An Evaluation Method of Power System Recovery Capacity Considering the Probability of Extreme Disaster Failure

Yujie Han
Tsinghua Shenzhen International Graduate School
Tsinghua University
Shenzhen, China
anheipingguo@163.com

Hongtao Wang*
School of Electrical Engineering
Shandong University
Jinan, China
whtwhm@sdu.edu.cn
*Corresponding author

2024 3rd Asia Power and Electrical Technology Conference (APET) | 979-8-3503-6769-0/24/$31.00 ©2024 IEEE | DOI: 10.1109/APET63768.2024.10882755

***Abstract*—With the increasing complexity and scale of power systems, the risk of large-scale power grid blackouts triggered by adverse weather or human-induced damages has significantly heightened. This emphasizes the critical necessity to enhance power generation speed and load recovery while minimizing outage impact. This study introduces a series of indices that can be utilized to measure the capacity of power system recovery, taking into account the failure probability during extreme events. Subsequently, a systematic and standardized evaluation system is proposed to uniformly assess and compare the performance of power system recovery capability under extreme disasters, considering different restoration schemes according to established standards. The evaluation system estimates power grid losses resulting from extreme disasters, which directly affect generator and transmission line outage states. By comparing resilience metrics before and after such failures occur, this approach provides a comprehensive evaluation of power system resilience in response to extreme disasters.**

Keywords—resilience, restoration, recovery, risk, extreme fault

I. INTRODUCTION

With the development of power system, modern society is becoming more dependent on the power supply, the large-scale and long-term power failure brings serious negative impact on the society and economy. For example, in March 2019, Venezuela's power grid was attacked by malicious attacks, two large-scale power outages occurred in just one month, affecting over 90% of the country's administrative areas and about 30 million people [1]. At 14:29 on December 28, 2020 (Mexico local time), a large-scale power outage occurred in Mexico, causing 10.3 million users in 12 states affected by the power outage, and the proportion of load loss accounted for about 26% of the total load at that time [2]. In February 2021, the winter storm caused more than 4.5 million households and enterprises in Texas, the United States, to lose power. At least 151 people directly or indirectly lost their lives, and the losses caused by the power outage were estimated to reach 195 billion [3].Therefore, how to set up a reasonable power system restoration scheme to enhance the recovery ability of the system under extreme disaster conditions becomes particularly important.

This work was financially supported by the National Natural Science Foundation of China under Grant (U22B2099).

The resilience of the power system usually refers to the ability of the power system to restore normal operation after a failure or disaster through a series of operations (such as black start, grid reconstruction, partial load recovery, etc [4].), which is crucial to ensure the reliability and stability of the power system. Resilience is affected by many factors. This paper aims to discuss the relevant concepts, influencing factors and improving methods of power system resilience, and verify the feasibility and effectiveness of improving power system resilience through practical case analysis.

In terms of the system as a whole, [5] proposes a quantitative method for assessing the elasticity of power systems to assess the impact of multiple transmission line outages on power systems. The proposed approach consists of system - and component-level indices to estimate the overall resilience of a power system and identify system weaknesses. In terms of disaster occurrence stage, in [6], the author focuses on the new power system, describes its changes after extreme natural disasters, analyzes the challenges brought by the new power system to elasticity, and discusses the measures to improve the elasticity of the new power system from the perspectives of pre-disaster, neutralization and post-disaster. In terms of different recovery stages, [7] evaluates the extended black start scheme from a time-series dynamic perspective based on the existing evaluation schemes, assigns different weights to different time periods of power grid restoration, and obtains the final evaluation results. In terms of actual demand, [8] analyzes the black-start boundary conditions, technical feasibility and other factors under each mode, comprehensively considers the fast running, systematic, economic and reliability of power grid restoration, and uses hierarchical envelope analysis method to evaluate different black-start schemes in combination with examples.

