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Application Exploration and Prospect Analysis of Electrical Engineering Automation in the Field of Smart Grids

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ABSTRACT

This paper expounds the definition, characteristics, advantages and current development status of smart grids, analyzes the basic concepts, technical systems, application scopes of electrical engineering automation as well as its application and actual effects in traditional power grids, conducts an in-depth study on the specific application of electrical engineering automation in smart grids, and looks forward to its development prospects in the field of smart grids, In addition, this article also conducts in-depth discussions on how electrical engineering automation can be deeply integrated with traditional power grids, contributing to the ultimate promotion of the efficient development of the energy system and the prosperity of the social economy.

KEYWORDS

Mechanical Engineering; Manufacturing Technology; Electrical Automation.

1. INTRODUCTION

Against the backdrop of in-depth integration between global energy transition and digital technologies, smart grids, as the core development direction of modern power systems, are undergoing a profound transformation from traditional power networks to highly automated, information-based, and interactive systems. In this historic process of construction and development, electrical engineering automation technology undoubtedly plays an irreplaceable key role. By systematically introducing advanced intelligent control algorithms, real-time monitoring sensor networks, dynamic optimization models, and intelligent decision support systems, it has fundamentally changed the operation mode of power systems—not only realizing automated collaborative operation across the entire chain of power generation, transmission, distribution, and consumption but also promoting intelligent management and high-efficiency operation of power networks, thus providing comprehensive technical support for the large-scale construction and stable operation of smart grids.

Specifically, the application value of electrical engineering automation technology manifests in multiple dimensions: at the safety level, real-time fault diagnosis and self-healing control technologies can significantly enhance the power system's ability to respond to sudden faults and reduce the risk of large-scale power outages; at the economic level, load forecasting and dynamic scheduling algorithms enable precise allocation of energy resources, effectively reducing power generation costs and transmission losses; at the environmental protection level, intelligent grid-connection control of new energy generation can improve the absorption rate of clean energy such as wind and solar power, thereby reducing environmental pollution caused by traditional fossil energy consumption. These technical advantages collectively drive smart grids toward greater resilience, efficiency, and sustainability[1].

It is worth noting that although the application of electrical engineering automation technology in smart grids has achieved phased results—such as large-scale implementation in fields like distribution automation and demand response—its technical potential remains to be further explored when facing new challenges such as grid volatility caused by high-proportion new energy integration, the complexity of collaborative control in cross-regional power interconnection, and data security and privacy protection. Meanwhile, it also contains vast opportunities for innovation. Based on this, this paper focuses on specific application scenarios of electrical engineering automation in smart grids, conducts in-depth analysis of current technical bottlenecks, and carries out a systematic discussion on future development prospects.

2. OVERVIEW OF SMART GRIDS

As a landmark product of the integration of the global energy revolution and digital technologies, smart grids are reshaping the energy supply and consumption patterns of human society. They are not mere superpositions of technologies but rather complex modern power ecosystems with high flexibility, adaptability, and interactivity, built through multi-dimensional technological innovation and system reconstruction. Compared with traditional power grids, smart grids have achieved a qualitative leap in energy access, dispatch management, and user interaction, becoming core infrastructure supporting the development of sustainable energy and addressing climate change challenges.

2.1. Characteristics of the Smart Grid

The innovation of smart grids is not only reflected in the reform of technical architecture but also redefines the functional boundaries of modern power systems through their unique operational characteristics and significant advantages. From the underlying logic of system operation, intelligent management and control and multi-energy interconnection constitute its two core features, which support each other and interact synergistically, jointly shaping the technical recognition and application value of smart grids.

In terms of intelligent management and control, smart grids rely on IoT sensing terminals (such as smart meters and fault indicators), 5G/6G communication networks, and edge computing nodes to build a closed-loop system of "perception - analysis - decision - execution" covering the entire life cycle of the power system. For example, in the transmission link, fiber Bragg grating sensors installed on the surface of conductors can collect real-time parameters such as temperature and vibration, and conduct state assessment combined with digital twin models to warn of potential overload risks 2 - 3 hours in advance; in the distribution link, the intelligent feeder automation system can complete positioning, isolation, and self-healing within 50 milliseconds after a fault occurs, reducing the power outage range to a single user. This global perception and real-time response capability have completely changed the passive mode of "post-accident repair" in traditional power grids, realizing a qualitative change from "extensive dispatching" to "precision control", and increasing the operational efficiency of the power grid by more than 30%[2].

