Comprehensive Analysis of Key Technologies for Smart Grid

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Abstract. Smart grid tech, using advanced comm info systems to enhance power system efficiency, reliability, sustainability, transforms energy sector, supporting global energy transition sustainable achievement. This article explores smart grid dispatch system research for improved power system reliability, security, and economics. It begins by outlining key research areas: real-time monitoring and data acquisition collect operational data via sensors, forming the basis for scheduling; forecasting and optimal scheduling, leveraging historical and real-time data to predict load demand and enhance efficiency; safety and fault monitoring, promptly identifying and mitigating risks; new energy access and management improving reliability and economics; smart grid scheduling system development integrating and managing distributed energy resources. These areas are pivotal for modernizing power systems. The research in this dissertation aims to elucidate how smart grid tech drives innovation in power systems, meeting future demands while advancing sustainable energy goals. Beyond the power industry, these technologies have profound societal and environmental implications, laying a robust foundation for a sustainable, clean energy future.

Keywords: Smart grid, energy, renewable energy, technology, applications.

1. Introduction

All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. With the increasing demand for electrical power and the ongoing transformation of our energy landscape, power system scheduling faces a mounting array of challenges [1]. The category of new energy resources encompasses primarily solar, wind, hydro, geothermal, and other emerging sources. In contrast to conventional energy sources, new energy exhibits distinctive characteristics:

Renewability: New energy resources are inherently renewable, implying an endless and sustainable supply. In stark contrast, traditional energy sources like oil and coal are finite reservoirs that deplete progressively over time.

Environmental Sustainability: The utilization of new energy sources yields significantly lower levels of pollution, mitigating adverse environmental impacts. Traditional energy sources, on the other hand, are notorious for their substantial pollutant emissions during extraction and combustion processes.

Long-Term Viability: New energy sources present the potential for enduring energy solutions, effectively meeting long-term demand requirements. In contrast, dependence on traditional energy sources exacerbates pollution and poses serious threats to energy security, potentially culminating in energy crises.

In China, the primary sources of new energy production currently encompass wind power generation, solar power generation, and tidal power generation, among others. While these renewable resources offer the potential for inexhaustible energy, these resources remain beyond human control, resulting in inherent challenges such as poor stability, high fluctuations, and erratic power output. Compounded by the limited presence of domestic hydroelectric and gas power stations, the integration of new energy into the grid faces obstacles in achieving seamless compatibility.

The nexus between new energy and the concept of a smart grid is integral. A smart grid represents an advanced power system underpinned by information and communication technologies, enabling efficient, secure, dependable, and sustainable electricity transmission and distribution. The widespread incorporation of new energy sources necessitates the bolstering support of a smart grid. This is because the inherent volatility and intermittency of new energy sources introduce complexity into power system management and scheduling [2]. Through real-time monitoring, forecasting, and

advanced technical tools, a smart grid can optimize the utilization of new energy resources while enhancing the overall stability and reliability of the power grid. Simultaneously, a smart grid offers improved accessibility and management capabilities for the expansion of new energy sources, thereby facilitating the widespread adoption and utilization of these sustainable energy technologies.

Implementing cutting-edge smart grid technology can significantly enhance the reliability and safety of power dispatching and also attain real-time monitoring capabilities of the power grid. This allows for prompt and precise early warnings, thereby minimizing the occurrence of anomalies and reducing losses attributed to system failures. Consequently, the highest level of operational efficiency within the power system is achieved. In this paper, various key technology for smart grid applications will be comprehensively reviewed and discussed.

