ISSN: 2688-9323

Resilience of Power Enterprises and Optimization of Business Environment

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Abstract

In recent years, escalating global climate change and the frequent occurrence of extreme weather events have posed severe challenges to the stability of power systems. Power systems urgently need to transition from traditional "robustness" designs to more adaptive and restorative "resilience" designs. This study constructs a three-dimensional "technical-operational-organizational" analytical framework to systematically explore the impact of power grid enterprise resilience on the business environment. The research finds that vulnerabilities in grid infrastructure, inefficiencies in operational management, and inadequacies in the policy environment are the main constraints on resilience, while electricity service costs, supply reliability, and user satisfaction are key dimensions for optimizing the business environment. In the short term, resilience can be enhanced by strengthening critical nodes and optimizing emergency resources. In the medium to long term, sustainable development should be driven by digital twin technology, resilient grid standards, and cross-departmental collaboration mechanisms. The study provides theoretical foundations and practical pathways for power grid enterprises to address climate risks and improve the business environment.

Keywords :

Power Grid Resilience; Business Environment; Extreme Climate; Power Reliability.

1. Introduction

In recent years, escalating global climate change and the frequent occurrence of extreme weather events such as hurricanes, ice storms, and floods have posed severe challenges to the stability of power systems. The 2022 report by the Intergovernmental Panel on Climate Change (IPCC) highlights that the climate risk index for global power infrastructure has risen by 47% compared to two decades ago. Taking the large-scale power outage in Texas, USA, in 2021 as an example, an extreme cold wave led to a complete grid collapse, resulting in economic losses exceeding 200 billion USD[1]. This incident underscores the urgent need for enhanced power grid resilience. Against this backdrop, power systems urgently need to transition from traditional "robustness" designs to more adaptive and restorative "resilience" designs to cope with increasingly complex climate and operational challenges.

The World Bank's "Doing Business 2020" report lists "Getting Electricity" as one of its ten core evaluation indicators, accounting for 18% of the total weight[2]. This indicator covers key dimensions such as the cost and time of connection, supply reliability, and transparency of electricity tariffs. According to statistics from the International Energy Agency (IEA), GDP losses due to power outages in developing countries account for as much as 2%-4%[3]. Since 2019, China has continuously advanced reforms in its business environment, with "Getting Electricity" identified as a key breakthrough area. Pilot cities like Beijing and Shanghai have successfully reduced average annual power outage times to within 50 minutes[4]. However, a significant gap remains when compared to international leading levels such as Singapore (15 minutes) and Tokyo (4 minutes).

In 2021, the Ninth Meeting of the Central Finance and Economics Commission proposed building a new power system primarily based on new energy sources[5]. With the rapid increase in the proportion of volatile power sources like wind and solar (projected to reach 40% by 2030), grid operations face new challenges from two-way uncertainty in both supply and demand. The "Interim Measures for Power Reliability Management" issued by the National Development and Reform Commission in 2022 explicitly incorporates "resilience" into regulations for the first time, requiring power grid enterprises to establish a full-chain risk management system[6]. Under the guidance of the "Dual Carbon" goals, resilient power grid construction is not only a technical guarantee for high-proportion integration of new energy but also an important pathway to improve the quality of the business environment.

Existing research predominantly focuses on single-dimensional analyses of power grid technical resilience or business environment evaluation, lacking a systemic study that organically integrates both[7,8]. This research aims to provide new theoretical perspectives and practical guidance for development economics and energy management by constructing a "technical-institutional-economic" three-dimensional analytical framework, integrating complex system theory, institutional economics, and power engineering, to deeply analyze the mechanism through which power grid resilience optimizes the business environment.

2. Defining Core Concepts

2.1. Multidimensional Definition of Power Grid Enterprise Resilience

As the core entity of the power system, the resilience of a power grid enterprise is directly related to the stability and reliability of electricity supply. In the context of power systems, resilience refers to the system's ability to maintain functionality or recover swiftly when faced with disturbances such as natural disasters, equipment failures, or external attacks. This study defines power grid enterprise resilience across three dimensions-technical, operational, and organizational-to comprehensively reveal its implications.

