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Enhancing the resilience of the power system to accommodate the construction of the new power system: key technologies and challenges

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The increasingly frequent extreme events pose a serious threat to the resilience of the power system. At the same time, the power grid is transforming into a new type of clean and low-carbon power system due to severe environmental issues. The system shows strong randomness with a high proportion of renewable energy, which has increased the difficulty of maintaining the safe and stable operation of the power system. Therefore, it is urgent to improve the resilience of the new power system. This paper first elaborates on the concept of power system resilience, listing the characteristics of new power systems and their impact on grid resilience. Secondly, the evaluation methods for resilient power grids are classified into two categories, and measures to improve the resilience of the new power system are reviewed from various stages of disasters. Then, the critical technologies for improving the resilience of the new power system are summarized. Finally, the prospective research directions for new power system resilience enhancement are expounded.

KEYWORDS

new power system, renewable energy, extreme events, resilience enhancement, resilience evaluation

1 Introduction

Fossil fuel is one of the most important sources of energy for humanity. With the development of the global economy in recent years, the consumption of fossil fuels has also rapidly increased, causing consistently high carbon emissions, the greenhouse effect, and abnormal global climate changes (Pachauri and Meyer, 2014; Michael, 2016; IEA, 2019). To address such issues, vigorously developing renewable energy sources such as wind and solar energy has become a common choice. Countries around the world promulgate energy policies and promote energiewende. The United States, Canada, Japan, and other countries have all carried out relevant engineering applications, attempting to upgrade traditional power systems into green and low-carbon new power systems (Peng et al., 2017). In March 2021, China claimed the goal of "carbon peaking and carbon neutrality" and the development of a new power system (Hu, 2021). The new power system involving a high proportion of renewable energy aims to promote energy production and consumption and construct a low-carbon, safe, and efficient energy system (National Development Reform Commission National Energy Administration, 2021). By March 2023, the total installed capacity of wind and solar power in China is 0.92 billion and it is expected to reach over 1.2 billion kW by 2030, and at least 3 billion kW by 2060 (National Development Reform Commission, 2016).

The new power system can fully utilize various resources and achieve multi-energy complementarity. The improvement of power electronics has also made the system more flexible and intelligent. Non-fossil energy sources such as wind power and photovoltaic will gradually become the main energy sources. However, as the proportion of renewable energy continues to increase, the new power system shows characteristics of large fluctuations and strong randomness. It is increasingly difficult to balance power supply and demand in the system (Zhang et al., 2018). With the frequent occurrence of extreme weather events in recent years, power systems with a high proportion of renewable energy are facing huge challenges in power supply (Wang et al., 2014; Lu et al., 2017). For example, in August 2020, the high-temperature weather in California caused a sharp increase in load. Meanwhile, the output of wind power and hydropower decreased, leading to a large-scale power outage accident ultimately (California ISO, 2020). In February 2021, Texas experienced extremely cold weather, causing a rapid increase in heating load. The wind turbine was shut down with blade icing, and natural gas production decreased as a result of wellhead freezing, resulting in a cumulative load shedding of 20,000 MW (Magness, 2021). In July 2022, because of the continuous high temperature and dry weather, the electricity consumption of State Grid Sichuan increased by 19.79% year-on-year. However, the hydropower decreased from about 900 million kW hours in the same period to about 450 kWh, causing a shortage of power supply and limited usage (Ma and Wu, 2021).

At present, numerous literature has summarized the research on the resilience of the current power system (Gao et al., 2023), but little consideration has been given to the changes in research for improving the resilience of new power systems with a high penetration of renewable energy. Studying the related issues of resilience improvement under the background of the new power systems construction is significant for further enhancing the system's ability to respond to extreme events and maintaining stable operation. The main contributions of this paper are summarized as the following:

- This paper elaborates on the concept of power system resilience, analyzes the impact of new power systems on grid resilience, and lists methods for evaluating resilient power grids.
- The measures to enhance the resilience of the new power system are reviewed from the perspectives of pre-disaster planning and configuration, disaster management and control, and post-disaster recovery response.
- The key technologies for improving the resilience of the new power system are summarized from the perspectives of planning and operation.
- The further methods for improving the resilience of new power systems are prospected, and corresponding research focuses are given, providing suggestions for the clean and low-carbon energy transformation in China.

2 Definition and evaluation method of resilient power grid

2.1 Definition of the resilient power grid

The concept of resilience was first proposed by Holling. C. S in the ecological field in 1973 to measure the ability of ecosystems to withstand, absorb disturbance, and maintain system stability (Holling, 1973).