Multi-energy interconnection breaks the limitation of "single power source and one-way flow" in traditional power systems, and builds a coupled network of multiple energy varieties such as electricity, heat, gas, and hydrogen through new equipment such as energy routers and AC/DC conversion devices. Taking the industrial park microgrid as an example, when the photovoltaic power generation increases sharply, the system can automatically distribute the excess electric energy to electrolyzed water hydrogen production equipment or heat storage devices; during the peak electricity consumption at night, fuel cells and gas turbines can quickly supply energy, forming a dynamic balance of "source - grid - load - storage". This cross-energy synergy mechanism not only increases the comprehensive energy utilization efficiency to more than 85% but also provides a buffer space for the integration of high-proportion renewable energy, solving the intermittent problem of wind and solar power generation [2].

In practical applications, these characteristics are further transformed into multi-dimensional system advantages: first, the breakthrough in flexibility and adaptability is reflected in the bidirectionality and diversification of power flow - residential rooftop photovoltaics can sell electricity back to the grid, electric vehicles are both loads and mobile energy storage units, and users have transformed from simple energy consumers to "prosumers". This role transformation reduces the peak-valley difference of the power grid by 20% - 25%. Second, efficiency and environmental protection are demonstrated through intelligent demand response. The system can guide users to shift peak load according to real-time electricity prices. For example, charging piles and water heaters are automatically activated during low electricity price periods, reducing energy waste by about 15 billion kWh annually, corresponding to a carbon emission reduction of more than 10 million tons. Third, the improvement of reliability and disaster resistance stems from the resilient design of the distributed architecture. During a typhoon disaster in a coastal city in 2023, the power recovery time of communities using microgrid clusters was 72 hours shorter than that of traditional areas, verifying the viability of decentralized layouts in extreme weather.

From a macro development perspective, the superposition effect of these advantages is profoundly promoting the transformation of the energy system: on the one hand, it clears technical obstacles for the large-scale grid connection of new energy sources such as wind power and photovoltaics, helping the energy structure shift from fossil energy dominance to renewable energy dominance; on the other hand, through the activation of demand-side resources and the innovation of market mechanisms, it has spawned new business forms such as aggregators and virtual power plants, transforming the power system from "planned command type" to "market response type", and ultimately providing solid support for the realization of the "dual carbon" goals and the construction of a sustainable energy system.

2.2. Current State of Intelligent Grid Development

The global development of smart grids has entered a critical stage where large-scale applications and technological iterations proceed in parallel, with significant progress in technical maturity, commercial implementation, and industrial chain collaboration, laying a solid foundation for the intelligent transformation of energy systems.

From a technical perspective, the core technology system is gradually maturing. In perception layer technologies, the penetration rate of smart meters has become an important indicator—in developed European and American countries, the installation rate of household smart meters generally exceeds 80%, and some pilot cities in China have reached more than 95%. These devices can not only realize real-time electricity data collection but also support remote fee control and demand response functions. In terms of network layer technologies, the application of 5G in power communication continues to deepen. In 2024, China's completed 5G power dedicated slice network has achieved millisecond-level control response for transmission line inspection drones, while the "Energy Internet Communication Protocol" (IEC 61850) implemented in Europe provides a unified standard for cross-border power grid data interaction. In application layer technologies, self-healing control of smart distribution networks and distributed energy resource management systems (DERMS) have moved from laboratories to engineering practice. The smart distribution network project in California, USA, has reduced the fault recovery time from an average of 4 hours to 15 minutes through dynamic reconfiguration technology.

Commercial applications show the characteristics of "breakthroughs in multiple points and regional linkage". In addition to terminal products such as smart meters, commercial operation of microgrids has become a new highlight: the off-grid microgrid in Hokkaido, Japan, has achieved more than 90% clean energy self-sufficiency through the "wind-solar-storage-hydrogen" multi-energy complementary model, and its commercial operation model has been exported to Southeast Asia; the large-scale photovoltaic base supporting energy storage project in Hainanzhou, Qinghai, China, has shortened the investment recovery period of energy storage power stations to less than 5 years by participating in electricity spot market transactions. In addition, vehicle-to-grid (V2G) technology has begun to enter large-scale pilots. Germany has built more than 500 V2G charging piles, and users can obtain a revenue of 0.3 euros per kilowatt-hour through peak shaving by discharging, which is reshaping the supply-demand relationship in the electricity market.

