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Application of Digital Twin Technology in Smart Grids

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Abstract: With the rapid development of smart grids, digital twin technology, as a crucial technology for smart grid construction, has garnered widespread attention. Applying digital twin technology to smart grids enables the stabilized operation, comprehensive perception, and networked connection of grid construction. Through digital twin technology, the projection of physical smart grid states into the virtual space can be achieved, promoting the development and transformation of smart grid construction management models. Based on this, this article takes digital twin technology as its entry point, explores smart grids under digital twin technology, and discusses the application of digital twin technology in smart grids in conjunction with various aspects.

1. Introduction

With continuous social development and increasing energy demands, the smart grid represents a significant stage in the evolution of traditional power grids towards intelligence, digitalization, and interconnectivity. It has become the goal of power industry development in the new era and will become the core of future power systems. Digital twin technology, a recently emerging technology, is one of the important means for constructing smart grids [1]. It has received widespread attention due to its characteristics such as informationization, adaptability, and scalability. Digital twin technology can combine the physical and mathematical models of real systems to achieve virtual-real integration, providing new means and ideas for real-time simulation, visualization, optimization, and decision-making. Applying digital twin technology to smart grids can improve the level of refined grid management, optimize grid operation modes, improve grid safety, stability, and reliability, and achieve interactive collaboration in supply and demand-side management. Therefore, research on the application of digital twin technology in smart grids has important theoretical and practical significance.

2. Overview of Digital Twin Technology

A digital twin refers to a high-fidelity, dynamic model of a physical entity built in a virtual space through digital means. It utilizes real-time data to drive simulation, analysis, and optimization, thereby enabling full lifecycle management of the physical entity. Its core elements are "virtual-real mapping, dynamic interaction, and intelligent decision-making," representing a bidirectional, real-time interaction between the physical and digital worlds. The concept of digital twins can be traced back to 2003, proposed by Professor Michael Grieves of the University of Michigan, initially for product lifecycle management (PLM) [2]. With the development of technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), and cloud computing, digital twins have gradually expanded from manufacturing to multiple fields including smart cities, healthcare, transportation, and energy. In the early 2010s, NASA first used digital twins for spacecraft health monitoring, marking the technology's entry into engineering applications. After 2017, Industry 4.0 and smart manufacturing drove digital twins to become a key technology, with Germany's "Industry 4.0" and the United States' "Industrial Internet" both listing it as a core supporting technology. From 2020 to the present, digital twins have combined with 5G, edge computing, the metaverse, and other technologies, entering a stage of rapid development and are widely used in areas such as smart energy, autonomous driving, and smart cities.

The realization of digital twins relies on the convergence of multiple cutting-edge technologies. In terms of multi-dimensional modeling technologies, these include geometric modeling (constructing 3D models of physical objects through technologies such as CAD and BIM), physical modeling (establishing simulation models based on physical laws), and data-driven modeling (using machine learning to learn system behavior from historical data)[3]. Real-time data acquisition and transmission technologies mainly rely on the Internet of Things (collecting data through sensors, smart meters, SCADA systems, etc.) and 5G and edge computing (ensuring real-time data synchronization). Simulation and optimization technologies involve real-time simulation tools and optimization algorithms, while artificial intelligence and big data analytics are used for fault prediction, health management, and data fusion. Visualization and human-computer interaction technologies include 3D visualization and AR/VR applications.

Digital twins have demonstrated significant application value in several fields. In the field of smart manufacturing, Boeing uses digital twins to shorten aircraft development cycles, and Siemens' "digital factory" achieves dynamic optimization of production processes. In smart city applications, Singapore's "Virtual Singapore" simulates traffic flow to optimize traffic light control, and digital twin cities can also be used to predict the impact of natural disasters. In the medical and healthcare field, digital twin technology is used for surgical planning and drug development. In energy and power systems, GE uses digital twins to predict wind turbine blade wear, and the State Grid Corporation of China builds digital twins of substations to achieve remote monitoring.