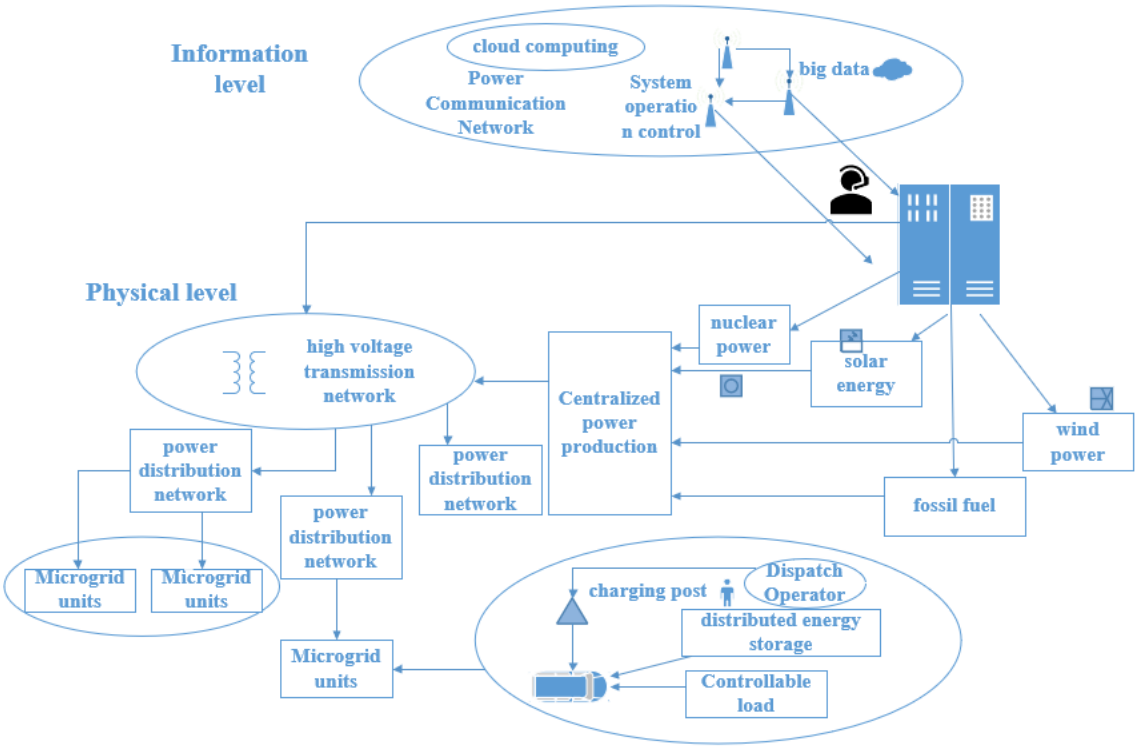


Fig. 1 Architecture of a smart grid with new energy [3].

2. Key Technologies in Smart Grid

Smart Grid is a state-of-the-art power system that utilizes advanced technologies and communication systems to improve the efficiency, reliability, and sustainability of the power system, as shown in Fig. 1 [3]. The following are some of the commonly used technologies in Smart Grid:

1) Advanced Metering Infrastructure (AMI): AMI includes smart meters and communication networks that allow utilities to monitor energy usage in real time and provide customers with detailed information on electricity consumption. This helps to better manage electricity demand and provide feedback on electricity usage data.

2) Automated Distribution Systems: This includes automated switches and equipment to quickly reconfigure the grid in the event of power failures or changes in demand. This helps to reduce outage time and improve grid reliability. 3.

3) Advanced Energy Management Systems (EMS): These systems use real-time data to optimize the operation of the power system, including generation, transmission and distribution. These systems can also help utilities better control the flow of electricity and reduce energy waste.

4) Integration of Renewable Energy Sources: Smart grids support the integration of solar, wind and other renewable energy sources into the power system. This requires advanced power electronics and control systems to ensure reliable energy delivery.

5) Smart Grid Communication Networks: In order to enable real-time data transmission and monitoring, Smart Grids require robust communication infrastructure, including wireless, wired, and Internet connectivity.

6) big data and analytics: big data analytics technologies are used to process large amounts of data from a variety of sensors and measurement devices for load forecasting, fault detection and energy optimization.

7) Energy storage technologies: Battery storage and other energy storage technologies help to balance electricity supply and demand to cope with renewable energy fluctuations and peak loads.

The combined use of these technologies can help to improve the efficiency, reliability and sustainability of power systems, while reducing reliance on fossil fuels and promoting clean energy.

Power scheduling automation primarily involves the utilization of cutting-edge technologies, including state-of-the-art computers, remote transmission, communication, and control instrumentation [4]. These automation technologies enable comprehensive remote monitoring and intelligent scheduling of power system loads. This empowers power automation monitoring and scheduling systems to concurrently manage multiple aspects of power system scheduling while providing comprehensive tracking and monitoring capabilities through a single computer interface.

In contrast, the smart grid leverages advanced sensors, communication infrastructure, and control technology to acquire real-time data from the power system, encompassing factors like power demand, grid conditions, and the operational status of power equipment. These data streams undergo analysis and processing within the smart grid system, delivering precise information and decision-making support for modern power system scheduling.