In 2009, the American Department of Energy released the Smart Grid System Report (U.S. Department of Energy, 2009), which for the first time clearly stated that smart grids should be resilient in the face of natural disasters, deliberate attacks, equipment failures, and human errors. The National Committee on Critical Infrastructure of the United States summarized that resilient systems should include four characteristics (National Infrastructure Advisory Council, 2010), namely, robustness (the ability to absorb disturbances and operate continuously), agility (the ability to control losses during the events), recovery (the ability to quickly restore power grid functions, especially the ability to continuously supply power to important loads) and adaptability (the ability to learn from disasters and enhance resilience). The report released by the UK Energy Research Organization in 2018 defined resilience as the ability to withstand and reduce the scale and duration of destructive events, including preparedness, absorption, adaptation, and rapid recovery (The ERP Working Group Members, 2018). In China, Professor Ouyang Min from Huazhong University of Science and Technology introduced the definition of resilience proposed for earthquake disaster management in the power system in 2014. It is proposed that resilience includes four attributes: robustness, redundancy, agility, and rapidity (Ouyang and Dueñas-Osorio, 2014). In 2015, Academician Qiu Aici and Professor Bie Zhaohong from Xi'an Jiaotong University proposed the concept of the "resilient power grid" and recovery ability (Zhaohong et al., 2015; Zhaohong et al., 2020). In 2015, Professor Chen Ying from Tsinghua University put forward the concept of "distribution network resilience," pointing out that resilience mainly measures the support and recovery ability of the distribution network to critical loads in natural disasters. Distribution network resilience is also defined as whether the distribution network can take proactive measures to ensure the power supply of critical loads and quickly recover the outage load in disasters (Gao et al., 2015).

2.2 The impact of new power systems on the grid resilience enhancement

The characteristics of the new power system are as follows.

2.2.1 Increased system randomness

The large-scale and high proportion of intermittent renewable energy inevitably brings strong stochastic output in various time scales, including seasonal or short-term uncertainty. As a result, it poses significant challenges to the supply guarantee of the power

TABLE 1 The impact of various extreme events on the power system.

References	Extreme events	Affected components	Specific equipment
Li et al. (2014)	Hurricane	Lines and towers	Distribution network lines, transformers, loads, isolation switches
He and Guo (2012)	Earthquake	Converting station	Traditional power plants, loads, lines, transformers, substations
Zhang et al. (2012)	Ice disaster	Lines	Generators, lines, loads
Wu et al. (2015)	Magnetic storm	Transformer	Transmission lines, transformers, substations
Liu et al. (2017)	Cyber attack	Protection Equipment	Generators, lines, loads, protective equipment

system. Table 1 lists the impacts of various extreme events on the power system.

2.2.2 Enhanced intelligence

The rising complexity and uncertainty of new power systems increased the difficulty in resilient modeling, analysis, and precise prediction. Currently, emerging cutting-edge information technologies such as artificial intelligence, big data, blockchain, and the Internet of Things are rapidly developing and is gradually being applied in smart grid. Various functions such as monitoring, measurement, control, protection, and scheduling have become more refined and intelligent after the application of these technologies (Gao et al., 2022).

2.2.3 Increased complexity

The application of information and communication technology in new power systems is more widespread. With a large number of automated and information-based communication devices involved, the complexity of the power grid is increasing. The interconnection of power grids in different regions and the coupling of multiple energy sources promote the consumption of renewable energy while also making the system more complex (Hui et al., 2022).

The characteristics of the new power system exacerbate the uncertainty in various stages of the grids (Bie et al., 2017). Considering the damage caused by disasters to intelligent monitoring equipment in the power grid, the system's ability of real-time situational awareness has decreased. How to clarify the uncertain factors and accurately constructing a model in uncertainty is the key to improving the resilience of new power systems. Meanwhile, for new power systems, the timing of natural disasters has become even more critical. The system shows strong randomness with a high proportion of renewable energy. Each type of renewable power generation resource is affected by disasters to various degrees, resulting in differences in the system's ability to withstand extreme disasters. How to effectively identify the fault time and location of new power systems in disasters, and analyze the interaction mechanism between specific disasters and new power systems, are the foundation for improving the resilience of new power systems.

2.3 Evaluation methods for power grids resilience

Power system resilience assessment can be divided into two categories: one is the static evaluation based on network topology, component redundancy, and resource adequacy; Another type is the dynamic evaluation, which establishes corresponding indicators based on the multiple processes of the system in response to extreme events.

2.3.1 The static evaluation

Arghandeh et al. (2014) calculated the system connectivity loss and distributed power redundancy, and evaluated the resilience of active distribution networks in the fault response and fault recovery stages; Bajpai et al. (2018) introduced performance indicators such as the number of common branches, switch operations, path redundancy ratio, and device availability. The Choquet integration method was used to quantify the system's resilience. Peng et al. (2019) used network graph theory to establish a static indicator system for resilience evaluation, taking topological resilience, component failure rate, and load power factor into account. Chanda and Srivastava (2016) proposed an evaluation method combining graph theory and analytic hierarchy process, which used topological characteristics such as Betweenness centrality, graph diameter, and clustering coefficient to measure system resilience.

It should be pointed out that static evaluation mainly evaluates the system's resilience from a specific aspect, which is difficult to effectively reflect the performance of grids during the fault recovery stage. It can also not quantify the differences under different extreme events. Therefore, it is advisable to use dynamic evaluation which considers different resilient stages including resistance, absorption, adaptation, and recovery.