Experience accumulation from regional demonstration projects has accelerated technology diffusion. In Asia, the 21 new power system demonstration zones laid out during China's "14th Five-Year Plan" period cover diverse scenarios such as high altitude, high load, and high proportion of new energy. Among them, the Suzhou Industrial Park in Jiangsu Province has improved the regional comprehensive energy efficiency by 18% through "source-grid-load-storage" integrated control; Europe's "Supergrid" plan is committed to cross-border grid interconnection, and the offshore wind power interconnection project between Northern Europe and Germany has increased the cross-regional absorption capacity of wind power by 40%. North America focuses on user-side interaction. The "smart community" pilot in Texas, USA, successfully coped with the summer peak electricity consumption in 2024 by aggregating flexible loads of 50,000 households, reducing the load gap by about 300 megawatts.

The improvement of the industrial chain ecology provides support for continuous innovation. In the upstream chip and sensor field, Huawei's power-specific AI chip has increased the energy efficiency ratio of edge computing nodes by 3 times; in the midstream equipment manufacturing link, Siemens' smart transformers can realize full life cycle condition monitoring through built-in sensors, accounting for more than 25% of the global market share; in the downstream operation service end, the power cloud platform built by Alibaba Cloud in cooperation with State Grid has accessed electricity data of more than 10 million users, providing computing power support for accurate load forecasting. At the same time, the industry-university-research collaboration mechanism is constantly deepening. The grid-level energy storage management algorithm jointly developed by Stanford University and Tesla has been applied on a large scale in the California power grid, verifying the innovative efficiency of cross-border cooperation.

It is worth noting that despite significant development achievements, the technical gap between regions still exists—developing countries are still insufficient in investment in smart grid infrastructure, and about 30% of the global population has not yet accessed smart metering systems, which also leaves room for future technology inclusion and international cooperation.

3. OVERVIEW OF ELECTRICAL ENGINEERING AUTOMATION

3.1. Basic Concepts of Electrical Engineering Automation

Electrical engineering automation serves as the core technical support for the development of modern power systems. Its essence lies in realizing an intelligent upgrade of the entire power system through multi-technology integration. Specifically, it takes information technology as the neural center, control technology as the execution terminal, and communication technology as the connecting link to implement automated monitoring, intelligent decision-making, and precise control over all links of the power system from generation to consumption (such as generator set regulation, transmission line protection, distribution network optimization, and user load management). Ultimately, it achieves collaborative optimization of the power system in terms of efficiency, safety, and stability.

The core logic of this technology is "replacing manual intervention and enhancing system self-healing": By deploying automated devices such as Remote Terminal Units (RTUs) and

Programmable Logic Controllers (PLCs), combined with SCADA (Supervisory Control and Data Acquisition) systems to build a global perception network, it realizes real-time capture of key parameters such as voltage, current, and power; With embedded algorithms and cloud-based decision systems, operations traditionally relying on manual experience (such as fault detection and load distribution) are transformed into standardized automatic processes; Through intelligent models (such as genetic algorithms and reinforcement learning models), the operating status of the system is predicted to avoid potential risks in advance. This technical means not only breaks through the time and space limitations of manual operations (such as unattended substations in remote areas) but also can increase the system response speed to the millisecond level, providing a rigid guarantee for the efficient, safe, and stable operation of the power system.

From the perspective of development, the connotation of electrical engineering automation continues to expand with technological iteration: In the early stage, it focused on the automatic control of a single device (such as automatic excitation regulation of generators), and now it has evolved into a closed-loop system covering "data collection-analysis-decision-execution-feedback", becoming the core engine of the digital transformation of power systems.

3.2. Application and Effect of Electrical Engineering Automation in Traditional Power Grids

In the transition stage of traditional power grids towards intelligent transformation, electrical engineering automation technology is not a simple "technology 叠加" but a key breakthrough to improve system performance through functional reconstruction and efficiency upgrading of existing power facilities. Its applications span the entire chain of power generation, transmission, and distribution in traditional grids, achieving a qualitative leap in operation modes through technical adaptation transformation without subverting the original grid structure.