Based on the partition parallel recovery method, this paper discusses the system recovery ability considering the impact of extreme faults. The evaluation index of power system recovery capability is discussed, and a feasible model of parallel recovery scheme based on partition is proposed. In terms of cases studies, the IEEE 118 bus system is taken as an example to simulate the recovery after a major outage caused by extreme faults, and evaluation indicators are applied to evaluate the changes in the resilience of the power grid under the influence of extreme faults, and targeted measures are proposed to enhance the resilience.

II. Evaluation Indicators of Power System Recovery Capacity

A. The Concept of Power System Recovery Capacity

The stages referred to in this paper are the recovery state and the return state after the fault occurs in the Fig. 1.

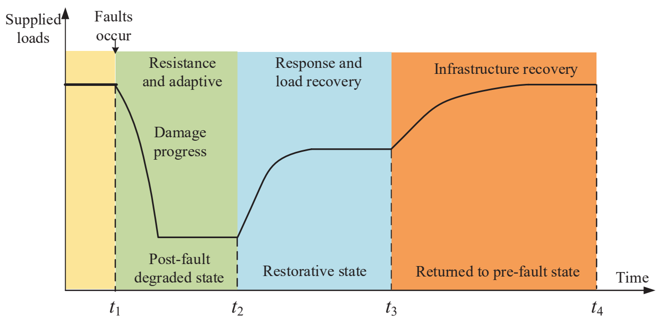

Fig. 1. The resilience curve of the power system

Recovery capacity of a power system typically refers to the ability of a power grid, when in a state of power outage, to transition to a normal operating state through a series of recovery operations such as black start, grid reconfiguration, and partial load restoration. It emphasizes the role of structural factors of the power grid, such as the capacity of black start power sources and the grid structure, in the rapid recovery of the power grid. It can be expressed by the recovery time for the parallel completion of generating units in the power grid and the available power generation within a certain period of time.

The concept of recovery capacity has been applied in material science, economics, sociology, psychology, and engineering. The recovery capacity of the power system is derived by combining the actual characteristics of the power system with the definition proposed in [9] and is considered to have the following characteristics:

- Being able to recover from the destructive events;
- Maintaining a high level of performance and recovering quickly;
- Adjusting its operation and structure to mitigate the impacts of the events.

B. Recovery Capacity Evaluation indicators

This part gives the evaluation index of power system fault recovery ability, which mainly consists of three parts: response ability, recovery efficiency and recovery economy.

1) System responsiveness: Responsiveness is uesd to evaluate power system's ability to act quickly after a disaster. Its constituent indicators includes:

a) LEDSR: The time Length from the End of Disaster (t_{ed}) to the start (t_{sl}) of load Restoration(LEDSR). Indicates the duration during which the system is in the most serious fault state.

b) RLRO: The Ratio of Load restored in One hour(RLRO) after the start of restoration(t_{sl}).

$$RLRO = \frac{\sum_{b=1}^{N_b} L_{1h,b}}{\sum_{b=1}^{N_h} \left(L_{nl,b} - L_{pl,b}\right)}$$

$L_{1h,b}$ is the load recovery of node b one hour after t_{sl}. t_{sp}:The length of time from the end of the disaster state to the restoration of the outage load to a certain percentage.

2) System recovery efficiency: System recovery efficiency is mainly used to evaluate the effectiveness of the recovery scheme, including the average system load recovery speed, system load recovery efficiency and important load recovery efficiency.

a) ARSS: The Average Restoration Speed of System(ARSS).

$$ARSS = \frac{\sum_{i=1}^{N_b} \sum_{j=1}^{ni} \int_{t_{sl}}^{t_t} \left[p_{ij} - p_{ij}(t)\right]dt}{(t_{re} - t_{sl}) \cdot \sum_{i=1}^{N_b} \sum_{j=1}^{ni} p_{ij}}$$

t_{re} is the end time of system recovery. According to the load importance, the load *j* on node *i* is divided into ni parts. At time t_{sl}, the outage power of the load is p_{ij}, and $p_{ij}(t)$is the outage power of load *j* during the recovery process. Essentially, ARSS is the ratio of the power outage loss during the recovery process to the power outage loss without recovery.

