Research on Operational Efficiency Optimization of Photovoltaic Power Generation Systems

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Abstract: Against the background of global energy structure transformation and carbon neutrality goals, photovoltaic power generation has received considerable attention due to its clean and low-carbon advantages. With the objective of improving the operational efficiency of photovoltaic systems, this paper adopts a combination of theoretical analysis and experimental verification to investigate the key factors affecting photovoltaic system efficiency and corresponding optimization strategies. An efficiency evaluation model for photovoltaic systems is constructed, and the action mechanisms of factors such as solar irradiance, ambient temperature, module aging, shadow shading, and inverter performance on power generation efficiency are analyzed. By integrating MPPT algorithm optimization, smart cleaning, dynamic tilt angle adjustment, and predictive maintenance, a comprehensive efficiency improvement scheme is established. The experimental results show that, after optimization, the average power generation efficiency of the system increased by 12.3%, with the respective contributions of the measures being 3.8%, 4.2%, 2.9%, and 1.4%. Comparative verification across photovoltaic power stations in different regions and at different scales demonstrates that the proposed optimization scheme has strong applicability and significant effects. This study provides theoretical and practical reference for the efficiency improvement and operation of photovoltaic systems and has high engineering application value and promotion prospects.

Keywords: photovoltaic power generation; operational efficiency; maximum power point tracking; smart optimization; predictive maintenance

1. Introduction

The global photovoltaic industry is developing rapidly. According to statistics from the International Renewable Energy Agency, global installed photovoltaic capacity increased from 586 GW to 1,419 GW from 2019 to 2023, with an average annual growth rate of 24.6%. China is the world's largest photovoltaic market. In 2023, China added 216.9 GW of photovoltaic capacity, bringing its cumulative installed capacity to 495.2 GW, accounting for 34.9% of the global total. However, due to environmental impacts, equipment aging, inadequate maintenance, and other factors, the actual power generation of photovoltaic power generation systems is generally 15%–25% lower than the designed value, which greatly reduces the economic performance and investment return of photovoltaic projects.

At present, many problems remain in the optimization of operational efficiency for photovoltaic power generation systems, such as the spatial and temporal variability of solar irradiance and ambient temperature, photovoltaic module aging, reduced inverter efficiency, and unreasonable system design. Traditional fixed operation modes can no longer meet the requirements for efficient operation of photovoltaic power generation systems. Therefore, systematic theories and methods for efficiency optimization are needed. By studying the factors affecting the operational efficiency of photovoltaic power generation systems, this paper proposes a method for improving system operational efficiency based on multi-dimensional collaborative optimization, which is of great significance for promoting the development of the photovoltaic industry and reducing costs.

2. Analysis of Factors Affecting the Efficiency of Photovoltaic Power Generation Systems

2.1 Effects of Environmental Factors on Photovoltaic Power Generation Efficiency

Solar irradiance and ambient temperature are the main environmental factors affecting the power generation efficiency of photovoltaic systems. Solar irradiance determines the light intensity received by photovoltaic modules. Under standard test conditions, the irradiance is 1,000 W/m², whereas in practical applications, irradiance generally fluctuates between 200 and 1,200 W/m². The output power of photovoltaic modules is positively correlated with irradiance. Ambient temperature has an adverse effect on photovoltaic modules. The temperature coefficient of crystalline silicon photovoltaic modules is approximately −0.4%/°C. When the module temperature increases from 25 °C to 75 °C, the output power decreases by approximately 20%. In addition, wind speed, humidity, atmospheric transparency, and other factors also affect the system to some extent. Higher wind speed is more favorable for heat dissipation from photovoltaic modules, while excessive humidity enhances the absorption and scattering of sunlight by the atmosphere, thereby reducing the irradiance intensity reaching the surface of photovoltaic modules.

2.2 Effects of Photovoltaic Module Characteristic Parameters on Efficiency

The conversion efficiency, power degradation characteristics, temperature characteristics, and spectral response characteristics of photovoltaic modules all affect the power generation of the system. At present, the conversion efficiency of mainstream monocrystalline silicon modules on the market is generally 20%–22%, while that of polycrystalline silicon modules is generally 17%–19%. The laboratory efficiency of perovskite tandem cells has exceeded 33%. Module power degradation is an important factor determining long-term operational efficiency. High-quality modules can achieve a first-year degradation rate of no more than 2%, followed by an annual degradation rate of no more than 0.55%. The current–voltage characteristic curve of a module varies under different external environmental conditions, and the position of the maximum power point changes with irradiance and temperature. Therefore, an accurate maximum power point tracking algorithm is required to obtain maximum power output [1].

2.3 Effects of Inverter Performance on System Efficiency

The inverter is one of the most important devices in a photovoltaic system, and its conversion efficiency and reliability determine the performance of the entire system. At present, the maximum conversion efficiency of mainstream string inverters on the market can reach 98.8%. However, due to variations in input power and temperature, the efficiency in practical applications generally reaches only about 95%–97%. The inverter efficiency curve shows clear load characteristics. The efficiency is relatively high at 20%–100% of the rated power, but decreases rapidly when the load is below 20% of the rated power. The maximum power point tracking accuracy, response speed, and stability of the inverter have a significant impact on system efficiency. Advanced MPPT algorithms can achieve a tracking accuracy of more than 99% in rapidly changing environments.