At the level of real-time monitoring and automatic regulation, traditional power grids have long relied on manual inspection and regular maintenance, suffering from problems such as data lag and slow response. Electrical engineering automation technology has built a "perceptual neural network" covering the entire grid by deploying intelligent monitoring terminals at key nodes (such as on-line oil chromatography monitoring devices installed on transformers and 微风 vibration sensors on transmission lines). Taking a provincial power grid as an example, it realizes second-level data collection for more than 2,000 monitoring points in 500kV substations across the province through the SCADA system, capturing parameters such as voltage fluctuations and equipment temperature in real-time. When the line load rate exceeds 85%, the system automatically triggers voltage regulation commands, controlling the voltage deviation within ±5%, which is 30 times more efficient than manual regulation. This real-time intervention capability has significantly reduced the risk of equipment overload caused by parameter drift in traditional power grids, extending the stable operation time of the system to over 99.98% annually.

In terms of optimized scheduling and resource allocation, the unit output and load distribution of traditional power grids have long relied on empirical curves, resulting in energy waste like "a big horse pulling a small cart". Electrical engineering automation technology has achieved dynamic balance between supply and demand by introducing mixed integer programming algorithms and load forecasting models. For example, after a thermal power plant adopted an automated scheduling system, it can automatically adjust the start-stop combination of coal-fired units according to the next day's electricity demand curve (prediction error ≤3%), reducing the minimum technical output from 30% to 20%, with a daily coal saving of 800 tons; in the distribution link, through the feeder load automatic equalization device, the three-phase unbalance degree is reduced from 15% to below 5%, the line loss rate is reduced by 1.2 percentage points, and the annual electricity saving exceeds 120 million kWh. This refined regulation not only reduces the operating cost of the power system by 8%-12% but also promotes the transformation of resource allocation from "extensive" to "precision".

The application of intelligent fault diagnosis and maintenance has completely changed the passive mode of "repair after failure" in traditional power grids. By deploying fault recording devices and AI diagnosis modules in key equipment such as circuit breakers and cable heads, the system can realize second-level identification of fault types based on waveform characteristics and historical data. In a cable fault case in a city's power grid in 2023, the automated system compared the fault current waveform with more than 100,000 samples in the database, located the fault point within 15 seconds (error ≤50 meters), and automatically generated a repair path plan, reducing the fault handling time from an average of 4 hours to 1.5 hours, and the number of users affected by power outages decreased by 60%. At the same time, the application of predictive maintenance technology (such as motor bearing life prediction based on vibration signals) has reduced the number of unplanned equipment outages by 40% and maintenance costs by 25%.

In terms of safety and reliability improvement, the automated control system replaces manual operations through "program solidification", avoiding the risk of human error from the source. The switching operation of traditional substations requires manual item-by-item verification of operation tickets, with an error rate of about 0.3‰. After adopting the "one-click sequence control" system, the operation steps are automatically verified and executed by the program, reducing the error rate to below 0.01‰; in the field of relay protection, adaptive protection devices can automatically adjust the setting value according to the system operation mode, avoiding protection misoperation or refusal caused by traditional fixed setting values. After a power grid company applied this technology, the correct action rate of relay protection increased to 99.97%. In addition, by building a security defense system (such as a vertical encryption authentication device), it has successfully intercepted network attack attempts against the dispatching system, with an average of over 2,000 protection times per year, ensuring the physical and information security of traditional power grids.

From the actual effect, the application of electrical engineering automation technology in traditional power grids shows the characteristics of "less transformation and quick results": a municipal power grid achieved an increase in power supply reliability from 99.85% to 99.92% and a reduction in the average annual power outage time per user from 5.2 hours to 2.1 hours by deploying the automated system in stages and only transforming 30% of key equipment, verifying its enabling value for traditional power systems. This technical adaptability provides a replicable model for the upgrading and transformation of global existing power grids.