b) RES: The Restoration Efficiency of the System(RES).

$$RES = \frac{\sum_{i=1}^{N_b} \sum_{j=1}^{ni} \int_{t_{sl}}^{t_{te}} w_{ij} \cdot \left[p_{ij} - p_{ij}(t)\right]dt}{(t_{re} - t_{sl}) \cdot \sum_{i=1}^{N_b} \sum_{j=1}^{ni} w_{ij} \cdot p_{ij}}$$

w_{ij} is the importance factor of load *j* on node *i*.

c) REI: The Restoration Efficiency of the Important load(REI).

$$REI = -\frac{\sum_{i=1}^{N_b} \int_{t_{sd}}^{t_{re}} (p_{id} - p_i(t))dt}{(t_{re} - t_{sl}) \cdot \sum_{i=1}^{N_b} \int_{t_{sl}}^{t_{re}} p_{id}dt}$$

p_{id} is the outage power of important loads on node *i* at time t_{sl}, and $p_i(t)$ is the actual outage power of important loads in load *j* at node *i* at time t during the post-disaster recovery process.

3) The economy of the restoration schemes(RSE)

In order to achieve rapid restoration of outage load, the economic cost of the restoration process is certainly not the first factor that decision-makers need to consider.However, a good recovery strategy generally needs to be able to balance the economy loss and efficiency.Therefore, it is necessary to evaluate the economy of the system post-disaster recovery process.This assessment needs to consider the economic loss of load outage, labor costs, transportation costs, system operation costs, etc. It can be defined as：

$$RSE = \frac{\sum_{i=1}^{N_b} \sum_{j=1}^{ni} \int_{t_{ii}}^{t_{ij}} c_{ij} \cdot \left[p_{ij} - p_{ij}(t)\right]dt - C_{\mathrm{rep}}}{\sum_{i=1}^{N_b} \sum_{j=1}^{ni} \int_{t_s}^{t} c_{ij} \cdot p_{ij}dt}$$

The economic loss of power outage per unit time for load *j* on node *i* is c_{ij}, and C_{rep} is the sum of the system's repair and operation costs.

III. Power System Recovery Capability Evaluation System

A. Assessment Framework for Power System Recovery Capacity

After determining the definition of system recovery capacity, it is necessary to design a systematic and standardized evaluation system to uniformly evaluate and compare the performance of different recovery schemes according to the standard. The recovery evaluation system is shown in Fig. 2.

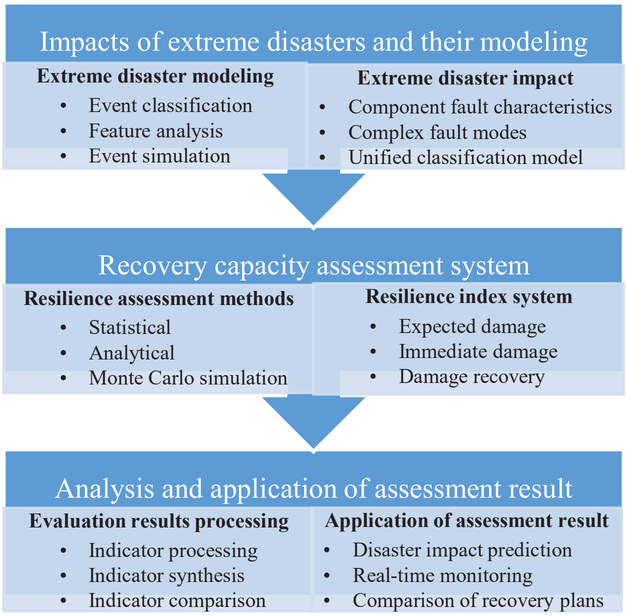

Fig. 2. Assessment framework for recovery capacity

B. Impacts of Extreme Disasters And Their Modeling

The assessment of power system recovery capacities increasingly focuses on the impacts of extreme disasters and the sophistication of their modeling techniques. Extreme disaster modeling involves a meticulous classification of events, wherein each type is analyzed for distinct features and simulated to predict outcomes under various conditions. This rigorous modeling is crucial for comprehending the potential scale and nature of disruptions, enabling more precise planning and mitigation strategies.