As a result, contemporary power dispatching systems necessitate the technical underpinning of smart grid technology to enhance their stability and efficiency. It is evident that the evolution of future dispatching systems is intrinsically linked to the continued advancements in smart grid technology.

Network technology constitutes an integral component of the smart grid framework, and its rapid evolution has found applications across various domains, including the domain of power dispatch automation technology. The deployment of power automation systems necessitates the incorporation of advanced computer network technology, with information technology playing a pivotal role in the seamless operation of power systems. Within the realm of power system scheduling and monitoring, the effective management of scheduling information assumes paramount importance. It is imperative to align with the requisites of the smart grid, offering robust support for the development of a scientific and rational early warning system for scheduling and monitoring. This includes the comprehensive processing and analysis of real-time scheduling data, facilitating timely and efficient control over grid operations, and ensuring the orderly and scientifically guided functioning of the entire grid.

However, it is worth noting that there are still numerous regions where the establishment of a scientifically sound early warning system for power system dispatching remains underdeveloped [5]. In addition, certain segments of the power system lack systematic management of critical information, and the structured, hierarchical management approach is yet to attain a level that aligns with the evolving scheduling requirements.

3. Advanced Technologies in Smart Grid

To improve the reliability, security and economy of the power system, as shown in Fig. 2, the research and development of smart grid scheduling system mainly includes the following aspects:

1) Real-time monitoring and data acquisition: The smart grid dispatching system collects real-time operating data of the power system, including voltage, current, power and other parameters, by installing sensors and monitoring equipment. These data can be used to analyze the operating status of the power system and load demand, providing a basis for scheduling decisions.

2) Forecasting and Optimized Dispatching: Based on historical data and real-time monitoring data, the smart grid dispatching system can use data analysis and optimization algorithms to forecast the future load demand of the power system and carry out optimized dispatching. The efficiency and

reliability of the power system can be improved by reasonably allocating generation resources and adjusting the power flow of transmission lines.

3) Security and Fault Monitoring: The smart grid scheduling system can monitor the security status of the power system in real time and discover potential fault risks in a timely manner. Once abnormalities are detected, the system can automatically take measures, such as switching power sources and adjusting loads, to ensure the safe operation of the power system.

4) New energy access and management: With the rapid development of renewable energy, smart grid scheduling systems need to study how to effectively access and manage large-scale distributed energy resources, such as solar and wind energy. This involves forecasting, controlling and coordinating new energy generation equipment to achieve maximum utilization of renewable energy and smooth access to the power system.