3. Key Needs and Challenges of Smart Grids

As an upgraded evolution of traditional power systems, smart grids aim to achieve the safe, efficient, and environmentally friendly operation of power systems through digital and intelligent technologies. Their core characteristics include self-healing capabilities, interactivity, compatibility, and high efficiency. With the large-scale integration of renewable energy sources, the widespread adoption of power electronic devices, and the diversification of user-side demands, modern power grids are facing unprecedented complexity and uncertainty. This makes the construction of smart grids both an urgent need and a daunting challenge. From a technical perspective, the first problem smart grids need to solve is the real-time monitoring and control of the system. The minute-level data acquisition cycle of traditional SCADA systems can no longer meet the dynamic regulation needs of power grids with high penetration of new energy sources. It is necessary to establish wide-area measurement systems (WAMS) with millisecond-level response and distributed control architectures. In terms of fault handling, smart grids need to have self-healing capabilities to quickly locate, isolate, and restore power supply. This places extremely high demands on the accuracy of fault detection algorithms and the reliability of communication networks. At the operational optimization level, with the increasing proportion of distributed generation, the power grid needs to shift from traditional centralized dispatching to coordinated optimization of source, grid, load, and storage. This requires the establishment of a new dispatching system that considers multi-time scales and multi-objective optimization [4].

From the macro perspective of energy transition, the biggest challenge facing smart grids is the system stability problem brought about by high proportions of renewable energy integration. Output fluctuations of intermittent energy sources such as wind power and photovoltaics can cause grid frequency deviations and voltage fluctuations. When the penetration rate of new energy exceeds 50%, the system's insufficient inertia support will lead to a significant decrease in frequency regulation capability. To solve this problem, smart grids need to deploy advanced prediction technologies (such as ultra-short-term power forecasting based on deep learning), flexible regulation resources (such as energy storage systems and demand response), and new power electronic devices (such as virtual synchronous machines). In terms of grid planning, traditional deterministic planning methods are difficult to adapt to the uncertainty of new energy sources. It is necessary to introduce probabilistic planning theories and digital twin technology for multi-scenario simulation. In addition, the access of massive distributed energy sources transforms the distribution network from a passive network to an active network. Changes in power flow direction may lead to protection misoperation, voltage over-limits, and other problems. This requires reconstructing the protection control strategies and voltage regulation mechanisms of the distribution network.

The evolution of user-side demands also brings new challenges to smart grids. With the popularity of new loads such as electric vehicles and smart homes, load characteristics exhibit high randomness and impulsiveness. For example, large-scale uncoordinated charging of electric vehicles may cause overlapping evening peak loads. To address this challenge, smart grids need to establish a sound demand response mechanism to guide user electricity consumption behavior through time-of-use pricing, direct load control, and other means [5]. At the same time, the deepening of power market-oriented reforms requires grid operation to have greater transparency and economic efficiency. It is necessary to establish a technical support system that supports real-time electricity prices, blockchain transactions, and other new business models. In terms of information security, as the degree of grid digitization increases, the harm that network attacks can cause is significantly increased. The 2015 cyberattack on the Ukrainian power grid that caused a large-scale power outage serves as a warning that we must establish a multi-layered defense network security system, including key technologies such as device authentication, data encryption, and anomaly detection.

At the technical implementation level, the primary bottleneck facing smart grids lies in the integration and coordination of heterogeneous systems. Existing power grids encompass various communication protocols (such as IEC 61850, DNP3, and Modbus), equipment deployed across different eras, and automation systems constructed in a decentralized manner. The interconnection and interoperability between these heterogeneous systems pose significant obstacles. Constructing a unified cyber-physical system (CPS) necessitates resolving a series of technical challenges, including protocol conversion, data standardization, and time synchronization. Furthermore, the volume of data generated and required to be processed by smart grids is growing exponentially; a single provincial-level power grid can generate data volumes reaching terabytes daily. This places extremely high demands on data storage, computation, and analysis capabilities. A hybrid architecture combining edge computing and cloud computing may be an effective approach to address this issue, but it requires careful design of data diversion strategies and computational task allocation mechanisms. At the algorithmic level, traditional physics-based analytical methods struggle to handle the highly nonlinear problems in power grids. Combining data-driven methods is necessary, but the interpretability and generalization ability of machine learning models still require further improvement.