When considering the impact of these disasters on power systems, it becomes imperative to delve into the characteristics of component faults. These components often exhibit intricate fault modes that can vary significantly in severity and impact, necessitating a robust and unified classification model. Such models aid in categorizing different types of faults and their potential effects on the system, allowing for a comprehensive analysis of power system vulnerabilities.

By combining advanced disaster modeling with an in-depth understanding of component behaviors during such events, it becomes feasible to enhance the resilience and recovery capabilities of power systems facing extreme conditions.

C. Power System Recovery Capacity Assessment System

The development of a robust Power System Recovery Capacity Assessment System is crucial for enhancing the resilience of power grids against disruptions. This system incorporates various resilience assessment methods, including statistical analysis that utilizes historical data to identify trends and vulnerabilities; analytical methods that employ logical reasoning and mathematical calculations to predict potential failures; and Monte Carlo simulations that utilize randomized variables to simulate a wide range of possible disaster scenarios and their impacts on the power system.

Integral to this assessment system is the resilience index system, which is structured around three core components: expected damage, forecasting the probable extent of disruption based on past events and current system status; immediate damage, assessing the direct impact at the moment of the disaster; and damage recovery, evaluating the efficiency and effectiveness of response strategies and the system's ability to restore normal operations.

Together, these methodologies and indices provide a comprehensive framework for understanding and improving power systems' resilience in face of unforeseen events.

D. Analysis and Application of Assessment Result

The analysis and application of assessment results are crucial for refining strategies and enhancing power system robustness against disruptions. The processing of evaluation results is a multifaceted approach that begins with indicator processing—where individual metrics are analyzed to derive actionable insights. This is followed by indicator synthesis, a method that amalgamates various metrics into a comprehensive resilience profile, providing a holistic view of the system's strengths and weaknesses. Furthermore, indicator comparison plays a pivotal role, involving a detailed juxtaposition of current and historical resilience metrics to track progress and identify areas requiring improvement.

The practical application of these assessment results is manifold. Firstly, they facilitate the prediction of disaster impacts, enabling preemptive actions to mitigate potential damage. Real-time monitoring is another critical application where continuous assessment allows for dynamic adjustments and immediate responses to emerging threats. Lastly, the evaluation results are instrumental in comparing different recovery plans, assessing their effectiveness in various scenarios to ensure optimal resource allocation and strategy implementation.

Collectively, these applications not only enhance the predictive accuracy and response readiness of power systems but also ensure more resilient infrastructure capable of withstanding unforeseen challenges.

IV. Case Study

This section takes the IEEE-118-node system as an example and, based on the partition parallel restoration method, explores the system restoration capacity considering the impact of extreme faults.

A. Power System Partition Parallel Recovery

Partition parallel restoration is an effective way to improve the restoration efficiency of power grids and reduce the outage time of loads.

The power system partitioning problem divides the system into multiple subsystems or islands [10], [11]. Each subsystem or island has a black-start (BS) generator. During the start-up process, the black-start generator will provide the power required for the start-up of non-black-start (NBS) generators.

In the parallel restoration problem, constraints such as line power flow constraints, necessary time interval constraints, and load balance constraints should be considered.

B. Parallel Restoration Results of the IEEE-118 Node System

The initial model of the power grid has a total of 118 nodes and 186 lines. Twenty generator nodes are set. It is assumed that the output power of the generator sets in the model rises according to the ramp rate after the generator start-up time ends and remains unchanged after reaching the rated power. Nodes 31, 54, and 92 are set as black-start nodes. After running the partition start-up program, the system will be divided into three parts and start simultaneously.