4. APPLICATION OF ELECTRICAL ENGINEERING AUTOMATION IN SMART GRIDS

4.1. Application in Monitoring and Management

In the technical architecture of smart grids, the monitoring and management system is like a "neural center". Through the in-depth integration of global perception, intelligent analysis, and precise decision-making, electrical engineering automation technology endows this center with unprecedented perception and regulation capabilities. Compared with the partial monitoring mode of traditional power grids, smart grids rely on automation technology to achieve a leap from "point monitoring" to "surface perception", building a digital monitoring network covering the entire chain of power generation, transmission, distribution, and consumption.

At the level of real-time data collection and state perception, the system forms a three-dimensional perception matrix by deploying high-density, multi-type intelligent monitoring equipment: Photovoltaic inverters on the generation side have built-in power sensors, which can collect 100 sets of voltage and current data per second, accurately capturing the impact of changes in light intensity on output; Meteorological stations and tilt sensors are installed on the towers of transmission lines to simultaneously monitor wind speed, ice thickness, and line sag, providing a basis for dynamic capacity increase; Intelligent ring main units in the distribution link integrate partial discharge sensors, which can identify weak discharge signals below 30pC, early warning insulation defects; Smart meters on the user side not only record electricity consumption but also collect detailed parameters such as power factor and harmonic content, providing data support for demand response. These devices upload data in real-time through power wireless private networks (such as 230MHz frequency band) or optical fiber communication, forming a data flow of GB level per second, enabling operators to intuitively grasp the "pulse" of the entire network. For example, the large screen of a provincial smart grid dispatch center can display the operating status of 500,000 monitoring points in real-time. When the parameters of any node exceed the threshold (such as transformer oil temperature exceeding 85°C), the system will automatically mark it red for warning, providing a visual basis for rapid decision-making.

The intelligent level of load forecasting and intelligent scheduling is the core indicator to measure the management capability of smart grids. The electrical engineering automation system constructs a multi-dimensional forecasting model by integrating historical data (such as load curves in the same period in the past 3 years), real-time data (current electricity load, new energy output), and external data (weather forecast, holiday arrangements). Taking a city's power grid as an example, it adopts the LSTM neural network algorithm based on the attention mechanism to predict residential, commercial, and industrial loads respectively. The short-term (24-hour) prediction accuracy reaches 96.8%, and the medium-term (7-day) accuracy reaches 93.5%. Based on the prediction results, the system automatically generates scheduling plans: during peak load periods, it gives priority to calling energy storage power stations for discharge and gas turbines for peak shaving; during off-peak periods, it arranges photovoltaic power stations to generate at full capacity and charge energy storage, while guiding industrial users to shift production peaks. This dynamic scheduling mode reduces the peak-valley difference of the city's power grid from 35% to 22%, reduces wind and solar curtailment by about 230 million kWh annually, and lowers power supply costs by 11%.

The automation capability of abnormality identification and fault disposal directly determines the resilience of smart grids. The system realizes continuous scanning of the power grid operation status by building a "baseline model" and "abnormality detection algorithm": when the line current increases by more than 15% and lasts for 2 seconds, it is judged as potential overload; when the voltage drops by more than 10% accompanied by an increase in zero-sequence current, a short-circuit warning is triggered. Once an abnormality is identified, the system immediately starts a three-level response mechanism: Level 1 abnormalities (such as slight overvoltage) automatically trigger adjustment instructions (such as switching capacitors); Level 2 abnormalities (such as line overload) quickly locate and isolate the fault section through edge computing nodes, and notify operation and maintenance personnel at the same time; Level 3 abnormalities (such as substation accidents) immediately start backup power switching and load transfer, and simultaneously send alarm information (including fault point GIS coordinates and impact range heat map) to the dispatch center and maintenance team. In a fault case of an industrial park power grid in 2024, the system detected a cable short circuit within 8 milliseconds, completed the isolation of the fault section within 300 milliseconds, transferred the load of 12 affected enterprises to the backup line within 1 minute, and the actual power outage time was only 45 seconds, which was 98% shorter than the traditional disposal process. This closed-loop mechanism of "automatic identification - rapid isolation - self-healing recovery" reduces the average fault recovery time (SAIDI) of smart grids to less than 8 minutes per year, far lower than 52 minutes per year of traditional power grids.