2.3.2 The dynamic evaluation

The classical dynamic resilience evaluation index is calculated by integrating the system performance curve and time in Figure 1.

$$R = \int_{t_1}^{t_4} [F_0 - F(t)]dt \tag{1}$$

where $F(t)$ represents the changes in the system function at each stage, and F_0 represents the system performance under normal operation. This indicator can to some extent reflect the robustness and recovery of the system and is widely used. Reference (Luo et al., 2018) took typhoons as a representative to draw the vulnerability curve of components. The entire process of extreme weather disasters was simulated using the Monte Carlo method. Different weights were assigned based on the importance of the load. The weighted losses of the load in all stages were selected as the evaluation index.

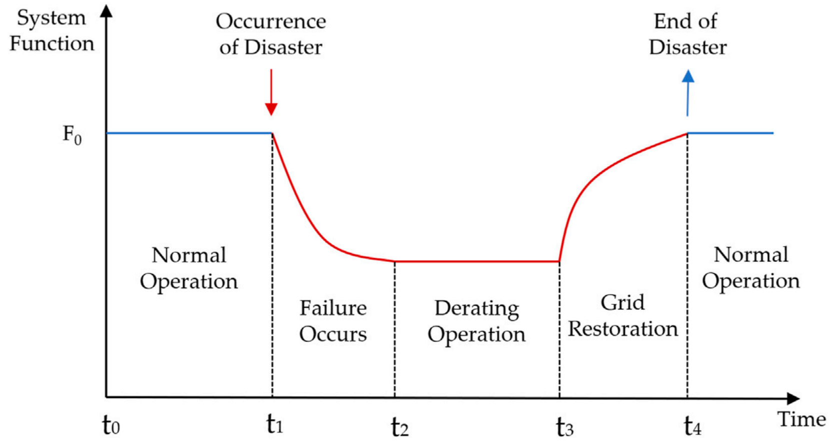

FIGURE 1
Schematic diagram of power system resilience curve.

He et al. (2021) composed resilience indicators based on robustness, adequacy, and safety, with power sources, power grids, and users as evaluation objects. Literature Gu et al. (2018), Li et al. (2020) divided extreme events into the fault prevention stage, adaptation stage, and recovery stage. Then a resilience evaluation index system was constructed including the defense time of the distribution network, coefficient of restitution, island sustainable time, and average interruption time of important loads. Bessani et al. (2019), Hosseini et al. (2019), Zhang et al. (2020a), Jiang et al. (2021) established resilience indicators for different stages of the resilience trapezoid, including maximum load loss R1, load interruption rate R2, self-healing recovery time R3, and maintenance time R4.

$$R_1 = \sum_{s\in S} \pi_s (F_0 - F_m) \tag{2}$$

$$R_2 = \sum_{s\in S} \pi_s \frac{F_0 - F_m}{\mathrm{t}_2 - \mathrm{t}_1} \tag{3}$$

$$R_3 = \sum_{s\in S} \pi_s (\mathrm{t}_4 - \mathrm{t}_3) \tag{4}$$

$$R_4 = \sum_{s\in S} \pi_s (\mathrm{t}_4 - \mathrm{t}_1) \tag{5}$$

where F_m represents the system performance during the fault adaptation stage, corresponding to the lowest system performance; S represents the set of fault scenarios; π_s represents the probability of failure occurrence. It can be seen that the maximum load loss R_1 and load interruption rate R_2 represent the robustness and absorption of the system; The self-healing recovery time R_3, and maintenance time R_4 are used for the system recovery level after the disaster, representing the system's rapidity and activeness.

Moreover, Paul et al. (2014), Dehghanian et al. (2018), Liu et al. (2021a) considered the dimensions of technology, organization, economy, and society to create a system resilience assessment matrix, wherein the technical dimension corresponds to changes in the system's power supply capacity; Organizational dimensions correspond to recovery strategies such as executing decisions, arranging the personnel, and coordinating resources during fault recovery; The economic dimension corresponds to the costs caused by power outages; The social dimension corresponds to the social impact caused by the loss of power supply to public institutions such as governments and hospitals.

3 Main measures and key technologies for improving the resilience of the power system

3.1 Main measures to improve the resilience of the power system

After extreme events occur, resilience improvement strategies can be divided into pre-disaster prevention strategies, disaster response strategies, and post-disaster recovery strategies. Measures such as strengthening and deploying flexible power generation are taken to maintain components with high failure rates so that resilience is enhanced before disasters (Wang et al., 2019; Bian et al., 2020); During the disaster phase, scheduling flexible resources and equipment such as distributed power sources, energy storage, controllable loads, interconnection switches, and intelligent soft switches to minimize power loss as much as possible (Chen et al., 2016; Chen et al., 2020); In the post-disaster stage, the repair of faulty components and the improvement of system resilience are achieved through collaborative scheduling of operation personnel, and emergency resources (Zhang et al., 2020b; Zhang and Xie, 2021).

