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The Impact-increment State Enumeration Method Based Component Level Resilience Indices of Transmission System

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Abstract

There are various kinds of disasters may incur power system blackouts and their impacts on power system are difficult to predict in advance. On the basis of existing resilience assessment indices, this paper proposes a component level resilience indices of transmission system. The component level resilience is defined as the contribution of each transmission line to system resilience under each failure scenarios. This newly developed indices can be used to quantify the resilience enhancement from the perspective of a certain component. Therefore, each failed transmission line can be ranked based on the component level indices, then optimal recovery strategies can be determined accordingly. An impact-increment state enumeration method, which is more efficient and accurate than tradition methods, is used to calculate the proposed indices. Case studies are performed on IEEE 30-bus test system to demonstrate the accuracy and computational efficiency of the proposed component level resilience indices.

Keywords: component level resilience, Impact-increment state enumeration method, repair sequences, transmission lines.

1. Introduction

With the continuous expansion of the power system, the number of transmission line is increasing rapidly and its structure becomes increasingly complex. Therefore, the potential external disasters, such as storm, are more likely to cause blackouts and further result in huge economic losses. Recently, the rarely occurred blackouts caused by external disasters have drawn increasing attentions of experts and scholars due to their tremendous damage. In order to enhance the ability of power system to recovery rapidity from those disasters, many scholars attempted to introduce the concept of resilience into power system.

Resilience can be regard as the ability of individuals or systems to maintain performance under external disasters and to recover rapidity from the damage state. Since the Canadian scholar HOLLING introduced the concept of resilience to ecology [1], this concept

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has been applied to various disciplines, such as economics, sociology, psychology, engineering and so on [2]-[8]. In recent years, the concept of resilience has also been applied to power systems [10]-[14]. Based on the existing definition of resilience, and the characteristics of the power system, this paper considers that the most remarkable characteristic of resilience is the ability to recover rapidity after system failure due to external disaster. A resilient power system can quickly recovery to its normal state after system failure. Although there is no uniform standard for the definition of power system resilience, its connotation includes how to recovery as soon as possible when power system failure due to external disaster. This is also the main focus of this paper.

The existing literatures mainly discussed the resilience of power system from the system perspective. However, in order to provide more detailed information to planners and operators, it is necessary to find a way to locate the most influential transmission lines of each failure scenarios caused by different external disasters. Regarding this issue, this paper focuses on the resilience assessment from the perspective of individual transmission line. When the most influential transmission lines have been repaired, the system resilience can be improved best. In addition, the impact-increment state enumeration (IISE) method is utilized to quickly calculate the proposed component resilience assessment indices. The main contributions of this paper can be summarized as follows. (1)The component level resilience assessment index of a certain transmission line is defined, which reflects the contribution of individual transmission line to the over system impact under different failure scenarios due to external disruptions. In addition, the IISE method is implemented to calculate the component level indices. (2)The ranking of failed transmission lines, according to the obtained component level resilience indices, can helps the planners and operators formulating the optimal restoration schemes of each failure scenarios.

2. System level resilience indices

Bruneau [2] first proposed a resilience assessment index for the community, from the connotation of robustness and rapidity, quantified by the integral of the system performance degradation and the degradation time after external disasters. The insight offered by this index can be very useful to assess power system resilience. The load shedding has been widely recognized as the impact of disasters and it directly reflects the effectiveness of recovery efforts [13]. Thus, in terms of the power system, the performance function usually selects the power supply level. The following equation can be used to quantify the total load shedding caused by a particular disaster, which is defined as the resilience index of power system, as shown in Fig.1. After the disaster, the performance function may decrease and then bounce back to its normal state.

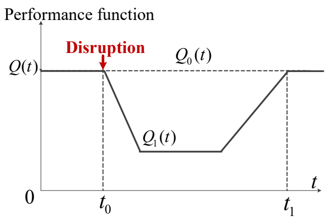

Fig. 1. The illustration of system resilience

$$RES = \int_{t_0}^{t_1} Q_1(t)dt \,/ \int_{t_0}^{t_1} Q_0(t)dt \tag{1}$$

where RES denotes the system resilience index, and $Q(t)$ denotes the system performance function at any time t. The system load supply level under normal condition can be expressed by $Q_0(t)$. If the disaster occurs, the load level will be expressed by $Q_1(t)$.