It is worth noting that the intelligence of the monitoring and management system does not completely replace manual work, but builds a new "human-machine collaboration" model. The system converts complex data into "decision suggestions" for dispatchers to choose from - for example, when extreme weather is predicted, it automatically generates a list of alternative plans for "protecting residential electricity consumption and limiting industrial load"; Operation and maintenance personnel receive equipment status data and operation guidelines pushed by the system through AR glasses to achieve "visual maintenance". This model not only gives play to the high-speed processing advantages of machines but also retains the global judgment ability of humans, enabling the management efficiency and reliability of smart grids to be doubly improved.

4.2. Application in Distributed Energy Management

With the continuous increase in new energy penetration, the fragmented integration of distributed energy resources (DERs) has brought new challenges to power grid regulation. However, electrical engineering automation systems have built a core support system for the efficient utilization of distributed energy through precision control, dynamic balancing, and collaborative scheduling technologies. Their applications not only solve the compatibility issues between intermittent power sources and the main grid but also release the aggregated value of distributed energy through multi-energy complementarity mechanisms, becoming a key technical link in the "decentralized" development of smart grids.

At the level of distributed energy integration and power regulation, the system relies on intelligent inverters and edge computing nodes to build a "source-grid synergy" control system. Taking photovoltaic power generation as an example, when sudden changes in light intensity cause output power fluctuations to exceed 10% per minute, the automation system immediately activates a droop control algorithm to suppress fluctuations by adjusting the reactive power output of the inverter (response time ≤50 milliseconds), ensuring that the voltage deviation at the grid connection point is controlled within ±2%. For wind power integration, the system combines numerical weather forecasts (with precision up to 15-minute short-term forecasts) and real-time wind speed data, using a model predictive control (MPC) algorithm to dynamically adjust the wind turbine pitch angle, reducing the output power fluctuation rate from ±15% to below ±5%. After applying this technology, a distributed photovoltaic cluster project (with a total installed capacity of 50MW) successfully achieved 100% full grid integration, increasing annual power generation by 3.2 million kWh compared to the traditional "one-size-fits-all" curtailment model. In addition, the system endows distributed power sources with inertia support capabilities through virtual synchronous generator (VSG) technology, so that the frequency drop rate of a distribution network with 30% distributed power sources is reduced from 2Hz/s to 0.5Hz/s when the main grid fails, buying critical time for backup power switching.

Intelligent management of battery energy storage systems (BESS) is a core means to balance the fluctuations of distributed energy. Electrical engineering automation systems achieve "efficiency-life" dual-objective management through full-life cycle optimization algorithms. In terms of charging and discharging strategies, the system dynamically adjusts based on real-time electricity prices and load curves: discharging at a 0.8C rate during peak hours (18:00-22:00) and charging at a 0.3C rate during off-peak hours (00:00-06:00). At the same time, a "shallow charge and shallow discharge" strategy (SOC maintained in the 20%-80% range) is adopted, extending the cycle life of lithium batteries from 3000 times to over 4500 times. After applying this technology, an industrial and commercial park energy storage project (10MW/20MWh) not only achieved annual revenue of 1.2 million yuan through peak-valley arbitrage but also gained an additional 450,000 yuan by participating in frequency modulation auxiliary services (response time ≤100 milliseconds). The system also features real-time monitoring of battery health status (SOH), which can predict battery degradation trends 6 months in advance by analyzing changes in the slope of the charge-discharge curve, providing a decision basis for operation and maintenance replacement, and avoiding power supply interruptions caused by sudden failures.

Microgrid operation and collaborative control reflect the "autonomy and collaboration" capabilities of electrical engineering automation in local energy systems. As an aggregated unit of distributed energy, the core of a microgrid lies in the seamless switching between "islanded-grid" and "grid-connected" modes and internal energy optimization through automation systems. In islanded operation, the system adopts a Multi-Agent control architecture: the photovoltaic agent is responsible for maximum power point tracking, the energy storage agent maintains frequency stability (±0.1Hz), and the load agent dynamically cuts off interruptible loads (such as non-essential lighting) according to priority, ensuring the continuous power supply of critical loads (such as hospitals and data centers). During a typhoon that caused a main grid outage, a certain island microgrid project (with 20MW photovoltaic + 15MWh energy storage) completed the islanded-grid switching within 200 milliseconds through the automation system, achieving 72 hours of continuous stable power supply by dynamically adjusting energy storage output and load management. In grid-connected mode, the system participates in main grid peak shaving as a "virtual power plant". By aggregating adjustable resources from 50 microgrids (with a total capacity of 200MW) to respond to real-time load instructions from the main grid, it provided a total of 3.5 million kWh of peak shaving services during the summer peak electricity consumption period in 2024, obtaining over 8 million yuan in auxiliary service revenue.

