Research on the Path of Artificial Intelligence Technology to Improve the Security of New Power System

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Abstract: This paper explores the application of artificial intelligence (AI) technologies to enhance the security of new power systems. It begins with an introduction to AI and new power systems, followed by a detailed analysis of the security requirements specific to these systems. The paper defines and classifies power system security, addressing the unique challenges posed by new power infrastructures, and identifies key security factors. It then discusses how AI can improve security in power systems through intelligent perception and monitoring, intelligent analysis and decision-making, network security protection, and intelligent collaboration and autonomy. The study concludes by highlighting the potential of AI in transforming the security landscape of modern power systems, emphasizing its ability to adapt to evolving threats and enhance system resilience.

Keywords: Artificial Intelligence; New Power System; Security Requirements; Intelligent Monitoring; Network Security

1. Introduction

In recent years, the application of artificial intelligence (AI) technology in new power systems has attracted wide attention, especially in the aspect of security improvement, and domestic and foreign scholars have conducted a lot of research. In the international research field, AI technology has shown significant advantages in the monitoring, regulation and optimization of power systems. European and American countries achieve accurate monitoring and fault prediction of power system operation status through deep learning, reinforcement learning and big data analysis. For example, organizations such as IEEE have repeatedly published studies exploring the application of AI-based IntelliSense and predictive models in high-proportion renewable energy grids. Some studies have greatly improved the prediction accuracy of renewable energy output and power grid load by constructing complex prediction models, and developed a scheduling algorithm based on reinforcement learning to effectively optimize power grid operation efficiency and economy[1,2]. In addition, artificial intelligence technology is also widely used in power system network security, especially the AI-based network security protection strategy proposed by the North American Electric Reliability Council (NERC) is widely adopted.

In China, the researches on the combination of artificial intelligence technology and power system is mainly concentrated in the fields of smart grid, microgrid and integrated energy system[3,5]. Through data mining and intelligent algorithms, the State Grid Corporation and other institutions realize real-time monitoring and security assessment of power grid operation status. For example, universities such as Tsinghua University in Beijing have developed intelligent analysis models for large-scale power grid data, significantly improving the efficiency and accuracy of transmission line fault diagnosis. At the same time, Chinese scholars have also explored the application of AI technology in distributed energy management, load optimization control, and power grid fault recovery, and achieved many theoretical and practical results[6,7]. In recent years, with the proposal of the "dual carbon" goal, China has launched a lot of innovative research on AI to help renewable energy access, improve system stability and optimize energy allocation[8].

Although important progress has been made in AI technology to improve the safety of power systems at home and abroad, there are still many problems and shortcomings. First of all, the lack of interpretability and applicability of the model is a major difficulty in the current research. Most AI algorithms such as deep learning models are considered "black boxes" whose decision-making processes are difficult to interpret, limiting their wide application in safety-demanding power systems. Secondly, the generalization ability of AI models is insufficient. Some algorithms perform well in small-scale experimental systems, but when applied in larger and more complex real power grids, the results are often unsatisfactory.

In addition, data quality issues also pose obstacles to the application of AI technology. There may be missing values or outliers in the large amount of data generated by power systems, which poses challenges to the accuracy and stability of AI models. Concerns about data privacy and security also limit the sharing of data between different institutions, further hindering the training and optimization of AI models. At the technical implementation level, the real-time and computational efficiency of AI algorithms still need to be improved, especially when dealing with power system emergencies, the existing algorithms may not be able to meet the needs of real-time response. Finally, insufficient support at the policy and institutional level is also a major obstacle to the full application of AI technology in power systems. Norms and standards in the power industry need to keep pace with the development of AI technology to ensure the safety and reliability of their applications.

To sum up, artificial intelligence technology has great potential in improving the security of new power systems, but to realize its full application, it needs to solve many problems such as model interpretability, data quality, real-time and policy support, which provides an important direction for future research.

2. Overview of the Application of Artificial Intelligence Technology in New Power Systems

2.1 Overview of Artificial Intelligence Technology

2.1.1 Main classification and characteristics of AI technology

Artificial intelligence (AI) is a collection of technologies that mimic human intelligent behavior and aim to perform tasks such as perception, reasoning, learning, and decision making through machines. Its core feature is data-driven and algorithm optimization ability, which is widely used in many fields. According to the technical implementation method and application scenario, AI technology is mainly divided into the following categories: Machine learning, Deep learning, Natural language processing, Computer vision, Reinforcement learning and so on[9].