Technical resilience focuses on the disturbance-resistance capability of the power grid's physical infrastructure and technical systems, emphasizing the system's capacity to withstand and recover from external shocks. Key elements include: the rationality of the grid's topological structure, which disperses risks through looped network designs and redundant configurations to reduce the likelihood of widespread outages caused by single-point failures; the enhancement of equipment reliability, leveraging high-quality equipment and intelligent fault detection technologies to quickly locate and isolate faults, thereby minimizing their impact; and the application of intelligent technologies, such as distributed energy resources, microgrids, and energy storage systems, which not only increase the flexibility of power supply but also enhance the grid's self-healing capabilities under extreme conditions. For instance, smart grids can achieve rapid isolation of fault areas through automated control, ensuring continuous power supply to critical users.

Operational resilience pertains to the power grid enterprise's emergency response and recovery capabilities during sudden events, reflecting its decision-making efficiency and execution in crisis management. Highly effective operational resilience relies on: well-developed emergency plans, which outline response strategies for different scenarios; sufficient reserves of emergency resources, ensuring rapid deployment of equipment and personnel during a crisis; and collaborative mechanisms with stakeholders such as government and communities, ensuring resource sharing and smooth information flow. Furthermore, promptly releasing information to the public regarding outage causes and recovery progress helps alleviate social unrest. For example, during large-scale power outages caused by natural

ISSN: 2688-9323

disasters, a power grid enterprise with strong operational resilience can prioritize restoring power to critical facilities like hospitals and transportation hubs, demonstrating efficient crisis response capabilities.

Organizational resilience, on the other hand, emphasizes the power grid enterprise's organizational culture, learning ability, and adaptability, reflecting its flexibility and long-term development potential in uncertain and changing environments. Its core lies in building a learning organization by summarizing historical experiences and lessons, establishing knowledge management systems, and enhancing employee skills; focusing on talent development through professional training and technological updates to strengthen the team's ability to cope with new challenges; and promoting innovation, introducing new models such as digital transformation and green energy development. For instance, a power grid enterprise with organizational resilience can quickly analyze the causes of major accidents, optimize management processes and technical solutions, thereby in Anno.

2.2. Evaluation Dimensions of Business Environment

The business environment is the sum of external conditions affecting business operations, and the quality and efficiency of electricity supply directly correlate with the business environment's quality. This study analyzes the business environment from two dimensions: the World Bank's evaluation system and China's business environment reforms.

The World Bank's "Getting Electricity" indicator assesses the ease with which businesses obtain electricity services across dimensions such as procedural complexity, time costs, economic costs, and supply reliability. Procedural complexity measures the number of steps required to apply for electricity supply, time costs examine the number of days from application to connection, economic costs focus on the proportion of connection fees to business revenue, and supply reliability involves power outage frequency, duration, and electricity tariff transparency. These indicators, through their assessment of 190 economies worldwide, provide references for optimizing electricity services in various countries.

In China, optimizing the business environment is a crucial task for deepening reforms, with reforms in the power sector being particularly critical. In recent years, China has significantly enhanced the efficiency and quality of electricity services, laying the foundation for continuous improvement of the business environment, through: power market-oriented reforms, allowing enterprises to choose their power suppliers through the market and reduce electricity costs; increased power grid infrastructure construction, improving supply coverage and capacity, especially in remote areas; simplifying connection procedures, shortening connection times, and enhancing supply reliability; improving electricity-related laws and regulations, safeguarding enterprise rights, and promoting fair market competition; and supporting renewable energy development, advancing energy structure optimization.

3. Current Situation Analysis

3.1. Infrastructure Level

Power grid infrastructure forms the material basis of resilience, directly impacting the reliability and risk resistance of the power system. The main grid frame, as the backbone network of the power system, has a structural reliability that is crucial for stable power transmission. In recent years, the construction of China's Ultra High Voltage (UHV) grid has significantly enhanced cross-regional transmission capacity, bolstering grid redundancy through looped network designs and multi-path transmission channels. The upgrading and retrofitting of aging lines and substations have also reduced equipment failure risks. However, main grid coverage remains insufficient in some remote areas, leading to weaker resistance to

ISSN: 2688-9323

natural disasters, and the impact of extreme weather events on the grid is becoming increasingly pronounced.

The distribution network directly serves end-users, and its automation level is a key indicator of grid modernization. The deployment of sensors and automated switches enables real-time monitoring of distribution network operational status, with some advanced distribution networks significantly reducing outage times through self-healing technologies. Nevertheless, automation coverage varies considerably across regions; less developed areas often rely on traditional manual operations, and the high maintenance costs of automated equipment also pose challenges to enterprises' technical and management capabilities.

