A Quantified Resilience Assessment Approach for Electrical Power Systems Considering Multiple Transmission Line Outages

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***Abstract*—Disruptive events, such as natural disasters, terrorist attacks and improper operations, may result in multiple transmission line outage of power system. In order to evaluate their impacts on power system, the concept of resilience is introduced. On the basis of existing resilience assessment methods, this paper develops a series of quantified resilience assessment indices, consisting of both system-level indices and component-level indices, as well as relevant assessment approach. With the system-level indices, the overall resilience of power system can be estimated. Based on the component-level indices, weak points of the system can be identified. Accordingly, the corresponding improving schemes can be raised to enhance the resilience of the original system. Finally, the proposed approach is tested on the IEEE RTS-79 test system under different disruptive events, and then the optimal improving scheme of this test system is determined based on the obtained resilience indices.**

***Index Terms*—Resilience assessment, disruptive event, power system, resilience indices, transmission line outage.**

I. INTRODUCTION

The operation conditions of transmission lines have significant impact on the electric power system. The outages of transmission lines may cause not only economic losses, but also personal injuries. In recent years, power system contingencies around the world caused by multiple transmission line outages under extreme weather have drawn increasing attentions of experts and scholars in power industry. Although the frequency of this kind of events is very low, their impact on the power system is remarkable. Traditional power system planning and designing need to meet reliability criterion. However, under extreme events, the power system may not be able to maintain safe power supply even the reliability criterion is satisfied. Regarding this issue, many scholars attempted to introduce the concept of resilience into power system, aiming to build a strong power system against those extreme events.

The concept of resilience has been applied in materials science, economics, sociology, psychology and engineering. A resilient power system, which is derived from the combination of the practical characteristics of power system and the existing definition of resilience in [1]-[6], is considered to have the following features:

a) Resistant to withstand majority disruptive events;

b) Maintain high levels of performance under disruptions and rapidly recovering from disruptions;

c) Absorbing lessons for adapting its operation and structure for preventing or mitigating the impact of the same or similar events in the future.

Although the definition of resilience vary from different areas, but how to quantify the strength of resilience still be a matter of concern for researchers. Bruneau defined the resilience index as the integral of the system performance function loss and the interrupted time, that is, the area of the performance function loss over time [4]. This is the most widely used index to quantified resilience. On this basis, many corresponding resilience assessment indices have been developed in [7]-[11]. Resilience was assessed in [12] as the probability of the situation that the system performance function loss was less than the maximum acceptable loss while the system recovery duration was less than the maximum acceptable recovery duration after the system has been disrupted. 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 [13]-[14].

Existing researches on power system resilience mainly focused on the impacts of extreme disruptive events which have low probability but high impact, such as natural disasters, terrorist attacks, improper operations, and so on. However, the characteristics of the above events are different from each other. Currently, there is no universal standard of indices and assessment approach for power system resilience. The key

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challenges remain as how to practically assess the resilience of power system against those different sorts of disruptive events. It is noteworthy that the direct impact of those events on the power system is the multiple transmission line outages, which may further results in voltage violation or load loss. Regarding this fact, this paper develops a quantified power system resilience assessment approach by analyzing the impacts of multiple transmission line outages. With this approach, comprehensive resilience indices, consisting of both system-level indices and component-level indices, can be calculated. Those indices can be used to assess the resilience of a given power system against different disruptive events, and provide enhancement schemes.

This paper is organized as follows: The theoretical basis of power system resilience index is described in Section II. The newly defined resilience indices of power system and the corresponding assessment approach are proposed in Section III. Numerical results based on the IEEE RTS-79 test system are given in Section IV. Conclusions are drawn in Section V.

II. Basic Theory of Power System Resilience

Considering the characteristics of power system resilience, it includes "4Rs": robustness, redundancy, resourcefulness, and rapidity. Robustness and rapidity are the direct manifestations of power system resilience, reflecting the impacts of disruptive events on power system. Redundancy and resourcefulness are the way to mitigate the impacts of disruptive events on power systems, and their effects are indirectly reflected in the impacts of disruptive events on power systems. Bruneau [4] proposed the community resilience index from the connotation of robustness and rapidity, which can be applied to assess power system resilience. Use (1) to quantify the descending amount of the system performance function during the disruption process to assess the resilience of power system, that is, quantify the area of the resilience triangle shown by the solid lines in Fig.1.