The impact of extreme events on power grid infrastructure is uncertain, which needs to be considered in the modeling. The resilience enhancement model is commonly constructed as a three-layer (defense-attack-defense) robust optimization (RO) model, which can be established as follows (Ma et al., 2018).

$$\begin{gathered} \min_{r} \left\{ \sum_{l\in\Pi_{line}} c_l^{str} r_l + \max_{u\in U} \min_{y} \sum_{t\in T} \sum_{j\in\Pi_{node}} c_j^{cur} P_{j,t}^{cur} \right\} \\ s.t.\;\; B_1 h + C_1 y + D_1 a + E_1 u \le g_1 \end{gathered} \tag{6}$$

where the binary variable r_l represents whether the line l is reinforced. When the line is reinforced, the value is 1, otherwise, it is 0; t and T represent the time index and its set, respectively; j and Π_{node} represent the distribution network node index and its set, respectively; $P_{j,t}^{cur}$ is the curtailment load of the node j; r represents the decision vector for line reinforcement composed of r_l; a represents the line state vector composed of al; y represents a vector composed of continuous variables related to distribution network power flow optimization; c_l^{str} indicates the reinforcement cost of the line l; c_j^{cur} represents the penalty coefficient for load curtailment at node j; B_1, C_1, D_1, E_1 are constant coefficient matrices; g_1 is the coefficient matrix of the corresponding constraints.

In response to the influence caused by extreme event attacks, numerous literature described it using an uncertainty set of damaged distribution network lines.

$$U = \left\{ u \in R^{N_{line}} \middle| \sum_{l \in \Pi_{line}} k_l \geq N_{line} - n_{\max} \right\} \tag{7}$$

where u represents the uncertainty of line damage; N_{line} is the number of distribution network lines; $n_{\max}$ is the maximum number of damaged lines; l and Π_{line} respectively represent the line index and its set; binary variables k_l represents the state of the line l, k_l = 1 indicates the circuit is closed and 0 otherwise.

Since the above model only considers the operation strategy of power flow optimization for resilience improvement after disasters occur, the vector y of the inner defense layer only contains continuous variables. When distribution network reconstruction and power flow optimization strategies are both considered after a disaster occurs, the RO model established is as follows (BIAN et al., 2020):

$$\begin{gathered} \min_{r} \left\{ \sum_{l \in \Pi_{line}} c_l^{str} r_l + \max_{u \in U} \min_{x,y,z} \sum_{t \in T} \sum_{j \in \Pi_{node}} c_j^{cur} P_{j,t}^{cur} \right\} \\ s.t. \;\; B_2 h + C_2 y + D_2 a + E_2 u + A_2 x + G_2 z \leq g_2 \end{gathered} \tag{8}$$

where x and z represent vectors composed of continuous and discrete variables related to network reconstruction, respectively; A_2, B_2, C_2, D_2, E_2, and G_2 are constant coefficient matrices; g_2 is the coefficient matrix of the corresponding constraints.

In the recovery stage, operations such as repairing faulty infrastructure and restoring the power supply are carried out to bring the distribution network back to its normal state. The operation of repairing faulty components can be modeled as a maintenance personnel scheduling subproblem (the first stage problem). Then, a power supply restoration subproblem (the second stage problem) can be established considering DG scheduling and network reconstruction. The two-stage optimization problem mentioned above achieves a smaller amount of load curtailment.

3.1.1 Measures in pre-disaster prevention stage

The new power system optimizes the energy structure through various energy combinations, making the system more and more complex. With the high proportion of various distributed energy, it is urgent to configure the location and capacity of these resources. The potential value of various resources should be fully utilized before disasters for improving resilience.

In the prevention stage, a multi-objective optimization model was established considering maintenance costs before the occurrence of faults, which achieved good results in reducing the overall costs (Liang et al., 2021). References (Arizumi et al., 2014; Bie et al., 2017) established disaster databases and prediction models according to historical disaster information. Various events are classified based on disaster scale and losses. At the same time, it is advisable to develop emergency plans before disasters occur. The scope of power outages is reduced by adjusting operation methods, ensuring the continuous power supply of critical loads.

In the disaster prevention phase, physical means are often used to enhance resilience, including increasing the strength of power lines/towers, replacing overhead lines with cables, and tree pruning. These methods can reduce the physical damage caused by extreme events, and reduce the failure rate of power system components (Barnes et al., 2019). However, components replacement in large quantities will bring high investment costs. It is better to replace key components that have a significant impact on system resilience or with a high failure rate. Further research is needed on how to identify these components and make the corresponding protection strategy. (Xia et al. 2021) proposed a method for the identification of vulnerable lines. A comprehensive model based on grid processing of the distribution network is established. Vulnerable lines are selected by information entropy to strengthen and reduce the power failure loss of the system in case of an earthquake disaster. It is indicated that laying cables can enhance the ability of power systems to withstand typhoons. However, in earthquake situations, it will lead to longer repair times for damaged lines.