The rapid growth of distributed energy resources makes grid integration capacity an important component of power grid resilience. The introduction of distributed energy management systems has optimized the coordinated management of dispersed energy sources, and the application of microgrids has enhanced local power supply reliability. However, the intermittency and volatility of distributed energy resources pose challenges to grid stability, and some regions lack comprehensive connection standards and technical support. The rapidly increasing demand for grid connection also puts pressure on the grid's carrying capacity.

3.2. Operational Management Level

Operational management reflects a power grid enterprise's response capabilities and management efficiency during emergencies. The completeness of emergency plans directly affects crisis management effectiveness. Many power grid enterprises have established comprehensive emergency response systems covering various scenarios, for instance, Chinese power grid enterprises have formulated detailed response procedures for disaster-prone areas susceptible to typhoons and earthquakes. However, some plans lack specificity and operability when facing complex disasters and require further optimization.

Fault response timeliness is a critical indicator of operational resilience. The application of smart grid technologies and data analytics has significantly reduced fault location and isolation times, with some advanced enterprises achieving fault isolation within seconds. Yet, in rural and remote areas, due to weak infrastructure and insufficient personnel, response timeliness is lower, and the efficiency of cross-departmental collaboration needs further improvement.

Post-disaster recovery agility demonstrates a power grid enterprise's ability to quickly restore power supply after major disasters. Through modular equipment and emergency power generation vehicles, many enterprises can rapidly restore power to critical areas, and collaborative mechanisms with government and communities are also gradually being improved. Nevertheless, recovery speed is slower in some regions due to resource scarcity or obstructed transportation, and communication with users and information transparency also need further strengthening.

3.3. Policy Environment Level

The policy environment provides external guarantees for the operation and development of power grid enterprises. A sound electricity regulatory system is the cornerstone of fair and efficient market operation. China's National Energy Administration plays a crucial role in market regulation, but in some regions, regulatory enforcement is insufficient, and policy implementation is inconsistent, leading to varying service quality.

Market incentive mechanisms guide enterprise behavior through prices and subsidies. Electricity market reforms, through peak-valley tariffs and renewable energy subsidies, have reduced user costs and promoted technological innovation. However, in some regions, incentive mechanism designs are incomplete, resource allocation is uneven, and the sustainability of renewable energy subsidies faces financial pressure.

ISSN: 2688-9323

A standardization system provides unified guidance for technology and management. Standards from the International Electrotechnical Commission (IEC) and China State Grid have enhanced equipment compatibility and system stability. However, some standards lag the development needs of distributed energy and smart grids, and enforcement varies across regions.

4. Diagnosis of Power Enterprise Resilience and Business Environment Issues

4.1. Manifestations of Resilience Gaps

Insufficient resilience in power grid enterprises is particularly evident during extreme weather events, critical event power guarantees, and inter-regional power mutual aid. Extreme weather events severely challenge the grid's disturbance resistance. For example, in 2021, a typhoon ("In-Fa") struck a southern province in China, causing widespread damage to transmission lines and power outages lasting several days in some areas. This revealed issues with the wind resistance of older lines, inflexible emergency response mechanisms, and inefficient post-disaster recovery. These shortcomings indicate that power grid enterprises need to further strengthen their technical and emergency coordination.

Critical event power guarantees demand exceptionally high supply reliability. Taking the 2022 Beijing Winter Olympics as an example, the power grid enterprise successfully ensured power supply through multi-source redundancy and real-time monitoring technology. However, during similar events in some regions, issues emerged, such as insufficient specificity in emergency plans, limited temporary power supply response capabilities, and low efficiency in inter-departmental collaboration. This highlights the need to optimize plan design and technical support.

Inter-regional power mutual aid is a vital means of enhancing resilience but faces bottlenecks. China's Ultra High Voltage (UHV) grid has improved transmission capacity, yet during the power crunch in East China in the summer of 2023, inter-provincial dispatch efficiency was low. This stemmed from insufficient transmission channel capacity, immature market-based trading mechanisms, and inadequate information sharing. Improving mutual aid efficiency requires expanding infrastructure and developing digital dispatch platforms.

4.2. Constraints on the Business Environment

The quality and cost of electricity services directly impact the business environment. Electricity costs are crucial for enterprise competitiveness; in 2023, electricity bills accounted for over 20% of total costs for some high-energy-consuming enterprises in China. Although power market reforms have reduced some costs, the complex electricity pricing structure, high connection costs in remote areas, and hidden fees increase the burden on businesses. There's a clear need to simplify the electricity pricing structure and enhance charging transparency.