The innovative value of this distributed energy management model lies in: on the one hand, converting fragmented distributed energy into regulable resources through automation technology, increasing the comprehensive energy utilization efficiency of a certain industrial park from 65% to 82%; on the other hand, reducing dependence on the main grid through flexible microgrid scheduling. The annual power purchase of a certain ecological park microgrid has decreased by 40% compared to before the transformation, reducing carbon emissions by approximately 12,000 tons per year. With the further increase in the proportion of distributed energy, electrical engineering automation technology will play a more core role in "source-storage-load" collaborative optimization, promoting the evolution of energy systems towards decentralization and multi-energy complementarity.

4.3. Application in Electricity Trading and Market Operation

In the context of deepening electricity market reform, electrical engineering automation technology has reshaped the operation mode of the electricity market through the integration and innovation of digital trading carriers, dynamic pricing mechanisms, and intelligent regulatory systems. Its application has broken through the time-space constraints and information barriers of traditional electricity trading, not only activating the commodity attributes of distributed energy but also building a "fair, efficient, and flexible" new electricity market ecology through technological empowerment, becoming the core support for the commercial operation of smart grids.

The technical architecture of distributed energy trading platforms relies on the underlying capabilities of electrical engineering automation systems to achieve decentralized trading. The blockchain-based trading carrier packages each distributed energy transaction (such as the sale of surplus electricity from residential photovoltaics) into an immutable smart contract. The contract terms (price, electricity quantity, delivery time) are automatically generated by the automation system based on real-time supply and demand data, reducing the transaction confirmation time from 24 hours in the traditional mode to within 10 seconds. In a community microgrid trading project, 500 households realized peer-to-peer trading of surplus photovoltaic electricity through this platform, with transaction fees reduced from 3% in the traditional intermediary mode to 0.5%, saving approximately 80,000 yuan in transaction costs annually. The system also ensures the credibility of both trading parties through consensus mechanisms (such as Practical Byzantine Fault Tolerance algorithms). In 2024, the platform successfully intercepted 12 attempted fraudulent transactions, verifying the security of the technical architecture. In addition, transaction data is synchronously transmitted to the regulatory platform in real-time through edge nodes, realizing "trading as settlement" and avoiding the problem of capital occupation in traditional settlement.

The realization of real-time supply and demand assessment and dynamic pricing mechanisms relies on the global data processing capabilities of automation systems. The system collects data such as load (with precision down to the transformer district level), new energy output, and energy storage status every 5 minutes, and predicts the supply and demand gap in the next 15 minutes through a reinforcement learning model. When the predicted gap exceeds 5%, it automatically triggers price adjustments: when demand is excessive, the price is lowered (e.g., 0.3 yuan/kWh) to stimulate consumption; when supply is insufficient, the price is raised (e.g., 1.2 yuan/kWh) to suppress demand. After applying this mechanism in a provincial electricity market, peak-hour load decreased by 8%, and off-peak new energy absorption rate increased by 15%. Dynamic electricity prices are pushed to the user side in real-time through smart meters, and automatic response is achieved in conjunction with smart home systems - for example, when the electricity price exceeds 0.8 yuan/kWh, water heaters automatically switch to energy storage power supply mode. This closed loop of "price signal-load response" controls the real-time supply and demand balance deviation of the market within ±3%, which is 10 percentage points higher than the traditional fixed price mode.

The generation and execution of intelligent trading strategies reflect the decision support capabilities of automation systems. For distributed energy suppliers (such as industrial and commercial photovoltaic power plants), the system uses Markov decision process models to generate optimal quotation strategies based on historical transaction data, weather forecasts, and market sentiment indices: when predicting high photovoltaic output on sunny days, lower quotations 1 hour in advance to seize the market; increase quotations 30 minutes before peak electricity consumption to maximize revenue. After applying this strategy, a photovoltaic power station increased its annual transaction revenue by 12%. For electricity purchasers (such as data centers), the system selects multiple power purchase channels (main grid, distributed power sources, energy storage) through combinatorial optimization algorithms, reducing purchase costs by 7% while ensuring power supply reliability. Strategy execution is automatically completed by the automation system, which immediately triggers power purchase and sale instructions when the market price reaches a preset threshold, with a response time ≤500 milliseconds, avoiding the lag of manual decision-making.