3.1.2 Measures in response stage in disasters

During the disaster, the corresponding measures include making full use of the diversified and flexible resources (distributed generation, interconnection switch, mobile energy storage, demand response, etc.) to reconstruct the network and optimize the power flow (Yao et al., 2020b; Nazemi et al., 2021).

In the disaster response phase, ensuring the energy supply is the most critical goal. Safe and reliable operation of the system takes priority over minimizing load loss (Zhang et al., 2019). Compared to traditional power grids, large-scale power electronic devices, and intelligent control systems are utilized in new power systems, providing diverse resilient response measures (Zhaohong et al., 2020). At this stage, the propagation of strong disturbances should be suppressed. The lines out of service should be cut off on time to prevent fault propagation and improve system resilience.

Moreover, the short-term resilience of the system can be improved by enhancing the primary equipment of the system, such as introducing fault current limiters. Achieving rapid response of secondary control and protection equipment also has positive significance. (Ton and Wang 2015) improved the system's situational awareness and response speed by configuring intelligent measurement devices in the power grid. Remote switches and automation switches were considered in (Bian and Bie 2021), which quickly changed the topology of the power grid. The timely operation of backup power sources was enabled and fault response and recovery time were shortened.

Currently, much literature has explored how to utilize the emergency response capabilities of distributed power sources and microgrids to enhance system transient performance (Zhou et al.,

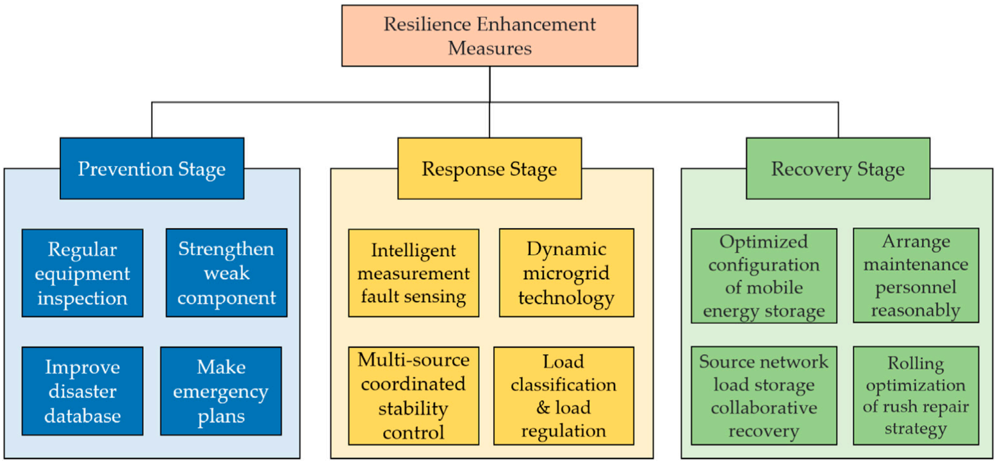

FIGURE 2
Measures to enhance the resilience of the power system.

2020; Chang et al., 2021). When a serious system failure occurs, both the direct and transfer paths of the superior power supply may be cut off. Multiple islands emerged. The integration of distributed power sources and microgrids can greatly increase system flexibility, provide powerful support for end loads, and ensure a reliable power supply for loads. (Lei et al. 2018) placed mobile emergency generators at a predetermined location to maintain the power supply for important loads.

3.1.3 Measures in post-disaster recovery stage

The post-disaster recovery phase aims to quickly coordinate all recovery resources and restore as much load as possible. After extreme disasters, operators need to dispatch maintenance teams as soon as possible to repair faulty components. Recovery resources such as locally distributed power sources, emergency power generation vehicles, and demand-side management should be scheduled to restore the system to a normal state (Chen et al., 2019a; Chen et al., 2019b). Based on this, a two-stage optimization problem is established. The first stage is a sub-problem for scheduling maintenance teams, and the second stage is for power supply restoration that combines the scheduling of multiple recovery resources and network reconstruction.

After a natural disaster, many electrical infrastructures may be severely damaged, and maintenance personnel needs to be mobilized to repair or replace the faulty road section. Due to the limited availability of resources in the system, how to allocate staff and reasonably arrange the repair sequence of components is an important issue. (Liu et al., 2021a) proposed a fault location, fault isolation, and service recovery method for improving system resilience. Based on the coupling relationship of the above three, differentiated recovery schemes were implemented for different fault conditions.