In terms of supply reliability, China's average power outage duration in 2023 was approximately 1.5 hours/year, which is lower than the global average but still lags leading countries like Singapore (0.2 hours/year). Key constraints include low automation levels in distribution networks in less developed regions, slow updates of aging equipment, and the impact of extreme weather. Increased investment in intelligent upgrades and equipment renewal is necessary.

Electricity service satisfaction is an important reference for the business environment. In 2023, the satisfaction rates for State Grid and China Southern Power Grid exceeded 85%. However, users in remote areas rated service efficiency and communication effectiveness lower, due to insufficient service outlets and poor information flow. The low penetration rate of digital

ISSN: 2688-9323

service platforms also limits user experience, necessitating strengthened service outlet layout and digital platform construction.

5. Policy Recommendations

5.1. Short-Term Improvement Measures

In the short term, power grid enterprises should focus on weak links to rapidly enhance system resilience and service efficiency. Addressing infrastructure vulnerability, strengthening critical nodes is a primary task. We recommend prioritizing wind and seismic upgrades for transmission lines and substations in high-risk areas, and optimizing grid structure to enhance redundancy. This will not only reduce outage risks but also lay the foundation for intelligent upgrades. Simultaneously, optimizing emergency resource reserves is crucial. We suggest establishing a regionalized reserve system, rationally distributing emergency power generation vehicles, spare parts, and repair teams, and utilizing digital platforms for dynamic dispatch. These measures can swiftly improve disturbance resistance and emergency response efficiency, ensuring a more reliable power supply.

5.2. Mid-to-Long-Term Development Paths

From a mid-to-long-term perspective, technological innovation and the construction of a robust standard system are key to building a resilient power grid. The application of digital twin technology can significantly enhance self-healing capabilities by simulating and predicting grid operational status in real-time, identifying risks in advance, and optimizing fault recovery strategies. Developing resilient grid standards is another important direction, encompassing distributed energy integration, microgrid operation, and intelligent equipment management, to meet the evolving needs of new energy and smart technologies. Furthermore, establishing a scientific resilience assessment system, which quantifies technical, operational, and organizational resilience indicators, will enable periodic evaluation of enterprise resilience levels and guide continuous improvement. These paths will provide technical and management support for the sustainable development of power grid enterprises.

5.3. Institutional Safeguard Mechanisms

Institutional safeguards provide crucial support for technological and managerial improvements. Regulatory sandboxes can offer an experimental space for power market reforms and new technology applications, allowing enterprises to test new models like distributed energy trading within a controllable range, thereby reducing innovation risks. Resilience investment return mechanisms, through tax incentives, subsidies, or special funds, can motivate enterprises to increase investment in disaster-resistant infrastructure and intelligent upgrades, ensuring economic sustainability. Establishing cross-departmental collaboration platforms can enhance information sharing and resource integration between power grid enterprises and meteorological agencies, emergency management bodies, and local governments, improving crisis response efficiency. These mechanisms will provide robust support for enhancing resilience and optimizing the business environment.

6. Conclusion

The resilience of power grid enterprises and the optimization of the business environment are crucial cornerstones for promoting stable operation of the power system and high-quality socioeconomic development. This study, through a multi-dimensional analytical framework, systematically revealed the strengths and weaknesses of power grid enterprises at the technical, operational, and institutional levels. In the short term, strengthening critical nodes and optimizing emergency resources can quickly enhance resilience and service efficiency. In

ISSN: 2688-9323

the mid-to-long term, digital twin technology, resilient grid standards, and a comprehensive resilience assessment system will drive the sustainable development of the power grid. At the institutional level, regulatory sandboxes, investment return mechanisms, and cross-departmental collaboration platforms will provide guarantees for resilience building. These measures will bolster the grid's ability to cope with natural disasters and ensure power supply for critical events, reduce electricity costs for businesses, and improve supply reliability and service satisfaction.

Looking ahead, climate change and energy transition will present both new challenges and opportunities for power grid enterprises. The growth of new energy technologies and increasing electricity demand will push the grid towards intelligent and decentralized development, while extreme weather and high user expectations demand higher standards for resilience. Power grid enterprises must continuously advance technological innovation, operational optimization, and policy coordination to build a more resilient power system. The collective efforts of government, industry, and academia will provide strong support for achieving the goals of green, low-carbon, and high-quality development.

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