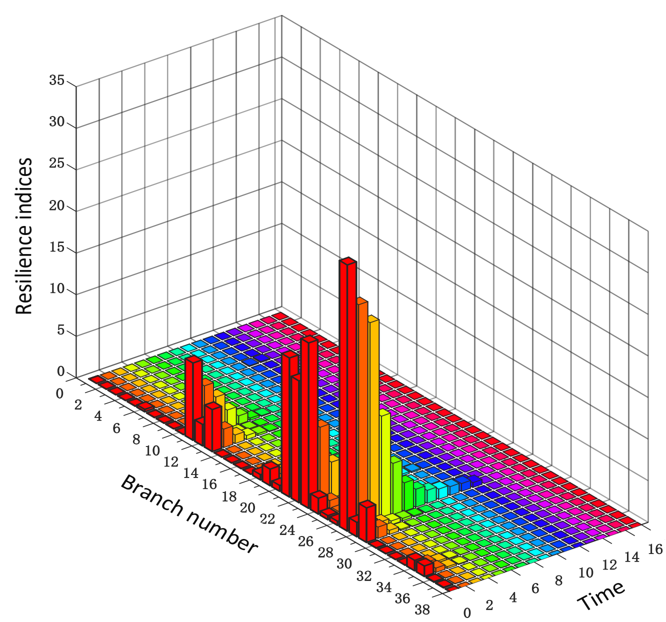

Fig 3 The component resilience index of each line

The results of the proposed component resilience indices are shown in Fig 3. From the numerical results, the overhead transmission line 27 (from bus 15 to 24) is the most influential one, its failure may lead to relatively large load shedding. Thus, the dispatchers and operators should pay more attention on it and avoid its failure due to windstorm.

5. CONCLUSION

Although the power system resilience under natural disasters has got extensive attention of the dispatchers and operator, its related work is just in its infancy. Before the windstorm landing, the precomputed system and component resilience indices can provide scientific technical support and decision-making reference for the power system disaster prevention. Therefore, the dispatchers and operators can take precautions and formulate emergency plans in advance to improve the system resistance ability, so as to minimize the impact of windstorm on power system. The resistance ability enhancement measures can be applied to improve the system resilience, from the perspective of planning and operation, such as upgrading the most influential overhead transmission lines with more robust materials. Those enhancement measures will be interesting to research in the following work.

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