2.1.2 Application status of AI in the field of energy

Artificial intelligence technology is rapidly penetrating the energy field, from energy production, transmission to consumption in all aspects, the application of AI technology significantly improves the efficiency and security of the system. It is mainly reflected in the following aspects. (1) Renewable energy prediction and optimization: the intermittency and volatility of renewable energy sources such as wind and solar pose challenges to grid stability. AI technology makes accurate prediction of meteorological data through deep learning models (such as LSTM and CNN), which greatly improves the prediction accuracy of wind power and photovoltaic output, thus reducing the impact of uncertainty on the system. (2) Power grid scheduling and optimization: AI technology realizes dynamic adjustment of power grid operation parameters through reinforcement learning and other methods to optimize resource allocation. Multi-energy collaborative regulation has also achieved comprehensive improvements in energy efficiency through AI algorithms, especially in demand response (DR) and power market operation. (3) Equipment health monitoring and fault diagnosis: AI algorithm performs well in the health management of power grid equipment, using sensor data and computer vision technology to achieve real-time monitoring and early warning of faults of transformers, lines and other equipment, improving operation and maintenance efficiency and equipment reliability. (4) User behavior analysis and load prediction: AI predicts the load change trend by analyzing the user's power consumption behavior, and provides accurate data support for demand-side management. At the same time, personalized energy services have been significantly optimized. (5) Network security: AI technology is widely used in power system network security to effectively deal with potential network attack threats through abnormal behavior detection, pattern analysis and real-time early warning system.

Artificial intelligence technology, with its powerful forecasting, optimization and decision-making capabilities, has brought profound impact to the energy field. AI technology helps address the uncertainty of renewable energy access, improves the efficiency of grid operations, and improves equipment security. However, the current application of AI technology in the energy field still faces challenges such as insufficient model interpretability, real-time and computational efficiency improvement, and data privacy protection, and the solution of these problems will further promote the in-depth application and development of AI in the energy field.

2.2 Overview of the New Power System

2.2.1 Composition and function of the new power system

The new power system is an intelligent power network system with renewable energy as the main body and full integration of information technology and modern energy technology[10]. Its core objective is to achieve efficient, clean, safe, flexible and economical production, transmission, distribution and consumption of electricity. The new power system is mainly composed of generation end, transmission and distribution system, energy storage system, user end, intelligent monitoring and scheduling system (as shown in Figure 1).

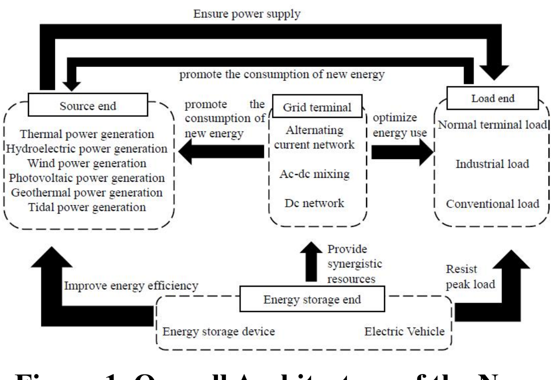

Figure 1. Overall Architecture of the New Power System

2.2.2 New demand in the context of energy transition

The general trend of global energy transformation is to reduce dependence on fossil fuels and promote low-carbon, clean and intelligent energy production and consumption. This background puts forward new demands on the power system. The proportion of renewable energy in the power system is increasing, but its volatility and intermittency pose challenges to the stable operation of the grid. The new power system needs to have stronger adaptability and flexibility, and balance the dynamic demand of the generation side and the power side through energy storage technology and intelligent scheduling optimization. Achieving carbon neutrality requires a significant reduction in the use of fossil fuels in favor of cleaner energy and electrification. New power systems need to support multi-energy complementarity, regional energy coordination and other models to improve energy efficiency. With the spread of distributed energy sources, electric vehicles and smart electrical devices, the complexity and dynamics of electricity demand have increased. The new power system needs to adopt demand response, virtual power plant and other technologies to realize real-time optimization management of users' power consumption behavior. The wide application of information technology in the field of energy promotes the transformation of power system to digital[11-13]. The deep integration of big data, artificial intelligence and Internet of Things technologies has promoted accurate prediction, dynamic control and efficient operation of power systems. In the context of high digitalization and connectivity, the power system faces increasing challenges of cybersecurity threats and natural disasters. The new power system needs to have stronger disturbance immunity and recovery ability to ensure the continuity and reliability of energy supply.