From an economic perspective, smart grid construction faces the challenge of long investment return cycles. Infrastructure such as advanced metering infrastructure (AMI) and distribution automation requires substantial investment, but their benefits often take years to materialize. Especially on the distribution network side, the vast number and wide distribution of equipment necessitate a careful evaluation of the cost-benefit ratio of intelligent upgrades. Moreover, the introduction of new technologies and equipment may bring additional operational and maintenance costs; for instance, the failure rate of power electronic equipment is generally higher than that of traditional equipment, and repairs are more complex. These factors place significant financial pressure on power companies in promoting intelligent transformation, requiring the establishment of reasonable cost-sharing and incentive mechanisms.

Looking ahead, the development of smart grids needs to focus on breakthroughs in the following areas: first, building a more open and flexible architecture that supports the plug-and-play functionality of various new devices and services; second, developing more powerful collaborative control algorithms to achieve optimized allocation of multiple resources across a wide area; third, establishing a more complete standards system to promote the interconnection and interoperability of equipment and systems from different manufacturers; and finally, developing more advanced security protection technologies to ensure the cybersecurity of critical infrastructure. Digital twin technology can play an important role in these areas by building a virtual representation of the power grid, enabling real-time monitoring of operating status, early warning of failures, and simulation verification of control strategies, providing strong support for the construction and operation of smart grids.

Overall, the construction of a smart grid is a complex system engineering endeavor, requiring the comprehensive consideration of technical feasibility, economic rationality, and implementation viability. While facing numerous challenges, smart grids, through technological and institutional innovation, will inevitably promote the power system towards a cleaner, more efficient, and more reliable direction, providing crucial support for energy transition and the achievement of carbon neutrality goals. In this process, the in-depth application of emerging technologies such as digital twins will play an increasingly important role, helping power systems cope with the growing complexity and uncertainty challenges.

4. Applications of Digital Twins in Smart Grids

4.1 Applications at the Smart Grid Device Layer

The application of digital twin technology at the device layer is entirely based on two technologies: refined digital modeling and integrated digital modeling. These two technologies serve as the blueprint for constructing the digital twin model corresponding to the smart grid. Its value lies in accurately projecting the real-time status and information of the physical entity devices of the grid onto the digital twin model, thereby achieving visualization of the device status.

(1) Achieving Friendly Interaction On-Site and Remotely

This application considers the differences present in on-site interaction scenarios. It establishes a dedicated smart IoT terminal based on physical object coding and labeling technologies such as radio frequency identification (RFID) and QR codes. This ensures a one-to-one correspondence between the physical devices and the different structures and data in the model. It also enables the perception and detection of all element-related data of the device. In this case, only accessing the digital twin model is needed to obtain physical entity smart grid operating data remotely, thereby determining the grid's actual operating status and other relevant information [3]. This application also supports autonomous equipment fault diagnosis and early warning. After matching the corresponding drivers, the digital twin model supports synchronized operation with physical equipment, enabling equipment operating status evaluation and fault prediction. Furthermore, it allows for continuous iterative optimization of model data, providing data support for the formulation of subsequent operation and maintenance strategies.