2.4 Analysis of the Effects of System Configuration and Operating Parameters

The DC/AC ratio, module arrangement, cable loss, and operating mode of a photovoltaic system all affect the efficiency of the entire system. A reasonable DC/AC ratio can balance system economy and power generation. In general, the DC/AC ratio of centralized photovoltaic power stations is 1.2–1.4, while that of distributed systems is 1.1–1.3. The spacing between modules should take into account land use and losses caused by shadow shading. If the distance between front and rear rows is too small, shadow shading losses of 2%–8% may occur in winter. Cable loss generally accounts for 1%–3% of the total system loss and can be reduced by increasing the cable cross-sectional area or shortening the transmission distance. Operating parameters such as grid-connected voltage, power factor, and harmonic control should be adjusted according to grid requirements and load characteristics.

3. Optimization Methods for the Operational Efficiency of Photovoltaic Power Generation Systems

3.1 Optimization of Maximum Power Point Tracking Algorithms

Traditional perturb and observe methods and incremental conductance methods are prone to oscillation or mistracking in rapidly changing environments. This paper proposes an adaptive MPPT method based on particle swarm optimization. First, a mathematical model is established according to the photovoltaic array. Then, the particle swarm optimization algorithm is used to conduct a global search of the entire photovoltaic array to locate the region near the maximum power point. Finally, an improved incremental conductance method is used for further refined searching. The main feature of the algorithm is the dynamic adjustment of the perturbation step size and search range. A larger step size is used when the irradiance changes rapidly, while a smaller step size is used when the irradiance changes slowly. The experimental results show that the proposed optimization method achieved a tracking efficiency of 99.7% under standard conditions, and the tracking efficiency increased by more than 15% under rapidly changing conditions, greatly improving the system response speed and steady-state accuracy.

3.2 Optimization of Photovoltaic Array Arrangement

The arrangement of photovoltaic arrays has an important impact on land use efficiency, shadow shading loss, and system cost [2]. This paper proposes an array layout design method based on multi-objective optimization, which minimizes land cost and shadow loss while ensuring maximum power generation. A three-dimensional shadow shading model is used to accurately calculate the shaded area and power loss under different solar altitude angles and azimuth angles, and a genetic algorithm is used to obtain the Pareto optimal solution set. The optimized array layout adopts a variable-spacing design. The north–south spacing varies with latitude and terrain slope, while a staggered arrangement is adopted in the east–west direction to reduce the influence of lateral shading. The experimental results show that, compared with the traditional equal-spacing layout, the optimized array layout increased land use efficiency by 8.5%, annual power generation by 4.2%, and comprehensive benefits by 12.7%.

3.3 Adaptive Regulation Strategy for System Operating Parameters

Timely optimization of photovoltaic system operating parameters is essential for improving overall system performance. This paper proposes an adaptive parameter regulation method based on machine learning. By using information on environmental parameters, equipment status, grid load, and other factors, a power generation efficiency prediction model and a parameter optimization decision-making system are constructed. The system uses deep neural networks to learn complex relationships from historical operating data and predict the optimal operating parameters for the next 1–24 hours. The main parameters include the operating voltage range of the inverter, power factor setting, and reactive power output strategy. The adaptive regulation strategy also considers weather forecasts. When clouds or abnormal temperatures are predicted, system parameters are adjusted in advance to reduce the impact of environmental changes on power generation. In practical applications, the adaptive regulation system can maintain power generation efficiency at a relatively high level under constantly changing environmental conditions. Compared with the fixed-parameter operation mode, the efficiency increased by 6.8%, greatly improving the environmental adaptability and economic performance of the system.

3.4 Fault Diagnosis and Maintenance Optimization Scheme

Data-driven predictive maintenance is an effective method for improving the long-term operational efficiency of photovoltaic power stations. This paper proposes a multi-level fault diagnosis method, which includes three levels of fault detection: module-level, string-level, and system-level diagnosis. Module-level diagnosis uses infrared thermography and electroluminescence detection to identify problems such as hot spots, cracks, and delamination. String-level diagnosis uses current–voltage characteristic curve analysis to identify problems such as open circuits, short circuits, and bypass diode failure [3]. System-level diagnosis identifies performance degradation through power deviation analysis and future trend prediction. The maintenance optimization scheme combines risk assessment with cost–benefit analysis and formulates different maintenance strategies according to fault type, severity, and maintenance cost. Serious faults causing power generation losses of more than 5% are addressed immediately, while minor problems causing power generation losses of less than 2% are handled through centralized maintenance. By reasonably arranging maintenance timing and methods, operation and maintenance costs were reduced by 15.3%, and system availability reached more than 98.5%.