The new power system is an important innovation to meet the needs of energy transformation. It builds a clean, efficient, intelligent and safe energy supply and demand system by means of multi-energy complementarity, intelligent scheduling and flexible user management. This new system not only guarantees the efficient use of renewable energy, but also lays the foundation for achieving the global low-carbon economy and sustainable development goals.

3. Security Requirement Analysis of New Power System

3.1 Definition and Classification of Power System Security

Power system security refers to the ability of power system to maintain stable operation, effectively provide power service and quickly restore to normal state under normal and abnormal conditions. It is concerned with the stability, reliability and resilience of the power system, ensuring that the power supply is not affected by external disturbances and internal failures.

Power system security can be classified in many ways. First of all, according to the different states of power system operation, power system safety can be divided into normal safety and accident safety. Normal safety refers to the ability of the power system to ensure reliable power supply under normal operating conditions. Accident safety, on the other hand, focuses on the ability of the power system to maintain the operation without large-scale instability or outage in case of failure or abnormal conditions. Secondly, according to the characteristics of various aspects of the system, power system security can be divided into stability, reliability and recovery. Stability refers to the ability of the power system to restore to the equilibrium state and continue to operate when it is subjected to external interference or failure. Reliability refers to the ability of power system to ensure no failure in long-term operation. Restorability refers to the ability of the power system to quickly return to normal operation after a failure or major event. In addition, power system security can also be considered from the economic and environmental perspectives. While ensuring the safe operation of the power system, it should also avoid excessive economic costs and environmental pollution.

To sum up, power system security is a multi-dimensional concept, the key is that the system can flexibly cope with different operating environments and fault scenarios, to ensure the stability and reliability of power supply.

3.2 Unique Safety Requirements of New Power Systems

With the acceleration of the global energy transformation, the traditional power system is gradually transitioning to the new power system, and the security requirements of the new power system have also changed significantly. The new power systems are characterized by a high proportion of renewable energy access, the development of distributed energy sources, and the widespread use of microgrids, and these changes create new security challenges that require greater flexibility, adaptability, and resilience in the system.

3.2.1 Security challenges under high proportion of renewable energy access

In the new power system, the proportion of renewable energy such as wind and solar energy is increasing. The intermittency and volatility of these energy sources pose significant challenges to the security of power systems. First, the stability of the power supply is affected. Traditional based-load power sources such as thermal power and nuclear power usually have strong adjustment capacity, while wind power and solar power are limited by natural factors such as weather and season, resulting in uncertainty in their power generation. This instability makes the power system may have the risk of power supply shortage when the load demand is large, and then affect the safe operation of the system. Second, power system frequency and voltage control becomes more complex. Traditional power systems rely on synchronous generators to maintain the frequency and voltage stability of the system, but because of the different grid-connected ways of renewable energy generators, these power supplies usually do not have enough inertial response ability, resulting in load fluctuations or system failures, system frequency and voltage fluctuations are difficult to be effectively controlled, which may lead to a wider range of system instability.

3.2.2 Complexity of distributed energy and microgrids

Distributed energy and microgrid are important components of new power systems. Distributed energy refers to small-scale power generation facilities deployed in the user end or local area, usually including solar photovoltaic, wind power, energy storage equipment, etc. Microgrid is a small-scale power grid composed of multiple distributed energy and energy storage systems, which can achieve dual functions of independent operation or connection with the larger power grid.