(2) Application to Equipment Lifecycle Management

After completing the refined digital twin model of smart grid equipment, it is necessary to input massive amounts of smart grid-related data into the digital twin model. By classifying, slicing, layering, and organizing the data, device data content is recorded in real-time in a multi-dimensional manner. Based on this, integrating big data analytics technology and AI learning algorithms enables the analysis of historical and real-time operating conditions of the equipment, thereby predicting the future operating conditions of the equipment to a certain extent. This, combined with physical object coding and labeling technology, allows for intelligent lifecycle management of structures and equipment in the smart grid. The application of digital twin technology at the device layer can significantly improve the accuracy and effectiveness of equipment status assessment, enabling the transformation of maintenance work from preventive to predictive, reducing unnecessary on-site operations, and improving the accuracy of equipment status assessment and fault diagnosis.

4.2 Applications at the Smart Grid Network Layer

The application of digital twin technology at the grid network layer can provide guidance for online analysis and decision-making of the grid and guide the grid to achieve autonomous planning.

(1) Providing Personalized Support for Power Grid Operation Risk Assessment

There are certain differences in the operational reliability performance of each device and component in the smart grid. Therefore, after collecting their specific data and inputting it into the digital twin model, the model can be iteratively optimized and predicted using artificial intelligence algorithms. At the same time, cluster analysis or other analysis methods can be used to analyze the historical data and future prediction data in the model, and the analysis results and processing measures can be fed back to the physical entity power grid, so as to realize the aid-based risk assessment of smart grid lines and equipment and provide data support for the planned management of the power grid.

(2) Optimizing Power Grid Dispatching Operations

Compared with traditional power grid automated dispatching work, this optimization brought about by digital twin technology increases the consideration of power grid equipment operating status and related factors. By integrating equipment operating status parameters, environmental parameters, and other real-time data, and inputting them into the smart grid digital twin model, the dispatching model can be iteratively optimized with the help of artificial intelligence algorithms and machine learning algorithms, so as to predict the operating status of the smart grid at specific time points in the future and improve the dispatching management department's understanding of the power grid operating status and the effectiveness of decision-making.

4.3 Applications in the Business Layer of Smart Grids

The smart grid model built upon digital twin technology enables data interoperability, sharing, and visualized interaction. The digital model supports applications in various departments, including smart grid infrastructure construction, equipment management, safety supervision, dispatch, marketing, and many others, thereby facilitating business collaboration and data interconnection among different business departments.

(1) Applying digital twin technology to batch business processing in distribution transformer areas

With the support of physical ID coding and labeling technology, artificial intelligence, and machine learning algorithms, the digital smart grid model constructed with digital twin technology can ensure that all data aspects possess highly unified characteristics. It also guarantees that the data supports large-scale editable operations. This implies that all business departments in the entire distribution transformer area can selectively apply data from the digital twin model according to their own business needs, thereby providing business support for the subsequent construction and improvement of the distribution transformer area. For example, the safety supervision department can access the transformer area's digital twin model to conduct intelligent safety management and fault handling throughout the smart grid's lifecycle. The infrastructure department can add other elements to the original digital twin model while simultaneously advancing the construction of the physical smart grid and the digital twin model.

(2) Providing support for operation and maintenance (O&M) services

The digital twin model of the smart grid, when combined with on-site and remote-friendly interaction of equipment, autonomous equipment defect diagnosis, and fault early warning applications, can provide functional support for fault early warning and remote O&M of the physical smart grid. Furthermore, safety operation simulations for equipment installation can also be realized in the digital twin model. This can be presented visually to O&M personnel, matching specific locations and requirements of safety operation installations, and providing early warnings against violations, thereby providing specific content and safety control requirements for O&M services as a reference and ensuring the safe and normal execution of O&M activities.