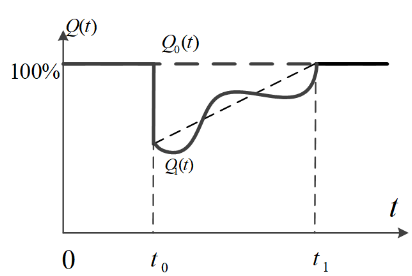

Fig.1 The resilience triangle

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

For power system, the system performance function $Q(t)$ describes the operating level of the power system, such as the power supply, bus voltage, line power flow, etc., at any time t .As illustrated in Fig. 1, the value of the performance function ranges from 0% to 100%, where 0% means that the system is out of operation and 100% means the system is normally operated. The system performance function ranges between 0% and 100% when subjected to the disruptive events. The system performance function maintains at the normal level under normal condition which, can be expressed by $Q_0(t)$. If the disruptive event occurs at time t_0, the performance function may reduce to less than 100% and then return to the normal level after a certain period of time. This process can be expressed by $Q_1(t)$. The resilience index of power system is described in (1), which is the integral of the system performance function loss over time. In order to facilitate the calculation it can be simplified into a triangle [8], as shown in Fig. 1 with dotted line, then the resilience index is equal to half of the product of system performance function reduction and recovery duration .

From the perspective of system performance, when the system is subjected to the disruptive event, the system performance function will decline. In order to return to the normal level, it is necessary to invest a certain amount of resources to recover the loss of performance function while guarantee the response time as short as possible. The amount of performance function loss and recovery duration depend on the strength of system resilience. Therefore, it is necessary to quantify the change process of the system performance function curve after the disruption in the practical application process, and propose a targeted system resilience enhancement measure according to the quantization result.

III. Resilience Assessment Approach Considering Multiple Transmission Line Outages

A. *Quantified Resilience indices of power system*

The research on power system resilience mainly aims to simulate the impacts of disruptive events and identify the weak points of power system according to the indices, thus enhance the resilience of whole system. However, the existing assessment approaches, mainly from the qualitative perspective, directly apply to the traditional reliability or risk indices to assess the power system resilience. It is noteworthy that those approaches do not embody the "4Rs" characteristics comprehensively and make it difficult to meet the actual engineering application needs. Therefore, it has a practical significance to establish a reasonable quantified resilience assessment approach to quantify the impacts of disruptive events and develop enhancement measures. The results of multiple transmission line outage may cause bus voltage violation, so the system performance function $Q_1(t)$ may be beyond or below its normal range constraint. Thus, this paper suggest that the resilience index described by (1) should improve to reflect the amount of deviation from the normal range of performance function, as described in (2). $Q_{\lim+/-}$ represents the boundary. If the performance function is beyond the upper boundary, the $Q_{\lim+}$ is subtracted by $Q_1(t)$. If the performance function is below the down boundary, the $Q_{\lim-}$ is subtracted by $Q_1(t)$.

$$R = \int_{t_0}^{t_1} \left| Q_{\lim+/-} - Q_1(t) \right| dt \tag{2}$$

The resilience indices proposed in this paper is mainly focused on robustness and rapidity. Redundancy and resourcefulness can be used as the approach to enhance the robustness and rapidity of the power system and thus boost the resilience of entire power system. On the basis of (2), this paper proposes a series of resilience indices for power system, consist of both system-level indices and component-level indices. The system-level indices comprehensively reflect the impact of the disruptive events on the power system. The component-level indices mainly analyze the impact of a specific disruptive event on a certain bus of power system.