While distributed energy and microgrids can improve the flexibility and self-resilience of power systems, they also increase the complexity of power systems. First of all, the problem of system coordination and control is more prominent. Distributed energy sources typically have autonomous generation and supply capabilities, and their grid-connection and dispatch require precise coordination with the central grid to prevent frequency and voltage instability caused by excess or insufficient power. In addition, because there are several independent power generation and energy storage units inside the microgrid during operation, how to realize the coordination and optimal scheduling among these units to ensure the safe operation of the system is a technical problem. Second, fault diagnosis and isolation become more difficult. Faults in traditional power systems can often be quickly detected and isolated by a central scheduling and monitoring system, but in distributed energy and microgrid environments, the occurrence of faults may be more decentralized and hidden due to changes in system topology and diversity of scale. When the microgrid is connected to the main grid, the failure can lead to more complex power flow problems, and even cause the grid to crash. Therefore, how to monitor and react quickly in real time for accurate fault location and isolation is an important security challenge faced by new power systems.

The security requirements of new power systems are significantly different from those of traditional power systems, especially in the context of high proportion of renewable energy access and distributed energy and microgrid applications. In order to ensure the safe and stable operation of the new power system, it is necessary to carry out technical innovation and improvement in dispatching control, fault diagnosis, system recovery and so on. By strengthening the intelligent monitoring and control system, the adaptive ability and flexibility of the power grid can be improved to better cope with complex power supply and demand fluctuations, and ensure the long-term safe and stable operation of the system.

3.3 Key Security Factors

The new power system is a complex system composed of traditional power network, renewable energy, distributed energy, energy storage and other emerging technologies. In the context of the energy transition, with the increasing proportion of renewable energy sources, the development of distributed generation and microgrids, the structure and operation of the power system have changed significantly, which brings new security challenges. There are many factors affecting the security of new power system, among which data quality and real-time, complexity and uncertainty of system operation, human factors and technical limitations are the key factors.

3.3.1 Data quality and real-time performance

Data quality and real-time performance are the basis to ensure the safe operation of power system. In new power systems, fluctuations in power supply and demand, access to various distributed energy sources, and deployment of intelligent devices all make data more diverse and complex. Data quality refers to the accuracy, completeness and consistency of the data, while real-time refers to the ability of the system to collect and transmit data at a fast enough speed. Whether it is the load forecasting of the power grid, the change monitoring of the landscape resources, or the operation status monitoring of the microgrid, the quality and timely transmission of data will directly affect the scheduling and control decisions of the power system. With access to a high proportion of renewable energy, data quality is particularly important. For example, wind and solar power generation has strong randomness and intermittence, and accurate meteorological data and real-time power generation data are crucial for predicting power generation. If the data is biased or delayed, it can lead to inaccurate load scheduling, which can lead to oversupply or undersupply of power, and even cause the frequency and voltage instability of the system. In addition, inaccuracies in data can also affect the health monitoring of equipment in the power system, resulting in the failure of early warning of equipment failure.

3.3.2 Complexity and uncertainty of system operation

The operation of new power systems involves multiple energy sources, complex grid structures and dynamic operating environments. As the proportion of renewable energy access increases, the operation of the power system is more dependent on flexible scheduling strategies and refined real-time control. The complexity of the system comes from many aspects, the first is the complexity of the grid structure. Traditional power systems are usually single and centralized, while in new power systems, microgrids, distributed energy and energy storage devices comprise a multi-level and multi-node structure, which makes the operation and scheduling of power grids more complex. Second, uncertainty is one of the important challenges faced by new power systems. Renewable energy generation has high uncertainty, solar radiation intensity and wind speed changes directly affect the power generation capacity. In addition, fluctuations in electricity demand are also a factor that cannot be accurately predicted, and these uncertainties increase the difficulty of operating the system. For example, in low wind speed or rainy days, the power generation of wind and solar energy may drop significantly, and the traditional power supply may not be replenished in time, resulting in insufficient power supply. Therefore, how to deal with these uncertainties through accurate load forecasting, real-time scheduling and flexible energy storage management is an important issue to ensure the safety of new power systems.

3.3.3 Human factors and technical limitations

Although the new power system integrates a large number of advanced technologies, such as smart grid, artificial intelligence, big data, etc., human factors and technical limitations are still factors that cannot be ignored to affect the security of the power system.