A total of 186 initial lines of the system are set in the model. Line parameters are set in the model, including the starting node, ending node, line r, x, b, and other parameters.

Set the recovery time T to 25 time periods. After running the partition startup program, the partition result is obtained as shown in Fig. 3.

It can be seen from the figure that the parallel restoration program divides the entire system into the corresponding three subsystems according to the number of black-start nodes.

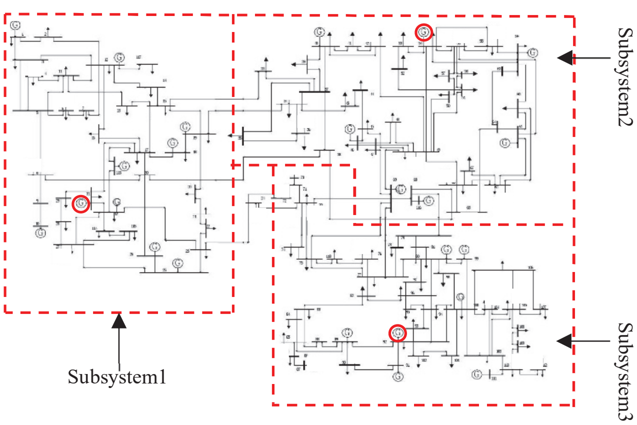

Fig. 3. The partitioned parallel restoration results of the IEEE-118 model

The proportion of the difference between generation and load in the three subsystems is shown in TABLE I. All partitions of the system meet the requirement that the generation capacity is greater than the load. The percentage of the difference between generation and load in the three partitions in the total restored load is between 3.85% and 3.88%, meeting the requirement of a rough balance between generation and load.

TABLE I. RATIO OF DIFFERENCE BETWEEN GENERATION AND LOAD IN THREE SUBSYSTEMS

Subsystem	Subsystem 1(31)	Subsystem 2(54)	Subsystem 3(92)	Total
Generation recovery(MW)	646.84	1124.908	967.48	2739.228
Load recovery(MW)	622.84	1082.908	931.48	2637.228
Unbalance(%)	3.85%	3.88%	3.86%	3.87%

C. Changes in resilience considering the impact of extreme disasters

The failure rate of the line in extreme weather is affected by multiple factors, such as the strength of the line itself, the length of the line and the intensity of the fault. Literature [12] proposes a method to evaluate the line failure rate by using normal function, which can combine the line length, wind condition and other factors to establish the brittleness curve of each transmission line so as to calculate the fault probabilityIn this part, the failure rate of IEEE-118 node line under extreme fault is discussed with the example of wind disaster on overhead transmission line. The fault tendency of each line is calculated, and the lines are ranked according to the failure rate to simulate the more likely line failure situation.

1) Extreme faults caused 1% of the total number of lines to be disconnected

According to the calculation results of the above part, the two lines with the highest failure rate (49-69 and 49-54) are selected to disconnect, and the change of recovery results is observed. It is found that the partition is basically the same as the load recovery amount without fault.

2) Extreme faults caused 5% of the total number of lines to be disconnected

According to the calculation results of the above part, the 10 lines with the highest failure rate are selected to disconnect, and the change of recovery results is observed. The changes in partitioning results are shown in Fig. 4 and TABLE II.

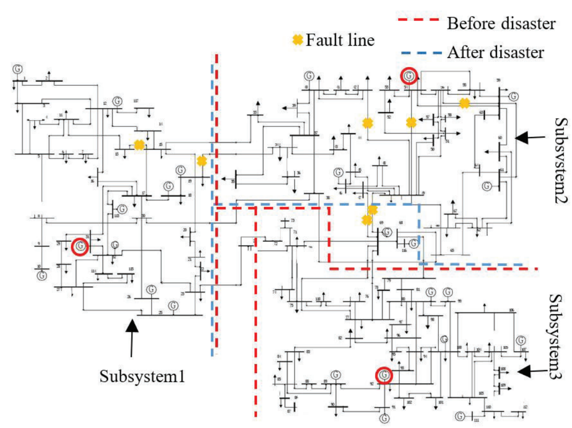

Fig. 4. Post-failure system partition (5% line failure)

The number of nodes in zone 2 becomes less and the number of nodes in zone 3 becomes more. Originally, node 24 did not belong to any partition, but after the disconnection, node 24 was reassigned to partition 3.