4. Experimental Verification and Performance Evaluation

4.1 Construction of the Experimental Platform and Test Scheme

The experimental platform was established based on a distributed photovoltaic power generation system. A 500 kW experimental power station was selected for this study, including two different types of photovoltaic modules: 250 kW polycrystalline silicon modules and 250 kW monocrystalline silicon modules. The system was equipped with high-precision irradiance sensors, temperature acquisition modules, power analyzers, data recording equipment, and other devices, which enabled the monitoring of key operating parameters. The test method adopted a comparative experiment, in which the experimental power station was divided into an optimization area and a control area. The improved MPPT algorithm, smart cleaning devices, and adjustable-angle supports were installed in the optimization area, while the traditional operation mode was still used in the control area.

The experiment lasted for 12 months, and tests were conducted under different seasonal and weather conditions throughout the year. Data were recorded once every minute to ensure a sufficient sample size. The test items included key parameters such as system power generation, module surface cleanliness, inverter operating efficiency, and maximum power point tracking accuracy. In addition, unified standard test methods were formulated, including equipment calibration, environmental factor recording, and fault handling procedures, to ensure the authenticity and reliability of the test results.

4.2 Comparative Analysis of System Performance Before and After Optimization

After one year of comparative testing, the power generation efficiency of the optimized photovoltaic system improved significantly. The average power generation efficiency of the original system was 16.8%, while that of the optimized system reached 18.9%, representing an increase of 12.3%. Among the optimization measures, the improved MPPT algorithm increased power tracking accuracy by 15.2% under complex illumination conditions. Especially under partial shading and rapidly changing illumination, the power loss was 3.8% lower than that of the traditional P&O algorithm. The smart cleaning system regularly removed dust from the module surface, increasing the module transmittance to more than 95% and improving power generation efficiency by 4.2% compared with manual cleaning.

The dynamic tilt angle adjustment system automatically adjusted the module angle according to the solar altitude angle and seasonal changes, increasing the annual average power generation by 2.9%. The effect was more pronounced in winter, with a monthly increase of 5.1% [4]. The predictive maintenance strategy monitored module performance degradation and inverter operating conditions, issued warnings before problems occurred, and took corresponding measures, increasing system availability to 98.7% and reducing power generation losses caused by equipment failures by 1.4%. Overall, the optimization scheme improved power generation efficiency while greatly enhancing system reliability and stability.

4.3 Efficiency Improvement Effects Under Different Operating Conditions

Under different environmental operating conditions, the optimized system showed good adaptability and consistent efficiency improvement effects. On sunny days, when solar irradiance was 1,000 W/m², the power generation efficiency of the optimized system increased by 11.8%, mainly due to MPPT algorithm optimization and dynamic tilt angle adjustment. Under cloudy conditions with large irradiance fluctuations, the improved MPPT algorithm showed strong adaptability, increasing efficiency by 13.7%, which was much higher than the efficiency improvement under sunny conditions. In high-temperature environments, where the module temperature exceeded 60 °C, the optimized system reduced the influence of the temperature coefficient by 0.8% through heat dissipation optimization and changes in the operation mode, corresponding to an efficiency increase of 2.1%.

Tests on photovoltaic power stations of different sizes showed that, from 50 kW distributed photovoltaic systems to 10 MW centralized photovoltaic power stations, the optimization scheme could increase power generation by 10%–15%, indicating good scalability. Different geographical locations also had certain effects on the optimization results. In high-latitude regions, due to greater changes in the solar altitude angle, the effect of dynamic tilt angle adjustment was more significant, reaching 4.2%. In northwestern regions with more dust and sand, the optimization effect of the smart cleaning system was more pronounced, increasing power generation by 5.8%. Comparison of the test results under various conditions demonstrated that the optimization scheme had good general applicability and robustness.

5. Conclusion

This paper comprehensively investigated the factors affecting the power generation efficiency of photovoltaic power stations by combining theoretical modeling with experimental analysis. Based on an analysis of the development of the global photovoltaic industry from 2019 to 2024, it was found that although global installed photovoltaic capacity increased at an annual rate of 22.8%, the average system efficiency grew slowly, indicating an urgent need for technological innovation. This paper proposed a comprehensive optimization method, including an improved MPPT algorithm, a smart cleaning system, dynamic tilt angle adjustment, and predictive maintenance. The method increased the overall efficiency by 12.3% on a 500 kW experimental platform. The optimization modules worked collaboratively, with MPPT algorithm optimization contributing 3.8%, the smart cleaning system contributing 4.2%, dynamic tilt angle adjustment contributing 2.9%, and predictive maintenance contributing 1.4%. System availability increased from the original 96.2% to 98.7%.

The experimental results show that the optimization method has good robustness and reliability under various operating conditions, indicating favorable application prospects and promotion value. The research work in this paper plays a positive role in improving the power generation efficiency of photovoltaic systems, reducing the unit cost of power generation, and promoting energy structure transformation. Future work may further investigate the application of artificial intelligence technology in photovoltaic system optimization, while also considering the influence of integrating energy storage systems on the optimization effect of the entire system [5].

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