First of all, human factors play an important role in the design, operation and maintenance of the system. The safe operation of a power system requires a large number of real-time monitoring and scheduling decisions, which often rely on the judgment and reaction of the operator. If the operator's judgment is flawed, or if the wrong decision is made in a high-pressure environment, it may lead to system security problems. In addition, the maintenance and emergency response of the system are also the key links that human factors affect the system security. As the equipment and technology of new power systems are constantly changing, the knowledge update and skill training of operators are crucial, and untimely training and technical adaptation may cause the system to react slowly when faced with complex failures. Secondly, the technical limitation is also an important problem facing the current new power system. Although the new power system uses many advanced technologies, these technologies still have some limitations. For example, existing grid architectures and scheduling algorithms may not be able to respond quickly to the dynamic changes of large amounts of renewable energy, and the adoption of smart grid technologies still faces high cost and technology maturity issues. At the same time, although the application of big data and artificial intelligence has made certain achievements in forecasting and scheduling, how to process a large amount of data and make efficient decisions in a very short time is still a technical problem. Due to the incompleteness and limitation of technology, the system's ability to deal with sudden failure or complex changes is limited.

The security of new power system is affected by many factors, among which data quality and real-time, complexity and uncertainty of system operation, human factors and technical limitations are the key factors. In order to ensure system security, it is necessary to strengthen the accuracy and timeliness of data acquisition and transmission, improve the flexibility of system scheduling, overcome the challenge of uncertainty, and strengthen the training of operators and technical updates to promote technological innovation and equipment optimization.

4. Artificial Intelligence Technology to Improve the Safety of the Power system Path

With the advance of energy transformation, the power system is changing from the traditional centralized grid to the new smart grid and distributed energy system. This transformation makes the power system face more complex operating environment and security challenges, such as frequency fluctuations, voltage instability, equipment failures, and energy supply uncertainties. Therefore, improving the safety of power system has become an important task in today's power field. Artificial intelligence (AI) technology, with its advantages in data analysis, pattern recognition, prediction and decision support, is becoming one of the key technologies to solve the security problem of power systems. AI can improve the security of the power system through multiple paths, and the following will be discussed in detail from four aspects: intelligent perception and monitoring, network security protection, intelligent collaboration and autonomy.

4.1 Intelligent Perception and Monitoring

Intelligent perception and monitoring is the basis of artificial intelligence to improve the safety of power system. The security of power system depends on the accurate perception and real-time monitoring of the system state. Only by understanding the operating state of the system, can the correct scheduling decision and fault response be made. Traditional monitoring systems usually rely on manual detection and traditional sensors, although they can meet basic needs, but in the face of increasingly complex power system structure, especially a large number of distributed energy sources and microgrid access, traditional monitoring methods are difficult to meet the requirements of accuracy and real-time.

Artificial intelligence technologies, especially machine learning, deep learning, and big data analytics, can greatly improve the perception of systems through intelligent perception and monitoring. First, AI can conduct comprehensive and real-time monitoring of the operating status of the power system through advanced sensors and smart meters. These sensors can not only detect conventional parameters such as voltage, current, frequency, but also monitor environmental factors such as temperature, humidity, and pressure of the equipment, thus assessing the health of the equipment in real time. Secondly, based on big data technology, AI can conduct real-time analysis of the large amount of data collected to dig out potential regularities and anomalies. For example, the use of machine learning algorithms to analyze equipment operation data can detect the potential risk of equipment failure early and predict the remaining life of the equipment, so as to achieve preventive maintenance and reduce the failure rate. Especially in the context of renewable energy access, AI technology can analyze the volatility of solar energy, wind energy and other energy sources in real time, provide accurate predictions, and provide scientific basis for power system scheduling and operation. Finally, the application of intelligent perception and monitoring is not limited to the health monitoring of equipment, but can also be extended to the condition monitoring of the entire power system. For example, AI can analyze the load changes, power fluctuations, frequency fluctuations, etc., of the power system, evaluate the stability of the system in real time, and find possible risk points in time, so as to avoid a wide range of power outages or system instability.