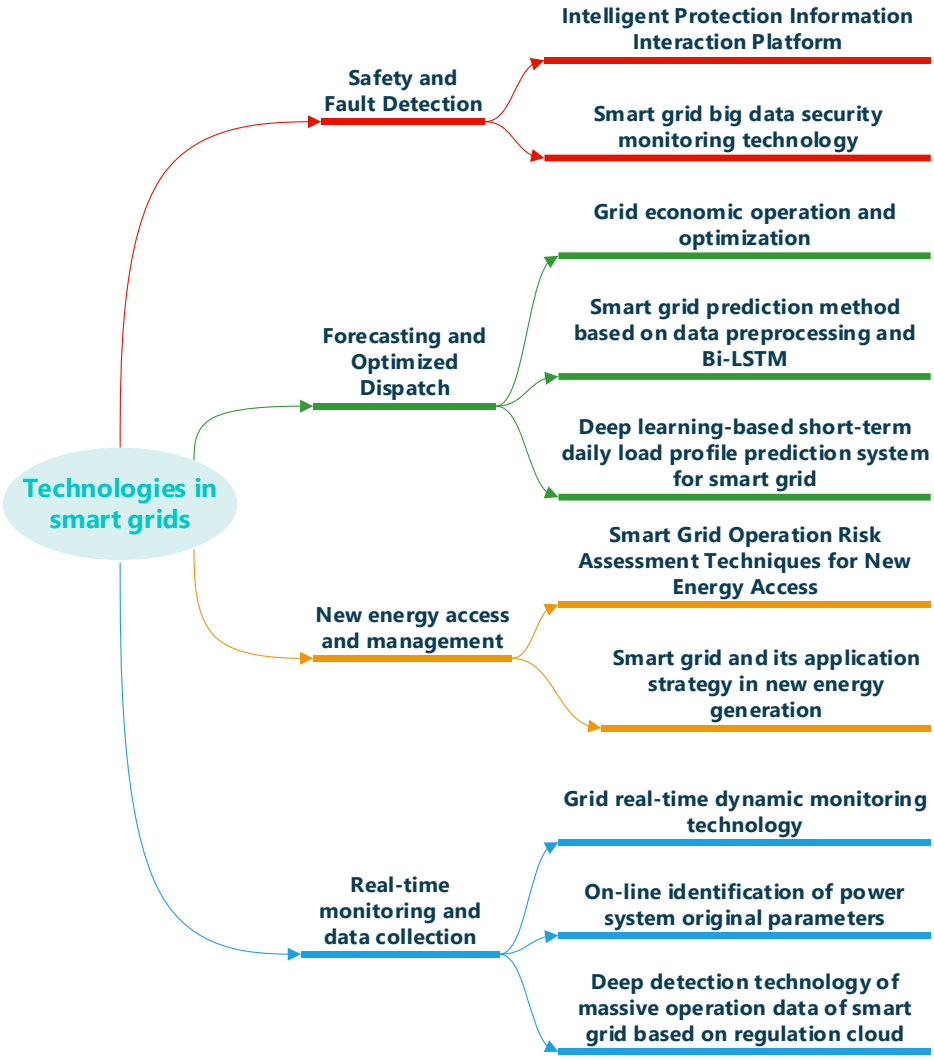


Fig. 2 Advanced technologies for smart grid [5]

3.1. Real-time Monitoring and Data Acquisition

The regulation and control of electricity hold a pivotal role in ensuring the overall stability of the power grid system, exerting a significant impact. This regulation and control, which underpins the smooth operation of the power grid, primarily takes on the form of comprehensive management and unified coordination. Through collaborative efforts and scientific deployment, it endeavors to uphold the high-quality functioning of the electricity regulation and control system, thereby enhancing the security and reliability of power dispatch.

Nevertheless, it is essential to acknowledge that the operation of power regulation and control still harbors certain security risks, which, in turn, affect system operation quality and its corresponding outcomes. This, at times, impedes the complete and effective assurance of electric energy dispatching efficiency. Considering these challenges, it becomes imperative to shift focus towards reshaping and optimizing the fundamental framework of power regulation and control, along with refining management mechanisms. Such adjustments and upgrades are necessary to guarantee the efficiency of power system operations fully and reliably.

Moreover, due consideration must be given to the critical technologies underpinning smart grid scheduling operations. This calls for in-depth analysis and research, aiming to effectively drive the stable and progressive development of smart grid systems.

3.1.1 Real-time dynamic monitoring technology for power grids

When it comes to the power system, the adoption of wide-area network dynamic monitoring technology emerges as a strategic choice, driven by its inherent advantages. Chief among these advantages is its ability to swiftly acquire vast quantities of information data in real-time. This capability plays a pivotal role in ensuring the stable and reliable operation of the power system and facilitating scientifically guided control operations, thus providing a foundational cornerstone of paramount importance.

3.1.2 On-line identification of power system original parameters

The complexity of the power system and the precision of calculations are profoundly influenced by the online parameterization of its components. This encompasses the identification of parameters for various components, including transmission lines, prime movers, excitation systems, and generators. By enabling accurate and rapid identification of these component parameters, we achieve the dual advantage of making swift, precise, and scientifically informed judgments regarding the specific operation of the power system, while also enhancing the degree of accuracy in power system security analysis.

3.1.3 Deep detection technology of massive operation data of smart grid based on regulation cloud

The application of advanced data analytics techniques to the extensive operational data generated by smart grids holds profound significance within the realm of power grid research. It necessitates an in-depth examination of the flow and transmission of grid data, followed by the implementation of data detection procedures based on the analysis outcomes.

Leveraging the conductance and impedance characteristics inherent to smart grids, an examination of the relationship between voltage and current at various grid data nodes is conducted utilizing established current calculation methods. This process allows for the calculation of current and power, derived from the active and reactive power injections of the smart grid, thus formulating nonlinear equations for the extensive grid data. Subsequently, a mathematical model is constructed.

To further analyze the data, trigonometric functions are applied, incorporating the angular frequency and operational time of the smart grid signal. This enables the determination of cosine and sine coefficients within the trigonometric functions, ultimately yielding component coefficients for the grid data. The smart grid data signals are then computed within the time domain, employing a coordinate system based on operational time and signal frequency. This comprehensive approach facilitates in-depth detection and analysis of massive smart grid data, anchored in cloud-based regulatory systems.