1) System-level Indices

System-level indices have comprehensively considered robustness, rapidity and the frequency. The robustness index ΔQ can be quantified by the deviation of system performance function from the normal range. As aforementioned, the results of multiple transmission line outage may cause bus voltage violation, so the robustness index ΔQ can be quantified by the violation amount of bus voltage. The rapidity index Δt is quantified by the recovery duration from the start time of the outage to the moment that system performance returns to the normal level. In addition, a frequency index f_i is used to measure the frequency of the fault state which caused the loss of system performance in a given period. Therefore, the system-level indices can be calculated by

$$R = \sum_{i \in s} f_i \cdot \Delta t_i \cdot \Delta Q_i \tag{3}$$

where s represents the set of fault state i that caused by disruptive events; f_i represents the frequency of system state i; Δt_i represents the duration from the outage occurs to the system performance return to normal level; ΔQ_i represents the impact of disruptive event.

2) Component-level Indices

For each fault state i caused by a specific disruptive event, component-level indices consist of three indices: frequency index R_f, rapidity index R_t and robustness index R_Q. The frequency index R_f represents the frequency of the fault state. The rapidity index R_t represents the recovery duration. The robustness index R_Q represents the deviation of system performance function from the normal range. The three indices can form a triangular radar chart, as shown in Fig. 2. The formula for calculating the component-level indices is shown in (4).

$$\begin{cases} R_{fi} = f_i \\ R_{ti} = \Delta t_i \\ R_{Qi} = \Delta Q_i \end{cases} \tag{4}$$

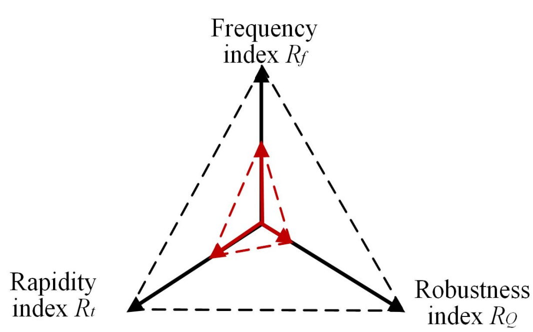

Fig.2 Radar chart of component-level indices

B. Quantified Resilience Assessment Approach Considering Multiple Transmission Outage

This paper intends to develop a comprehensive quantified resilience assessment approach to evaluate and boost the resilience of power system. The various features of different kinds of disruptive events make their impacts difficult to assess. However, from another viewpoint, the direct impacts of those disruptive events on power system are multiple transmission line outages. Therefore, this section intends to simulate the impacts of multiple transmission line outages instead of the original disruptive events. Then the proposed quantified resilience assessment approach can be applied to various kinds of disruptive events. The performance function can be selected according to the requirement of the application situation. Bus voltage violation may happen when transmission lines are tripped. So the performance functions are selected based on this case. Also, in order to evaluate the recovery duration, it is necessary to simulate the generation dispatch process when those violations happen. If there is still a violation after the generation dispatch, the load curtailment will be necessary.

Therefore, the system-level indices can be obtained by utilizing the formulas below.

$$R_{bus} = \sum_{i \in s} f_i \cdot \Delta t_{bus.i} \cdot \sum_{m=1}^{M} \Delta Q_{im} \tag{5}$$

Where $\Delta t_{bus.i}$ represents the durations from the outage occurs to the system performance return to normal level; ΔQ_{im} represents the voltage violation amount of bus m under system state i (m=1,2,…,M).

The formulas for calculating the component-level indices are shown in (6).

$$\begin{cases} R_{bus.fi} = f_i \\ R_{bus.ti} = \Delta t_{bus.i} \\ R_{\text{bus}.Qi} = \sum_{m=1}^{M} \Delta Q_{im} \end{cases} \tag{6}$$

According to the above formulas and the actual characteristics of power system, the corresponding frequency index can be calculated. Firstly, calculate the probability of present state, then use the state enumeration method to obtain the possible disruption state i and calculate the probability of the state i. The frequency of state i can be obtained by using the Markov method as show in (7). This formula reflects the frequency index R_f, where P_0 represents the probability of present state and λ represents the state transition rate of present state to disruption state i, that is to say, the failure rate of transmission line.