TABLE II. POST-FAULT ZONING CONDITION (5% LINE FAILURE)

Subsystem number	1(31)	2(54)	3(92)
Node	1-23、25-33、113-115、117	34-67	24，68-112、116、118
Node amount	36	34	48

As can be seen, due to the disconnection of lines 69-47 and 69-45, nodes 68, 69, 116 and so on are re-divided into partition 3.

System load recovery is shown in TABLE III.

TABLE III. SYSTEM LOAD RECOVERY (5% LINE FAILURE)

Subsystem		Sub.1 (31)	Sub.2 (54)	Sub.3 (92)	Total	Total (%)
Before disaster	Generation recovery (MW)	646.84	1124.908	967.48	2739.228	62.58%
	Load recovery (MW)	622.84	1082.908	931.48	2637.228	62.36%
After disaster	Generation recovery (MW)	646.84	953.68	1093.48	2694	61.54%
	Load recovery (MW)	622.84	917.68	1051.48	2592	61.29%

It can be seen from the Table III that the power generation and load of the whole system recovered after 5% line failure are reduced. Before and after the fault, the power generation and load recovery in zone 1 remained the same, while the power generation and load in zone 2 decreased, and the power generation and load in zone 3 increased. This is because the channel between nodes in zone 1 and BS generators was not damaged, and some nodes in zone 2 were reassigned to zone 3 due to line faults. The node situation in the zone is related to the load and power generation recovery of the zone. When 5% of the lines are faulty, the total power generation and total load recovery are affected mainly by affecting the node zone.

3) Extreme faults caused 10% of the total number of lines to be disconnected

According to the calculation results of the previous part, 19 lines with the highest failure rate are selected to disconnect, and the changes in partitioning results are shown in Fig. 5 and TABLE IV.

TABLE IV. POST-FAULT ZONING CONDITION (10% LINE FAILURE)

Subsystem number	1(31)	2(54)	3(92)
Node	1-23、25-43、113-115、117	44-67	24，68-112、116、118
Node amount	46	24	48

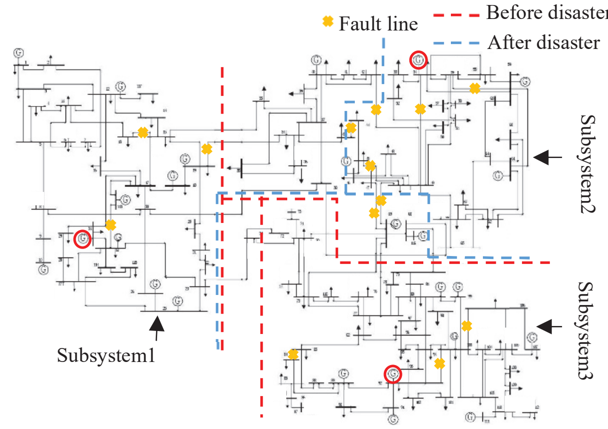

Fig. 5. Post-failure system partition (10% line failure)

After 10% disconnection, some nodes are disconnected from BS generators at node 54, so they are re-divided into subsystem 1.The number of nodes in zone 1 increases while the number of nodes in zone 2 decreases. The influence of line fault on the partition situation is shown directly.

TABLE V. shows the power generation and load restoration of each region after the rezoning.