4.2 Intelligent Analysis and Decision-making

Intelligent analysis and decision making is another important application of AI technology in improving the safety of power systems. With the continuous expansion of the scale of power systems, especially the widespread application of distributed energy, microgrids and smart devices, the operation of power systems is becoming more and more complex. Traditional scheduling and decision-making methods are difficult to deal with this complex system. The introduction of AI technology provides a new idea for intelligent decision-making of power system. Through intelligent analysis and decision-making technology, AI can quickly process data from different power equipment and distributed energy sources, conduct comprehensive analysis, find potential safety hazards, and propose reasonable solutions. Taking power load forecasting as an example, AI technology can accurately predict future load demand by analyzing historical load data, weather changes, seasonal changes and other factors. This is very important for the power system scheduling, which can help the scheduler to take effective scheduling measures before the system overload and avoid the system failure caused by overload. In addition, AI can combine real-time data from the power system to make scheduling decisions based on optimization algorithms. For example, in a multi-energy environment, AI can automatically optimize the energy distribution scheme according to the power generation situation of various energy sources, the state of energy storage equipment, the load demand of the grid and other factors, so as to ensure the supply of electricity, avoid energy waste, and improve the overall efficiency of the system. When the power system fails, AI can also automatically determine the type and location of the fault, quickly locate the fault point, and guide maintenance personnel to take the most effective repair measures to reduce the system outage time and improve the recovery speed.

4.3 Network Security Protection

With the rapid development of information technology, the digital and networking degree of power system is getting higher and higher, and the wide application of smart meters, automation equipment, cloud computing platform and other equipment makes the power system become more intelligent, but also faces more complex network security risks. Network attacks, data leaks, equipment tampering and other security issues pose serious challenges to the stable operation of the power system. Although the traditional network security protection method can provide a certain guarantee, it is difficult to meet the needs of system security in the face of complex and changeable network attacks.

In this context, artificial intelligence technology is widely used in the network security protection of power systems. AI technology can detect abnormal behavior in the network and identify potential security threats through real-time monitoring and intelligent analysis. For example, using machine learning algorithms, AI can monitor communication traffic in real time in the network of a power system, analyze whether there is abnormal network activity or data flow, and detect and warn of cyber attacks in time. AI technology can also improve the ability to identify unknown attacks through adaptive learning and pattern recognition. While traditional firewalls and intrusion detection systems often rely on known attack patterns, AI is able to constantly update the identification model through training and learning to respond to new cybersecurity threats. Especially in the critical infrastructure of the power system, such as power plants, substations, etc., AI technology can monitor the operating status of the system in real time and prevent external attackers from controlling equipment or tampering with system parameters through network means. In addition, AI can also be combined with blockchain technology to further improve the network security of the power system. Blockchain technology can provide decentralized data storage and immutable transaction records, which provides a new means of network security protection for power systems.

4.4 Intelligent Collaboration and Autonomy

With the increasing complexity of power system, especially in the context of distributed energy and microgrid, the operation and management of power system not only needs central control, but also needs to have a certain degree of self-adaptation and self-recovery ability. Intelligent cooperation and autonomy is another important way to improve the security of power system. AI technology can give the power system autonomy, so that when the system is faced with failure or external impact, it can automatically take appropriate response measures, reduce manual intervention, and improve the reliability and resilience of the system. In the scenario of distributed energy and microgrids, AI technology can achieve intelligent collaboration to ensure coordination and cooperation between various energy units. For example, when the power demand is high, the energy storage device in the microgrid can automatically adjust the output to meet the load demand. When renewable energy generation is high, energy storage devices can automatically store excess electricity for use during peak demand. In addition, AI can coordinate the power exchange between the microgrid and the main grid, enabling two-way flow and improving the overall efficiency of the system. In the event of a failure, AI can quickly identify the type of failure through intelligent perception and real-time analysis, automatically adjust the power flow, and dispatch standby equipment for recovery, ensuring the continuity of the power system. For example, in the event of a local failure, the smart grid can ensure the power supply of other areas by regulating the power output of other areas, reducing the scope of power outages.

5. Conclusion

Artificial intelligence technology provides a variety of effective paths for the security improvement of power systems, including intelligent perception and monitoring, intelligent analysis and decision, network security protection, intelligent collaboration and autonomy. The introduction of AI not only improves the operation efficiency of the power system, but also enhances the system's ability to respond to various emergencies. In the future, with the continuous development of artificial intelligence technology, the security of the power system will be more comprehensively guaranteed, and it will be able to better cope with the complex and changeable operating environment to ensure the reliable supply of power.

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