$$f_i = P_0 \cdot \lambda \tag{7}$$

Then, utilize the power flow calculation to obtain the rapidity index R_t and robustness index R_Q. The objective function of optimal power flow under normal operation level is the minimal generation cost. The voltage of each bus and active power output of each generator are denoted by U_{i0} and P_{k0}, respectively. Assume that the transmission lines outage occur at time T_0 and the topology of the system is changed correspondingly. At this moment, the output of each generator cannot be changed immediately, so the active output of each generator still remains at P_{k0}. The voltage of each bus can be calculated through power flow calculation. Therefore, the robustness index R_Q can be quantified by the value of bus voltage violation.

The violation of bus voltage can be improved by generator dispatching, regulating the generator excitation or redistributing the output. Because the dispatch of each generator output is constrained by its ramp rate, the dispatch time is relatively long comparing with excitation regulation time. Therefore, it is assumed that the generator terminal voltage can reach the voltage that obtained from the optimal power flow in a short time after the line tripped. When the generators dispatch process completes at time T_1, the voltage of each bus return to the normal range. The output of each generator reaches the optimal dispatch P_{k1}. The maximum value of each generator dispatch time is selected as the rapidity index Δt_i . It can be obtained by utilizing the formula below.

$$\Delta t_i = \max \left| \frac{P_{k1} - P_{k0}}{rate_k} \right|, k = 1, 2, \ldots\ldots, K \tag{10}$$

where $rate_k$ represents the ramp rate of generator k and there are K generators in all.

C. Resilience enhancement measures of power system

Based on the proposed system-level and component-level resilience indices, the resilience enhancement measures can be put forward for the weak points of power system. First, the system-level indices can be used to check if there is any insufficient resilience. If so, analyze the component-level indices to determine the weak points of the system as the basis of the follow-up enhancement measures. According to the component-level indices, the enhancement measures can be taken from three perspectives: reducing the possibility of outage, the impact of outage or the recovery duration. These three perspectives correspond to the frequency index R_f, the rapidity index R_t and the robustness index R_3, respectively. Fig. 3 intuitively illustrates the effect of scheme A, B and C according to frequency index R_f, the rapidity index R_t and the robustness index R_Q respectively. Select the original value of these three indices under the disruptive event as the normalization, where the length of each index only acts as illustration. The optimal scheme can be obtained by considering both effectiveness and economy comprehensively.

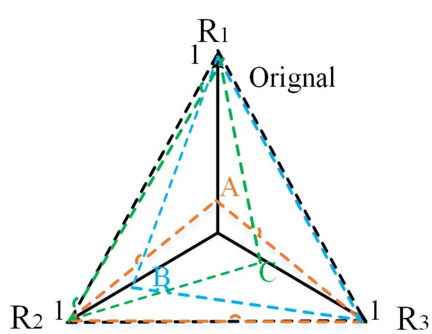

Fig.3 Diagram of resilience nhancement measures

IV. CASE STUDY

In this section, the IEEE RTS-79 test system is implement to testify the performance of the proposed resilience assessment approach. The system consists of 38 lines and 24 buses, including 10 PV buses and 17 PQ buses. The total load is 2850 MW.

The ramp rate of each type of generator unit are shown in Table □. It is notable that the ramp rate of U50 (the slack generation unit) is N/A, indicating that it has a high regulation speed.

TABLE I. RAMP RATE OF GENERATOR UNIT

Unit number	Capacity (MW)	Type	Ramp rate (MW/Min)
U12	12	Oil/Steam	1
U20	20	Oil/CT	3
U50	50	Hydro	N/A
U76	76	Coal/Steam	2
U100	100	Oil/Steam	7
U155	155	Coal/Steam	3
U197	197	Oil/Steam	3
U350	350	Coal/3Steam	4
U400	400	Nuclear	20

A. Sumulation resutls

The system-level and component-level indices under N-1 to N-3 disruptive events are calculated. The results of bus resilience indices are shown in Table II. The results of each bus are shown in Fig. 4.