In the post-disaster recovery stage, operations such as black start, network reconstruction, and component repair are usually involved. Black start and network reconstruction aim to improve the short-term resilience of the power system, while component repair aims to improve the long-term resilience of the system. During the black start process, the system mainly establishes a power supply path by restarting some units. (Qiu et al. 2016) elaborated on the important steps of parallel recovery for multiple units, namely, the partition method and startup sequence. With the objective function of minimizing unit startup costs, a fault recovery strategy was provided. In the later stage of the black start, the system needs to rely on distributed power sources for network reconstruction, readjusting the network topology structure, and restoring important loads (Yao et al., 2020a; Yu et al., 2021). Existing research utilized heuristic algorithms, mathematical programming algorithms, and artificial intelligence algorithms to transform network reconstruction into mixed integer programming problems so that the optimal solution and fault recovery strategies were obtained (Liu et al., 2020). (Gilani et al. 2020) proposed a resource scheduling model based on mixed integer linear programming, and effectively restored the system by using distributed generation, regional communication system, and other resources. Figure 2 shows potential measures to enhance the resilience of the power system, and the implementation methods of certain strategies are shown in Table 2.

3.2 Key technologies for improving the resilience of new power systems

3.2.1 The perspective of grid planning

The probability of extreme events occurring is small and the frequency is low. If a large amount of funds is invested in the resilient resources of the power system to cope with extreme events, it will inevitably reduce the economic efficiency of the system and also hinder the low-carbon development process of the new power system (Huy et al., 2020). Therefore, in the planning mode, it is necessary to consider both economic efficiency and system security. Based on the characteristics of regional resource distribution and natural conditions, a detailed evaluation of resilient resources should be conducted to guarantee the economic benefits of power supply and consumption. This will provide an effective foundation for the new power system in the planning stage.

TABLE 2 The implementation method of resilience enhancement strategy.

Resilience indicators	Resilience enhancement measures	Objective function	Optimization solution	References
Load reduction	Optimize the configuration of remote switches	Minimize post-accident load-shedding power	C&CG (column and constraint generation)	Bian and Bie (2021)
Load supply and fault recovery time	Active islanding and remote switch fault isolation	Minimize power outage losses	CPLEX/GUROBI	Liu et al. (2020)
Fault recovery time	Adjusting distributed power sources and dynamic microgrids	Minimize operating costs and maximize benefits	Two-stage rolling horizon optimization	Wang and Wang (2015)
Load reduction, power outage level	Optimize scheduling resources and optimize load reduction	Minimize total expected outage costs	GUROBI	Ding et al. (2021)
Economic Factors and Resilience Curve Functions	Improving the penetration rate of distributed energy	Minimize power outage losses and minimize maintenance costs	heuristic algorithm	Liu et al. (2021b)

China has a vast territory and diverse natural resources in different regions. The construction of power grids interconnected with each province can promote the optimal allocation of resources (Huang et al., 2021). Considering that the uncertainty of wind and solar power varies in different regions, the construction of interconnected large power grids can not only achieve a larger spatial balance between power supply and demand but also improve the overall resilience of the system (by offering power support between provinces) (Ding et al., 2022). Meanwhile, mutual support among different regions through inter-regional transmission can enhance the flexibility of each regional power grid, thereby reducing investment in flexible resources and improving economic efficiency (Yang et al., 2020). These flexible resources can also help enhance the system resilience under extreme events.

In the planning stage, it is possible to consider the integration of hybrid energy storage and other energy conversion technologies with the new power system to enhance its resilience (Tao et al., 2020a). In times of power shortage, other forms of energy such as natural gas and hydrogen can be converted into electricity to ensure a stable power supply. Conversely, during periods of power surplus, electricity can be converted into other forms of energy to promote the complementary use of diverse energy sources (Wu et al., 2022a).

3.2.2 The perspective of grid operation

The scenario of new power system scheduling has multiple uncertain factors, and it is necessary to fully utilize the collaborative operation of multiple resources. On the power side, adjustable power sources represented by thermal power and hydropower can provide certain resilience. But their response speed and ability are different, and the flexibility of energy storage is usually constrained by temporal coupling, which affects their operation modeling. On the load side, the characteristics of the fixed load and adjustable load are different in their response potential, response speed, and response time (Cui and Zhou, 2018). Similarly, when providing resilient support for cross-regional interconnected power grids, it is also significant to consider the operational constraints and regulation capabilities of different regional power grids in different regions. So that the stable operation of the entire interconnected system is ensured and can endure extreme events (Hu et al., 2022). Therefore, refining and organizing resources with different resilience abilities to participate in multi-time scale scheduling optimization are important. For example, resilient resources with slower response rates are preferred to participate in the day-ahead scheduling or even monthly/weekly plans, while resilient resources with faster response rates should be utilized in short-term adjustments on a daily plan. In addition, the collaborative scheduling of resilient resources under extreme events also requires special attention. The development trend of disasters can be deduced by analyzing multiple characteristics. And research on grid scheduling strategies with high efficiency and self-adaptation based on machine learning methods can be carried out to enhance the resilience of the system in collaboration with multiple resilient resources under extreme events.