TABLE V. SYSTEM LOAD RECOVERY (10% LINE FAILURE)

Subsystem		Sub.1 (31)	Sub.2 (54)	Sub.3 (92)	Total	Total (%)
Before disaster	Generation recovery (MW)	646.84	1124.908	967.48	2739.228	62.58%
	Load recovery (MW)	622.84	1082.908	931.48	2637.228	62.36%
After disaster	Generation recovery (MW)	646.84	907.26	1086.86	2640.96	60.33%
	Load recovery (MW)	622.84	871.26	1044.864	2538.96	60.04%

After the above three line-breaking schemes are respectively run in the parallel recovery model, the change rate of the total load of the system is shown in the table. Compared with the case of 5% line fault, the total load and total power generation recovery amount are slightly reduced when 10% line fault occurs. It can be seen that when a small number of lines are faulty, although the system can be partitioned normally, the power generation and load recovery will be affected by the faulty lines.

V. CONCLUSION

This paper explores the assessment of power system recovery capacity considering the impact of extreme disasters. Taking IEEE-118 bus system as an example, the influence of the damage of power grid components such as generators and lines on the restoration of power grid is discussed by using the established zonal parallel restoration scheme. Parallel partition recovery after power outage is simulated, and the main conclusion is as follows:

- Several indexes of power system recovery capacity are defined, including system response capability, system recovery efficiency, system recovery economy, system performance loss quantification, etc.
- When a small number of transmission lines are damaged, the system can still complete the task of partition startup, but the partition situation will change according to the line conditions, and the recovery speed of load and power generation will decrease with the increase of disconnected lines.
- When a large number of transmission lines are damaged, the system may not start properly due to the absence of BS generators.

REFERENCES

[1] Fang LF, Huang L, Zhao Q, et al. Power grid security in large cities: a view from the power outage in Venezuela [J]. Electric Power and Energy, 2019, 40(6): 674-677.

[2] Sun CW, "Analysis of the '12.28' Mexico Blackout and its Implications and Suggestions for China's Power Grid Operation," Electric Times, no.9,pp. 44-46,2021.

[3] Chopra S, Qiu F, Shim S. Parallel power system restoration[J]. INFORMS Journal on Computing, 2023, 35(1): 233-247.

[4] Zhao J, Wang H, Wu Q, et al. Optimal generator start-up sequence for bulk system restoration with active distribution networks[J], IEEE Transactions on Power Systems, vol. 36, May 2021, pp. 2046-2057.

[5] Liu X, Hou K, Jia H, et al. A quantified resilience assessment approach for electrical power systems considering multiple transmission line outages[C]//2017 IEEE Electrical Power and Energy Conference (EPEC). IEEE, 2017: 1-5.

[6] Jing X, Qin WP, Yao HM, et al. Research on measures and key technologies for improving elasticity of new power systems under extreme natural disasters [J]. Journal of Taiyuan University of Technology, 2022, 53(3):432-442.

[7] Gu XP Wang DJ, Liang HP, Liu Y et al. Dynamic Comprehensive Evaluation of Extended black Start Schemes for Power Systems [J]. Transactions of China Electrotechnical Society, 2015, 30(3): 44-52.

[8] Wu Y, Fang X, Zhang Y, et al. Generalized assessment algorithm for power grid black-start modes[J]. Diangong Jishu Xuebao(Transactions of China Electrotechnical Society), 2011, 26(3): 155-161.

[9] Park J, Thompson S E, Seager T P, et al. Design for resilience in coupled industrial-ecological systems: Biofuels industry as a case study[C]//Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology. IEEE, 2011: 1-1.

[10] Talib D N A, Mokhlis H, Talip M S A, et al. Islands determination for parallel power system restoration using heuristic based strategy[C]//2018 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia). IEEE, 2018: 30-35.

[11] Ngo M K, Mai V C, Huynh Q C, et al. Performance comparison of impedance-based fault location methods for transmission line[J]. International Journal of Electrical and Electronic Engineering & Telecommunications, 2022, 11(3): 234-241.

[12] Billinton R, Wu C, Singh G. Extreme adverse weather modelling in transmission and distribution system reliability evaluation[C]//14th Power Systems Computation Conference. 2002.