3.2. Forecasting and Optimal Scheduling

Smart grid forecasting and optimization scheduling technology plays an important role in the power system with the following functions:

Optimizing energy allocation: based on forecast information, power system operators can better plan and optimize the allocation of power resources to ensure the balance between power supply and demand. This helps to reduce energy waste and improve energy utilization.

Improve power system reliability: Through load and fault forecasting, the power system can identify potential problems earlier, take preventive measures, reduce outage time and improve system reliability.

Support renewable energy integration: The volatility of renewable energy is one of the challenges of power systems. Predictive technology can help system operators and power producers better adjust other generation resources to compensate for the instability of renewable energy sources and achieve a high percentage of renewable energy integration.

Economic Benefit: Power system participants in the market can use power price forecasting to optimize their power purchase strategies and thus achieve economic benefits in the market.

In summary, smart grid forecasting and optimal dispatch technologies have a key role to play in improving the efficiency, reliability and sustainability of the power system and help to address the challenges facing modern power systems, including renewable energy integration and load management. The development and application of these technologies will play an increasingly important role in the future power industry.

3.2.1 Grid economic operation and optimization technology

The effective enhancement of the economic efficiency of power grid operations stands as a critical concern for both management and a fundamental challenge to address in the future development phases of power grids [6]. To achieve this objective, several key steps are necessary.

First, given the diverse array of equipment and electrical components within the power system, it is imperative to gain a comprehensive understanding of the specific characteristics underpinning economic power supply operations. This understanding forms the basis for making scientific and well-reasoned optimizations in line with the economic operation of the power system's electrical components.

Secondly, conducting online calculations and auxiliary analyses of network losses plays a pivotal role. Such efforts enable a comprehensive assessment of actual network losses, empowering the development of specific measures and solutions aimed at ensuring the grid system's ability to operate economically and efficiently.

3.2.2 Smart grid prediction method based on data preprocessing and Bi-LSTM

The current state of short-term prediction methods in the smart grid domain can be broadly categorized into two distinct approaches: statistical methods and artificial intelligence-based methods [7].

Statistical methods, often considered classical, encompass techniques such as multiple linear regression, exponential smoothing, and the autoregressive integrated moving average (ARIMA) algorithm. These methods are rooted in the principle of establishing mathematical relationships between current and past data series, measuring their variations over time. While these methods consider time series correlations, traditional statistical methods face limitations when dealing with complex curves and struggle to achieve the required prediction accuracy, especially in the presence of non-stationary series. This limitation hinders their adaptability to the evolving requirements of modern power systems.

More recently, a novel short-term prediction framework (Bi-LSTM-DP), has emerged. Bi-LSTM-DP combines data preprocessing (DP) with Bidirectional Long Short-Term Memory (Bi-LSTM) models. This framework addresses challenges related to data quality by employing the DP strategy, which handles issues such as missing, overflowing, and noisy data. It accomplishes this by means of techniques like mean-filling and Savitzky-Golay filters, thereby significantly enhancing prediction accuracy. To further boost prediction performance, Bi-LSTM is employed to identify short-term correlations. The model's capacity to learn from sequences is expanded through the utilization of two layers of Bi-LSTM, enabling deeper understanding of data patterns.

3.2.3 Deep learning-based short-term daily load profile prediction system for smart grid

The system focuses on researching public transformers with a substantial electricity consumption base and relatively stable overall patterns. It employs Python web scraping technology and a MySQL database to establish a foundational data platform for short-term load curve forecasting [8]. This platform facilitates the efficient entry of historical load data and influencing factors' data into the database through web scraping, significantly enhancing data accessibility for load forecasting. The system further leverages NumPy, Pandas, and association analysis algorithms to address missing data and analyze the impact of various factors on load patterns. It delves into the intricate relationships between variables such as weather conditions and working day types and their influence on electricity load.

Recognizing that existing shallow neural network methods struggle to fully capture the intricacies of load data, thus limiting short-term load forecasting accuracy, the system adopts a novel approach. It employs a multivariate hybrid neural network model, which integrates Convolutional Neural Networks, Long Short-Term Memory (LSTM), and Attention mechanisms. This advanced model is designed to enhance prediction accuracy by effectively extracting and modeling the intricate features within the load data.