4 Practice and prospect of resilient grid construction

4.1 Practice of resilient power grid construction

At present, there are many resilient power grid construction practices both domestically and internationally. In terms of policy, the U.S. government promulgated the “21st Century Energy Act” in 2016 to promote the use of renewable energy and the development of smart grids, aiming to improve the resilience and flexibility of the grid. The purpose of this act is to achieve a more reliable, secure, economical, and environmentally friendly electricity system by improving energy efficiency, reducing emissions, and encouraging the use of renewable energy sources (U.S. Department of Energy, 2016). The Japanese government integrated renewable energy with traditional power systems and promotes the construction of smart grids. After the Fukushima nuclear disaster in 2011, the Japanese government invested more resources in the construction of smart grids to enhance their resilience (Cao, 2018). The German government has formulated the “Energy Transition” plan, aiming to make Germany’s electricity completely supplied by renewable energy by 2050. The core of this plan is to combine renewable energy with smart grids to enhance the resilience and flexibility of the grid. The German government also encouraged individuals and businesses to adopt renewable energy and energy-efficient technologies (REN21, 2020). The Chinese government proposed in the 13th Five-Year Plan to accelerate the development of smart grids and improve the resilience of the power system. The Chinese government has also introduced a series of policies and measures to promote the application of renewable energy and energy-saving technologies, and strengthen the coordination and control of the power grid (National Energy Administration of the People's Republic of China, 2016). The Canadian government improved the resilience of the power system by promoting the construction of smart grids. The Canadian government supported the application of renewable energy and energy-saving technologies and promotes the reduction of energy efficiency and carbon emissions (Board, 2011). The Australian government is promoting the construction of smart grids to enhance the resilience of the power system. The Australian government encourages the application of renewable energy and energy storage technologies, promotes energy diversification, and reduces carbon emissions (Australian Renewable Energy Agency, 2020).

In terms of specific projects, many countries and regions have begun the construction of resilient power grids. Denmark's "Bornholm Energy Island" project (Early Detection Of Value, 2022) aims to build a highly flexible and resilient power grid. The renewable energy facilities on Bornholm Island were interconnected to achieve intelligent management of the power supply. The "Hornsdale Power Reserve" project (Hornsdale power reserve, 2017) in Australia built a huge energy storage facility that can store a large amount of solar and wind energy. The project also includes intelligent grid control technology to provide a reliable power supply to local communities. The Funeng cogeneration project by China Huaneng Group in Longyan City has constructed a flexible, schedulable, and scalable power system. Renewable energy sources, a large-capacity energy storage system, and a digital control center are involved to improve the resilience of the power grid (Ministry of power, 2022). The resilience microgrid project of Xili Primary School in Shenzhen has built a microgrid that integrates energy storage, intelligent control, and multi-energy complementarity, including PV, energy storage, gas boilers, heat pumps, and ground source heat energy, aiming to improve power supply reliability and sustainability (SZTV, 2022). The resilience power grid construction project in Ya'an City, Sichuan adopts the technology of "energy storage + renewable energy + smart microgrid". Through the construction of a smart microgrid, effective management and scheduling of various dispersed renewable energy sources such as wind power and photovoltaic have been achieved (People's Daily, 2020). The Huairou District Urban Resilience Grid Demonstration Project in Beijing has achieved efficient utilization and management of renewable energy by introducing various renewable energy technologies and smart microgrid control strategies, improving the resilience and security of the power grid (Beijing Municipal People's Government, 2017).

4.2 Challenges and prospects

4.2.1 Enhancing the perception and prediction of extreme events

The construction of the new power system, accompanied by increasing complexity and uncertainty, poses great challenges to the modeling, analysis, and precise prediction of the system resilience under extreme events (Wang et al., 2021). The application of artificial intelligence technology, which has less dependence on mathematical models of physical systems and possesses the ability to self-learn from massive data, enables better perception and prediction of extreme events. Operators rely on the construction of the Electric Internet of Things to store massive environmental data on servers and upload them to the cloud through the Internet. These data are collected by devices such as wide-area monitoring, sensors, and intelligent devices. It achieves reliable distribution of multi-source heterogeneous data which provides a platform for artificial intelligence technology. These are new methods for improving the resilience of new power systems.

4.2.2 Enhancing the resilience of the system through multi-network integration

The Energy Internet, centered around the power grid, connects diversified energy systems such as electricity and natural gas, as well as transportation, information, and other non-energy critical infrastructure systems. It forms a multi-layer coupled network architecture that enables optimal regulation and efficient utilization of energy flows (Tao et al., 2020b). The Internet of things (IoT) is an extension and expansion of the network based on the Internet, which combines various information sensing devices form a huge network. The utilization of Internet of Things technology helps the smart grid better connect and sense each power device. It is necessary to carry out research on the messaging patterns, protocols and technologies in the area of information exchange (Górski, 2022). Considering the existence of diversified coupling nodes in a multi-network system, the traditional resilience assessment methods based on a single network are no longer applicable. Therefore, a unified network topology evolution model needs to be established for the system to effectively characterize the propagation mechanism of faults across spatiotemporal scales in any subsystem. On the other hand, at different stages of disasters, the operational states of each subsystem show complex coupling relationships. It is necessary to reveal the dynamic interaction mechanism of different subsystems for comprehensive analysis. On this basis, combining the research of network topology evolution models and system performance analysis to establish a multi-dimensional system resilience evaluation is an important focus in the research of resilience evaluation for multi-network fusion systems.