TABLE II. RESULTS OF SYSTEM-LEVEL INEICES

Disruptive event	Bus index
N-1	7.506
N-2	1.063
N-3	0.032
System-level	8.601

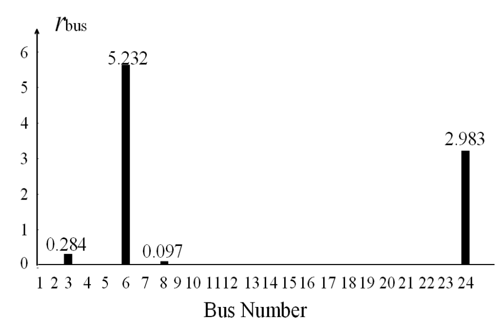

Fig.4 Bus voltage index

In terms of bus resilience results, resilience index of bus 6 is the worst according to the bus resilience results. By analyzing the disruptive event, the results demonstrate that only line 2-6 can supply the load of bus 6 after line 6-10 is tripped. Also, line 2-6 is a long transmission line with large reactance, so bus 6 faces severe low voltage problem when line 6-10 is tripped.

B. Resilience enhancement measures of RTS-79 system

As discussed in Section □. C, three kinds of enhancement measures can be implemented according to the component-level indices. In this case, scheme A aims to reduce the frequency index R_f by strengthening the maintenance of line 6-10. Scheme B aims to reduce the rapidity index R_t by allocating a 68 MVA energy storage equipment with high ramp rate on bus 6, so as to reduce the dispatch duration. Scheme C aims to reduce the robustness index R_Q by allocating a 33 MVar shunt reactive compensatory equipment at bus 6.

In scheme A, according to [15] and (7), the repair rate can be reduced by 1.265 times when conducting comprehensive maintenance instead of partial maintenance. The obtained indices are normalized based on their original values of the original case, so the maximum values of the three indices are all equal to 1. So the frequency index R_f of scheme A reduces from 1 to 0.327; the rapidity index R_t of scheme B reduces from1 to 0.268; and the robustness index R_Q of scheme C reduces from 1 to 0. The results are illustrated with radar chart as showing in Fig.5.

It can be seen from Fig. 5 that all the three enhancement schemes can effectively boost the system resilience. In the choice of the schemes, both effectiveness and economy should be comprehensively considered. It can be seen that allocating the energy storage equipment need more funds than forcing line maintaining management and allocating the reactive power compensation device, So Scheme A and C have less investment comparing with scheme B. In addition, Scheme B and C can eliminate the voltage violation completely, while Scheme A cannot. Therefore, the comprehensive analysis shows that the scheme C is the optimal one, with which the system-index R_{bus}' reduces from 5.232 to 3.369.

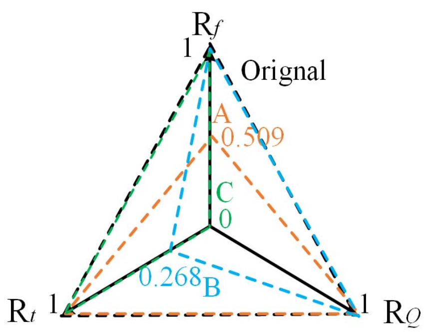

Fig.5 Results of resilience enhancement measures

V. CONCLUSION

This paper proposes a quantified resilience assessment approach for power system considering multiple transmission line outages. Both system-level indices and component-level indices are defined to give a comprehensive evaluation of the resilience of power system. The system-level indices reflect the overall power system resilience, while the component-level indices reflect the resilience of each bus. In addition, further analyses on the component-level indices can help determining the weak points of the system and providing the follow-up enhancement measures. Then the most cost-effective enhancement scheme can be selected for different options.

The proposed approach is applied to the IEEE RTS-79 test system to test its performance, where all N-1 to N-3 disruptive events are considered. As far as the bus resilience indices of this test system, the component-level resilience indices show that the weak point of this system is bus 6. Regarding this issue, corresponding enhancement measures are provided. Then the optimal scheme is selected by comprehensive consideration of the resilience improvement and the economic cost.

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