3.3. Grid Safety and Fault Detection

Smart grid security and fault detection technology plays a vital role in the power system with the following functions [9]:

Improving the security of the power system: security and fault detection technologies help to identify potential security problems, such as power short circuits and voltage instability, at an early stage, thus reducing the risk of accidents and improving the security of the power system.

Reducing outage time: These technologies enable rapid detection and localization of power system faults, enabling operations and maintenance personnel to take quicker action to fix problems, thereby reducing outage time and improving system reliability.

Prevent equipment damage: By monitoring the operating conditions and performance of equipment, security and fault detection technologies can help prevent equipment damage and damage-induced failures.

Improve network resilience: These technologies help to improve the resilience of the power network, i.e. the ability of the system to recover in the face of failure or attack. By quickly identifying problems and taking action, power systems can recover from failures more quickly.

Reduced operational costs: By increasing the automation and intelligence of the power system, security and fault detection technologies can reduce operational costs and the need for manual intervention.

Overall, smart grid security and fault detection technologies play a key role in ensuring the safe, reliable and efficient operation of power systems. These technologies help reduce the vulnerability of the power system, minimize the impact caused by faults, and provide better decision support to meet the needs and challenges of modern power systems.

3.3.1 Big data security monitoring technology of smart grid based on metamodel control

To address the challenge of disparate data in traditional smart grid security monitoring technology, a novel approach known as Smart Grid Big Data Security Monitoring Technology based on Metamodel Control is introduced [10].

This technology operates through a structured process involving the extraction, transformation, and loading of data, all guided by specialized metamodels: the Extracting Metamodel, the Converting Metamodel, and the Loading Metamodel. Each of these metamodels plays a pivotal role in streamlining data handling and management.

In practice, this technology dynamically assesses data using a sliding window mechanism, carefully monitoring for any abnormal patterns. Leveraging the insights gleaned from this assessment, it discerns whether the data exhibits anomalies and subsequently initiates the necessary security

measures. This comprehensive approach ensures effective big data security monitoring within the smart grid ecosystem.

3.3.2 Building an Intelligent Protection Information Interaction Platform to Optimize Relay Protection Technology

In the context of the smart grid environment, there is a pressing need to enhance the efficacy of relay protection measures. To achieve this, it is imperative to establish a robust Intelligent Protection Information Interaction Platform tailored to the specific requirements of the system. This platform should draw upon statistical theory, big data analytics, computational technology, and data coordination methodologies, among others, to furnish an abundance of information resources. These resources are essential for ensuring the secure and stable operation of the smart grid system, thereby facilitating the systematic and consistent progression of grid relay protection efforts.

Furthermore, it is essential for technicians to maintain a dynamic approach to monitoring, expanding, and upgrading the Intelligent Protection Information Interaction Platform in accordance with the evolving demands of the smart grid. This adaptability is crucial to meet the evolving protective requirements imposed by the smart grid's ongoing development and to ensure the concurrent advancement of relay protection (secondary) alongside the primary construction of the smart grid.

3.4. New energy access and management

Smart grid technologies play a pivotal role in enabling sustainable, efficient, and dependable power systems, particularly in the context of accessing and managing new energy sources [11]. These technologies are instrumental in advancing clean energy objectives and diminishing reliance on conventional energy sources, all the while ensuring the steadfastness and robustness of power provision. The ongoing evolution and implementation of these technologies are poised to steer the power sector towards a more sustainable trajectory.

3.4.1 Smart Grid Operation Risk Assessment Techniques for New Energy Access

To ensure the security and reliability of smart grid operations, it is imperative to conduct a comprehensive risk assessment of grid operations, especially considering the integration of new energy sources. A smart grid operation risk assessment methodology that incorporates the inclusion of new energy sources utilizes the Latin Hypercube Sampling-Monte Carlo Simulation (LHS-MCS) technique to extract distribution grid state information inclusive of new energy integration. It further involves developing a grid operation risk assessment index system based on the extracted information. The calculation of the weights for these risk assessment indexes is accomplished through the entropy weighting method. Additionally, determining the basic confidence distribution functions for these indexes is done using gray correlation theory. To obtain the smart grid operation risk assessment probability, multiple basic confidence distribution functions are integrated. This resulting probability represents the likelihood of risk occurrence during the operation process. Finally, the assessment of smart grid operation risk is achieved by combining the probability of risk occurrence with several basic confidence allocation functions. This comprehensive approach ensures a thorough evaluation of the security and reliability of smart grid operations, particularly in the context of new energy integration.