When an external disaster occurs, it usually unable to foresee the accurate failure scenario, that is, which transmission lines will fail. Thus, it is necessary to measure all possible failure scenarios of the system in advance. State enumeration (SE) method is a commonly used technique to enumerate the system states based on given failure orders. The efficiency and accuracy of SE method goes up exponentially with the increment of component number and it typically ignores high order failure scenarios. In our previous work [15]-[16], an impact-increment state enumeration method (IISE) was initially developed. Compared with traditional state enumeration method, IISE method can partially transfer the impact of higher order contingencies to the corresponding lower order ones. In addition, if the failed transmission lines are independent from each other, it can be proved that the impact-increments of the failure scenarios which consist of the mutually independent transmission lines are always 0. Thus, for a transmission system with N lines, the system resilience index can be obtained by

$$R = \sum_{k=0}^{N} \sum_{s\in\Omega_A^k} \left(\prod_{i\in s} U_i \right) \Delta I_s \tag{2}$$

where ΔI_s denotes the impact-increment of load shedding and U_i denotes the failure probability of ith transmission line. N denotes the number of transmission lines. A denotes the set of all transmission lines and Ω_A^k denotes the k order subset of A.

3. Component resilience indices

The analysis of power system resilience should include determining which transmission lines are most influential on the system performance. It is generally known, the failure of some transmission lines may not affect the system performance, while the failure of other transmission lines may cause the system failure which lead to significant load shedding. In addition, under limited resources, repair sequences play a crucial role in system recovery after suffering external disasters. The existing resilience indices only assess the system level resilience. For a system that is lack of resilience, those indices is difficult to determine the weak points of overall system. This paper has put forward the component level resilience indices which can help determining the most influential transmission lines and their failure may have strong impact on the system performance. After calculating the expected load shedding of potential failure scenarios R by IISE method, the component level resilience index can be easily obtained.

The component level resilience indices are defined to quantify the contribution of individual transmission line to the total load shedding suffering the potential disasters. For the mth transmission line, its component level resilience index is defined as follows.

$$\begin{aligned} R_{\Omega} &= R\Big|_{U_m=0, m\notin\Omega} \\ &= \sum_{s\in\Omega} \Delta I_s \end{aligned} \tag{3}$$

$$\begin{aligned} R_{\Omega,m} &= R_{\Omega}\ |_{U_i=1, i\in\Omega} - R_{\Omega}\ |_{U_i=1, i\in\Omega \& i\neq m, U_m=0} \\ &= \sum_{k=0}^{K}\left[\sum_{m\in s}\Delta I_s + \sum_{m\notin s}\Delta I_s\right] - \sum_{k=0}^{N}\left[\sum_{m\notin s}\Delta I_s\right] \\ &= \sum_{k=0}^{K}\left[\sum_{m\in s}\Delta I_s\right] \end{aligned} \tag{4}$$

where $R_{\Omega,m}$ is component level resilience, $R_{\Omega}\ |_{Um=1}$ represents the system resilience of failure scenario Ω by considering that the mth line has failed during the disasters, $R_{\Omega}\ |_{Um=0}$ represents the system resilience by considering that the mth line has been repaired, K represents the number of failed transmission line of scenario Ω, Ω^k denotes the k order subset of failure scenario Ω.

A three transmission line system is used as an example to illustrate the idea of component level resilience indices. Assume that 1th line and 2th line have failed due to a certain external disaster. The system level resilience index and the impact of this failure scenarios can be obtained by

$$R = U_1\Delta I_1 + U_2\Delta I_2 + U_3\Delta I_3 + U_1U_2\Delta I_{12} + U_1U_3\Delta I_{13} + U_2U_3\Delta I_{23} + U_1U_2U_3\Delta I_{123} \tag{5}$$

$$\begin{aligned} R_{\Omega} &= R\Big|_{U_3=0} \\ &= U_1\Delta I_1 + U_2\Delta I_2 + U_1U_2\Delta I_{12} \end{aligned} \tag{6}$$

Based on (1), when 1th transmission line has definite failed, the excepted impact of all potential failure scenarios can be obtained by

$$R_{\Omega}\ |_{U_1=1, U_2=1} = \Delta I_1 + \Delta I_2 + \Delta I_{12} \tag{7}$$

When 1th transmission line has been repaired, the excepted impact of all potential failure scenarios can be obtained by

$$R\ |_{U_1=0, U_2=1} = \Delta I_2 \tag{8}$$

Based on the IISE method, all the impacts related to the 1th transmission line have been eliminated. Bring this result into (6), the component level resilience index of 1th transmission line can be obtained by

$$R_{\Omega,1} = R_{\Omega}\ |_{U_1=1, U_2=1} - R_{\Omega}\ |_{U_1=0, U_2=1} = \Delta I_1 + \Delta I_{12} \tag{9}$$

Likewise, the component resilience index of 2th transmission line can be obtained by

$$R_{\Omega,2} = R_{\Omega}\ |_{U_1=1, U_2=1} - R_{\Omega}\ |_{U_1=1, U_2=0} = \Delta I_2 + \Delta I_{12} \tag{10}$$

Then, the component level indices are ranked to determine the most influential ones and suitable resilience enhancement scheme and repair sequences can be planning. If the transmission lines which have relatively greater component level indices have higher priority for repair, the resilience of the whole system can be improved.