4.4 Applications in Intelligent O&M of Power Grids

Power network systems are complex in structure, composed of numerous devices with high precision requirements. Different devices have different operation and maintenance needs due to variations in type and structure, which brings great challenges to the staff. The application of digital twin technology can reverse the difficulty of equipment O&M and build a highly efficient and systematic O&M process. Specifically, digital twin technology constructs a real-virtual mapping, displaying a virtual model, and realizing panoramic displays and various function demonstrations through the virtual model, serving as the foundation for enhancing actual equipment operations. The virtual scenario can complete the operating conditions of power grid transportation, distribution, etc., and perform simulation of fault simulation and solution measures. In addition, the system can provide personnel with professional training services, such as demonstrating the power grid system repair method guidance process with the help of a three-dimensional system, providing technical reference for the staff. Digital twin technology can also rely on AI algorithms to analyze traditional data resources and provide management decisions. For example, in the digital twin technology platform, it can sense fault information and maintenance processing data transmitted from other twin platforms, and rely on virtual reality panoramic perception to integrate a large amount of data resources, actively handle fault problems, sense data and feedback information, intelligently judge fault types and locations, and provide solutions. At the same time, the solutions proposed by the system are applied to the virtual model and tested through practice to provide staff with processing basis. In addition, the technology platform can also determine the impact scope of the fault and the estimated power recovery time, and notify affected customers to provide customers with a new service experience. In short, digital twin technology has the characteristics of intelligence and dataization. It can display the twin function and integrate the power network system architecture to build a virtual power grid system model. The actual effect of maintenance can be improved through intelligent data acquisition, intelligent fault problem identification, intelligent maintenance decision-making, and model synchronization strategies. Because of this, digital twin technology can be regarded as the core technical content for realizing the digital transformation of the power grid system, and it is also an important technology for promoting the power grid system towards informatization, digitization, and truly awakening a large amount of data resources to realize efficient interaction and other intelligent development directions. Through digital twin technology, the power grid system can upgrade the network system and implement observation, description, synchronous demonstration, intelligent control, efficient interaction, self-healing, and bearing capabilities. In the intelligent O&M of power grids, the application of digital twin technology is of great significance for building a safe and stable power grid system development environment, reducing the development costs of power companies, and improving the operational efficiency and safety of enterprises.

5. Conclusion

In the new era, digital twin technology has become a crucial support for the digital development of power grid systems. Combining technologies such as big data, cloud computing, AI algorithms, and artificial intelligence, digital twin technology constructs virtual models of power grid systems, enabling virtual-real mapping and connection. This allows for real-time monitoring of the operational status, maintenance conditions, and other aspects of real-world power grid systems, reducing the use of manual resources while enhancing system operational stability and security. Consequently, digital twin technology provides new technical pathways and methodological support for the construction of smart grids. As the technology continues to mature and its applications are further advanced, digital twins will undoubtedly become a core enabling technology for driving the digital transformation of power grids, making significant contributions to building a clean, low-carbon, safe, and efficient modern energy system. In the future, continuous efforts should be made to strengthen technological innovation and practical exploration, fully leveraging the empowering role of digital twins in the development of smart grids.

Reference

[1] Wang Zhipeng, Lan Feng, Zhao Yong, et al. Discussion on the Application of Digital Twin Technology in a Strong Smart Grid [J]. Electrical Applications, 2021,40 (6) : 111-115.

[2] Alicia Tang Yee Chong, Moamin A Mahmoud, Fung-Cheng Lim, et al. A review of smart grid technology, components, and implementation[C]//2020 8th International Conference on Information Technology and Multimedia (ICIMU). IEEE, 2020: 166-169.

[3] Wu Yun-na, Jian Chen and Li-rong Liu. Construction of China's smart grid information system analysis[J]. Renewable and Sustainable Energy Reviews, 2011, 15(9): 4236-4241.

[4] Jafari M, Kavousi-Fard A, Chen T, et al. A review on digital twin technology in smart grid, transportation system and smart city: Challenges and future[J]. IEEE Access, 2023, 11: 17471-17484.

[5] Li Peng, Xi Wei, Cai Tiantian, et al. The Concept, Architecture and Key Technologies of Digital Power Grid [J]. Proceedings of the CSEE, 2022, 42(14): 5002-5017.