In the context of the Energy Internet, different dimensional entities such as the power grid, gas network, transportation network, and information network are coupled, making disturbance infiltration and fault propagation in the multi-dimensional entity fusion system more complex under the influence of extreme events (Wu et al., 2022b). Disturbance and fault in a certain entity (such as line fault in the distribution network, pipeline damage in the natural gas network, road congestion in the transportation network, and communication interruption in the information network) can spread to other subjects through energy flow, traffic flow, and information flow. In serious cases, it may cause in-stability or even paralysis of the overall fusion system. In addition, the significant differences in modeling methods and operating time scales between different networks pose technical challenges to the research on enhancing the resilience of multi-energy fusion systems.

Therefore, it is urgent to study resilient improvement measures of the multiple coupling entities.

4.2.3 Fully utilizing user-side resources

The user side has numerous distributed resources and can operate in a flexible way. Fully utilizing the resources with flexible adjustment capabilities on the user side can promote the further consumption of renewable energy. Virtual power plants (VPPs) are currently one of the main means of resource aggregation in distribution networks.

VPPs do not have specific constraints on the geographical location and operational characteristics of distributed energy, providing an emerging and highly flexible distributed energy management approach for power systems. However, the current research on VPPs only simply aggregate all resilient resources, without considering the synergy of these resources under network constraints. In the context of a high proportion of renewable energy, VPPs need to integrate various types of flexible resources to provide a larger adjustable power range. Dealing with the diverse and large-scale distributed energy in VPPs, existing algorithms of adjustable power domains and cost aggregation of regulated power cannot simultaneously balance efficiency and accuracy, so further research is needed. After the occurrence of extreme disasters, the operational goal of VPPs needs to be shifted from ensuring economic efficiency to improving resilience. As disasters cause damage and disturbance on the grids and various resilient resources, it increases the difficulty of aggregating resources for VPPs. Therefore, it is necessary to study post-disaster resource aggregation technology for VPPs to provide support after disasters and ensure the safe and reliable operation of the power grid.

4.2.4 Exploring market mechanisms

A reasonable market mechanism is an important foundation for building a new power system with a high proportion of renewable energy. It is necessary to establish a diversified auxiliary service market with the participation of various entities, which is no longer limited to thermal power and hydropower units. Other diversified flexible resources can be involved (Xiao et al., 2018). In the future, various resources such as energy storage and distributed resource will gradually be included in the auxiliary service market. Specifically, considering the frequent occurrence of extreme events, auxiliary services that enhance resilience, such as emergency power supply and black start services are needed. The compensation mechanism under extreme disasters should be adjusted to incentivize various resilient resources to participate in different resilient auxiliary service markets based on their regulatory capabilities and costs. Their optimal economic benefits can be achieved while enhancing the ability to quickly restore power supply after accidents. Furthermore, the combination of various resilient resources with existing market mechanisms can be explored, and guide resilient resources to actively participate in the market through reasonable price mechanisms under extreme events.

Moreover, blockchain technology can help manage energy systems with different operators (Yan et al., 2022). Based on blockchain technology, new mechanisms and platforms for energy trading can be developed and implemented at various levels between generators, suppliers, traders, end-users, and prosumers (Zhao et al., 2023).

5 Conclusion

To achieve the goal of low-carbon and energy transformation in power systems and cope with the impact of extreme events, it is imperative to study methods for improving the resilience of new power systems. The conclusions of this paper can be summarized as follows:

- This paper gives a broad survey of the concept of power system resilience and analyzes the impact of the new power system on grid resilience with the characteristics of high randomness, high intelligence, and high complexity.
- Static and dynamic resilient evaluation methods are summarized.
- Research on resilience improvement measures such as pre-disaster configuration, management and control during disasters, and post-disaster recovery are summed up.
- Key technologies are outlined from the planning and operation levels.
- The prospect of improving the power system resilience is presented from four aspects, i.e., enhancing the perception and prediction of extreme events, enhancing the overall resilience of the system through multi-grid integration, fully utilizing user-side resources, and exploring market mechanisms.

In general, research on the resilience improvement of new power systems is still in its infancy. Further in-depth research is needed. It is recommended that the future work can be focused on Cyber-Physical Power System. Research on its resilience modeling, evaluation and enhancement methods can resist cyber attacks and protect the new power system from the information level. It is hoped that this article can provide a reference for subsequent related research.

Author contributions

SZ: Conceptualization, methodology, software, and writing the original draft. YL: Methodology and reviewing and editing. CJ: Conceptualization, funding acquisition, supervision, and reviewing and editing. ZX: Methodology and reviewing and editing. JZ: methodology and reviewing and editing. LW: Conceptualization, funding acquisition, supervision, and reviewing and editing.

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Conflict of interest

Author YL was employed by State Grid Shanghai Procurement Company, Shanghai Municipal Electric Power Company.

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Publisher's note

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