4. Case study

The proposed component level resilience indices for transmission system is first tested on the IEEE 30-bus test system[17].The IEEE 30-bus system is composed of 6 generators, 21 load buses, and 41 transmission lines. The topology of the system and the moving trajectory of the storm are shown in Fig. 2. Table 1 shows the affected areas and the corresponding failed transmission lines. Limited by resources, only one repair crews will be able to maintain one area at a time, and the maintenance time is the same. The total load shedding of this failure scenario is 44.52MW.

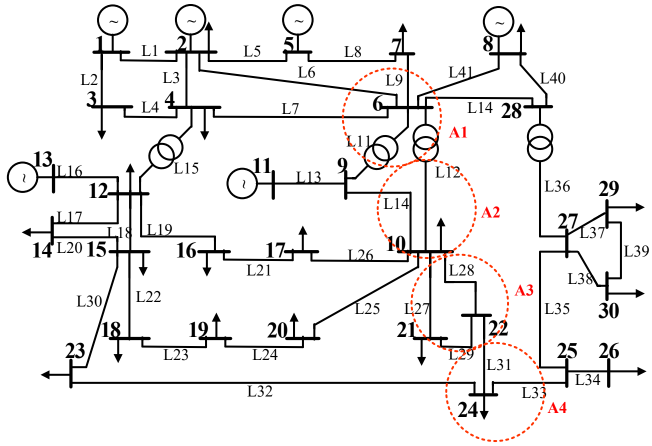

Fig. 2. The topology of the IEEE 30-bus test system

Table 1. Affected areas and the corresponding failed transmission lines.

Area	Failed transmission line
A1	L6,L7,L9,L41
A2	L14,L25,L26,L27,L28
A3	L27,L28,L29,L31
A4	L31,L32,L33

Table 2. The component level resilience indices.

Area	indices	priority
A1	18.06MW	4
A2	34.41MW	2
A3	43.47MW	1
A4	27.63MW	3

Table 3. Resilience of each repair sequence.

Repair sequence	RES	Repair sequence	RES	Repair sequence	RES
A3-A2-A4-A1	0.940	A2-A1-A4-A3	0.938	A4-A3-A2-A1	0.895
A3-A2-A1-A4	0.940	A2-A1-A3-A4	0.938	A4-A3-A1-A2	0.895
A3-A1-A2-A4	0.939	A2-A4-A3-A1	0.932	A1-A4-A2-A3	0.894
A3-A4-A2-A1	0.939	A2-A4-A1-A3	0.932	A1-A4-A3-A2	0.894
A3-A1-A4-A2	0.939	A1-A2-A3-A4	0.918	A4-A2-A3-A1	0.890
A3-A4-A1-A2	0.939	A1-A2-A4-A3	0.918	A4-A2-A1-A3	0.890
A2-A3-A4-A1	0.938	A1-A3-A2-A4	0.917	A4-A1-A2-A3	0.872
A2-A3-A1-A4	0.938	A1-A3-A4-A2	0.917	A4-A1-A3-A2	0.872

The component level indices of this failure scenario have been listed in Table 2. All possible order of repair sequences of all affected areas are enumerated in Table 3. The system level resilience are calculated according to (1). It use to verify whether the repair sequences determined according to the component level resilience indices can make the system resilience the best. As shown in Tab. III, the repair sequences A3-A2-A4-A1, which developed according to the results of the component level resilience indices, makes the system strongest resilience. That is, first repair Area3, then Area2, Area4, finally Area1.

In this term, the significance of the resilience assessment is not aiming to avoid all potential disasters, but to have a rapid recovery after the system performance decrease. The proposed component level resilience indices can provide useful information for the formulating optimal repair sequence and enhancing system resilience.

5. Conclusion

This paper proposes the component level resilience indices for power transmission system and those indices can be used to quantify the impact caused by a certain transmission line, rather than from the system perspective. The component level resilience is defined as the contribution of individual failed transmission line to the overall impact due to the external disasters. This newly developed indices can help determine the most influential lines and providing the follow-up optimal repair sequences under different failure scenarios due to the external disasters. Case studies are performed on the IEEE 30-bus test system. Results shows that the ranking of failed transmission lines, according to the component level resilience indices, can help formulate the optimal repair sequences.

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