3.4.2 Smart grid and its application strategy in new energy generation

Equipment and technology constitute the cornerstone and essential prerequisites for effective new energy generation and grid integration. Energy suppliers must expedite the procurement of high-quality and standardized equipment. To meet the burgeoning demand for new energy on a large scale, it is imperative to establish seamless grid connections for power generation. This ensures the smooth and dependable operation of new energy sources upon grid integration.

Embracing market-oriented strategies is instrumental in achieving a harmonious energy infrastructure and continuously enhancing operational mechanisms. This approach fosters the

development and application of new energy production while significantly augmenting the utilization rate and penetration of new energy sources. Market-oriented tactics effectively mitigate regional trade barriers, thereby catalyzing the expansion of new energy consumption and addressing current challenges in new energy generation.

In tandem with the evolution of new energy technologies, it is imperative to establish and refine a comprehensive standard system. This system encompasses multi-dimensional monitoring platforms, equipment status monitoring systems, and development status monitoring platforms, among others. These systems serve as the bedrock for diverse management approaches. This system facilitate the effective capture of pertinent data and the elucidation of patterns in new energy power generation. Such insights are pivotal for better serving the needs of enterprises in this domain.

4. Future Development of Smart Grid Technology

The future outlook for smart grid technologies is highly promising, as they are poised to address various shortcomings and cater to a multitude of needs in the following areas:

1) Energy Sustainability and Cleanliness: Smart grids will continue to play a pivotal role in facilitating the seamless integration of renewable energy sources on a large scale. This integration will be complemented by enhanced capabilities in renewable energy forecasting, advancements in energy storage technologies, and the establishment of robust energy interconnection systems. These developments will not only meet the escalating demand for clean, low-carbon energy but also contribute significantly to achieving carbon neutrality and sustainable development objectives.

2) Stability and Resilience of the Power System: The evolution of smart grids will further bolster the stability of power systems through the implementation of automated control mechanisms, real-time monitoring, and fau power supply restoration, and increased resilience of the grid in the face of faults and natural disasters. lt detection technologies. This proactive approach will result in reduced outage durations, expedited

3) Security and Data Privacy: Addressing concerns surrounding data privacy and cybersecurity, future smart grid technologies will place a paramount emphasis on enhancing data protection and authentication measures to safeguard the integrity of the power system. Concurrently, legal frameworks, regulations, and industry standards will undergo refinement to establish best practices for data privacy and cybersecurity.

4) Energy Decentralization and Distributed Energy: Smart grids will exhibit improved support for decentralized energy systems, encompassing distributed solar and wind power generation. Upcoming technologies will streamline consumer participation in electricity production, fostering energy sharing initiatives and the establishment of community microgrids to cater to diverse energy requirements.

5) User Experience and Smart Homes: Future iterations of smart grids will seamlessly integrate with smart home technologies, delivering an enhanced energy management and control experience to users. Smart grid systems will have the capability to interconnect with home devices and electric vehicles, enabling real-time adjustments to energy consumption in alignment with user preferences and needs.

6) Markets and Feasibility: Anticipated developments in smart grid technologies will result in their wider deployment across various regions and markets. This expansion will offer increased choices and opportunities. Government policies and market mechanisms will actively promote the feasibility and sustainability of smart grids, thereby attracting greater investments and fostering innovation in the field.

5. Conclusion

In conclusion, the evolution of smart grid technologies in the future will strive to overcome current limitations and cater to the increasing demand for clean energy, power system reliability, and

enhanced user experiences. This ongoing advancement will steer the power industry towards a more sustainable, intelligent, and adaptable future, offering extensive benefits to society, the environment, and the economy. To sum up, the key drivers of future smart grid development will encompass the integration of renewable energy sources, continuous innovations in energy storage technologies, the widespread adoption of smart meters and metering solutions, the utilization of big data and artificial intelligence, and the establishment of the energy internet. These efforts collectively aim to realize intelligent, efficient, and sustainable power systems. The research conducted in this thesis will provide valuable insights into the transformative potential of smart grid technologies. These innovations and enhancements are essential for accommodating the future surge in electricity demand while concurrently advancing the cause of sustainable energy. It is imperative to recognize that the influence of smart grid technology extends far beyond the confines of the power industry; it has far-reaching implications for society and the environment. The findings of this research will contribute to the establishment of a sturdy framework for a sustainable and environmentally-friendly energy future.

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