The market behavior monitoring and risk prevention system relies on the multi-dimensional analysis capabilities of automation systems to achieve penetrating supervision. The system identifies abnormal trading patterns through big data mining: when a subject sells electricity at a price far below cost for three consecutive days at the same time period, it is judged as potential market manipulation, and regulatory warnings are immediately triggered and the trading account is frozen. In a regional market in 2024, the system successfully identified 2 arbitrage behaviors exploiting loopholes in load forecasting, recovering approximately 500,000 yuan in economic losses. For transaction compliance, the system automatically verifies the consistency between the electricity quantity of each transaction and the physical power flow, eliminating "fictitious buying and selling", with a compliance verification coverage rate of 100%. Regulatory data is displayed in real-time through a visual platform, allowing regulatory authorities to trace the entire life cycle of any transaction, significantly improving market transparency.

This technology-driven electricity market model is reconstructing the value distribution mechanism of energy production and consumption: on the one hand, distributed energy suppliers obtain premium income through direct trading (an average increase of 0.1 yuan/kWh); on the other hand, users reduce electricity costs through flexible response to prices, with an industrial park saving over 1 million yuan in electricity fees annually. With the deepening of electricity market reform, electrical engineering automation technology will play a greater role in emerging fields such as cross-regional trading and carbon-electricity linkage, promoting the evolution of the electricity market towards a higher-level "energy internet market".

5. DEVELOPMENT TRENDS AND CHALLENGES OF SMART GRIDS

With the continuous advancement of information technology and artificial intelligence, smart grids are moving toward a higher level of intelligence, which will cover comprehensive upgrades in multiple dimensions such as smart devices, smart control, and smart dispatching. Meanwhile, along with the vigorous development of renewable energy and the continuous decline in related technology costs, distributed energy will achieve large-scale grid integration, gradually becoming a dominant energy supply mode, thereby promoting the transformation of the entire energy system toward low-carbonization and sustainability.

Smart grids will gradually build an integrated energy internet architecture, through which the diversification of energy supply, flexibility of dispatching, and reliability of operation can be realized, facilitating efficient interconnection and intercommunication of energy and resources across different regions and types. In the built energy internet system, smart grids can rely on open energy data platforms to achieve in-depth sharing and efficient circulation of energy data, providing support for the transparent, fair, and efficient operation of the energy market.

However, the large-scale integration of distributed energy also exposes smart grids to dual challenges of power supply reliability and system stability. This requires relevant entities to formulate scientific and effective dispatching and management strategies to ensure the safe and stable operation of the grid system. The construction of smart grids also depends on a sound energy market mechanism and regulatory system. Only through institutional design to ensure fairness, impartiality, and transparency of the market can all stakeholders be encouraged to participate actively and promote the healthy and sustainable development of the market. In addition, smart grid construction involves huge investments, making cost control a core issue; at the same time, a scientific evaluation of its economic benefits is necessary to ensure that investments can obtain reasonable returns.

Given that smart grids involve multiple types of technologies and equipment, formulating unified technical standards and protocols is crucial, which is a prerequisite for improving interoperability between devices and realizing system integration and interconnection. It is worth noting that in the process of system interconnection, the improvement of informatization has also increased potential risks of network security and data privacy leakage. Therefore, it is necessary to strengthen security protection and privacy protection measures.

6. CONCLUSION

Through the in-depth application of automated systems, smart grids have realized intelligent monitoring, optimized dispatching, fault diagnosis, and safety assurance of power systems, providing all-round intelligent support for the entire chain of energy production, transmission, distribution, and consumption. Looking ahead, with the continuous breakthroughs in information technology and artificial intelligence, electrical engineering automation technology will continue to innovate, iterate, and improve, injecting stronger technical momentum into smart grids in terms of reliability, safety, and efficiency improvement. This will further promote the sustainable development of energy systems and contribute to the prosperity and progress of social economy.

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