Systematic Study of Renewable Energy Power Generation Simulation Technology

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Abstract. This study examines the simulation techniques for renewable energy generation, with a focus on the Maximum Power Point Tracking (MPPT) algorithms in photovoltaic (PV) systems and the simulation models of Doubly-Fed Induction Generators (DFIG) in wind power systems. The research reveals that optimized MPPT algorithms can significantly enhance the efficiency of PV power generation by dynamically tracking the maximum power point under varying environmental conditions. Additionally, accurate DFIG models improve the operational stability and control performance of wind power systems, particularly in complex grid environments. These findings provide valuable insights for the simulation design and performance optimization of renewable energy systems, offering a robust theoretical basis and practical guidance. The results are expected to contribute to the advancement and large-scale deployment of renewable energy technologies, supporting the transition towards sustainable energy systems. Future work will explore multi-energy coordinated simulation and intelligent control strategies to further enhance the integration and stability of renewable energy systems.

Keywords: Rnewable Energy Power Generation, Simulation Technology, Maximum Power Point Tracking (MPPT) Algorithm, Doubly-Fed Induction Generator (DFIG)

1 Introduction

Against the backdrop of global energy transition and climate change, the development of renewable energy systems is of paramount importance. Photovoltaic (PV) power generation and wind power generation, as representatives of clean energy, rely heavily on simulation technology for their technological advancements. Simulation technology facilitates the optimization of system design, performance prediction, and enhancement of control strategies, ensuring the efficient operation of renewable energy systems.

In the field of PV power generation, Maximum Power Point Tracking (MPPT) technology plays a pivotal role in improving power generation efficiency by dynamically adjusting the operating point of the PV array to maintain proximity to the maximum power point. Relevant research includes the development of MPPT algorithms, the design of controller hardware, and performance evaluation under

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varying environmental conditions. Wei Lu et al. proposed an MPPT control strategy for PV power generation based on the incremental conductance method, achieving effective tracking of the maximum power point [1]. Sun Chen et al. analyzed the mathematical model of PV cells and implemented a strategy combining a Boost circuit with the perturbation and observation method, effectively tracking the maximum power point of PV cells and enhancing solar energy utilization efficiency [2].

In wind power generation, the doubly-fed induction generator (DFIG) model serves as the foundation for investigating the operational characteristics of wind turbines. The DFIG model integrates modules such as the wind turbine, drive train, generator, and converter. These modules are used to simulate the operational characteristics of wind turbines, optimize control strategies, and improve stability. Ye Jianhui et al. developed a simulation model of a direct-drive wind turbine control system based on Simulink, accounting for the power generation efficiency of the generator under varying wind speeds [3]. Wang Hao et al. proposed a control strategy combining an extended state observer with model predictive direct power control, mitigating the impact of disturbances on wind turbine performance [4].

This paper focuses on MPPT technology for PV power generation and the DFIG model for wind power generation. Through a combination of theoretical analysis, simulation, and experimental methods, the study explores the optimization and implementation of MPPT algorithms, the development and validation of the DFIG model, and their applications in renewable energy systems. The research findings provide theoretical support for improving PV power generation efficiency and wind power stability, contributing significantly to the advancement of renewable energy systems.

2 MPPT Simulation Technology for Photovoltaic Power Generation

2.1 Principle of MPPT Technology

The output characteristics of photovoltaic (PV) cells are nonlinear, with their output power varying with output voltage. Under specific light and temperature conditions, the output power of PV cells reaches a maximum value, known as the maximum power point (MPP). MPPT technology monitors the output voltage and current of PV cells in real time, calculates the current output power, and adjusts the operating point to approach the MPP. As shown in Fig. 1, this is the MPPT schematic diagram corresponding to different voltage levels.

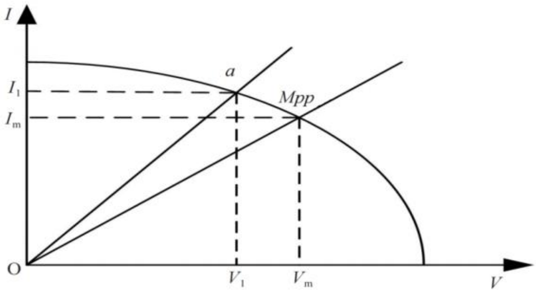

Fig. 1. Schematic Diagram of MPPT Technology[5]

2.2 Traditional MPPT Algorithms

Currently, numerous MPPT algorithms are available. Traditional maximum power point tracking algorithms primarily consist of single-peak value algorithms, including the perturbation and observation method and the incremental conductance method.

(1) Perturbation and Observation Method: The perturbation and observation method is one of the earliest algorithms applied to MPPT. It periodically perturbs the working voltage of PV cells and tracks control. Du Juan et al. focused on the implementation algorithm of voltage-type perturbation and observation, using the MPPT controller to determine the voltage perturbation direction of PV cells to achieve the MPP [6].

(2) Incremental Conductance Method: The incremental conductance method determines the MPP by comparing the relationship between the incremental conductance and the instantaneous conductance of PV cells. Its mathematical basis is that the incremental conductance of PV cells is zero at the MPP. Li Ping optimized the step size of the Incremental Conductance algorithm by utilizing the P-U characteristic curve and further refined the dynamic step size with a coefficient related to current, thereby rapidly and accurately tracking the maximum power point (MPP) of the photovoltaic cell while reducing the oscillation amplitude at the MPP [7].

2.3 Improved MPPT Algorithms

In PV systems MPPT technology is crucial for improving energy conversion efficiency. Traditional perturbation, observation, and incremental conductance methods, although simple to implement, are prone to misjudgment and power loss under rapid light changes or partial shading conditions. To address these issues, researchers have proposed several improvement strategies, as detailed below:

(1) Adaptive Perturbation and Observation Method: To overcome the limitations of traditional perturbation and observation algorithms under rapid light changes, the adaptive perturbation and observation method dynamically adjusts the perturbation step size, enhancing the algorithm's response speed and tracking accuracy. Liu Jiqing

et al. introduced adaptive inertia weight and nonlinear learning factors to accelerate MPPT tracking during global optimization, local optimization, and re-global optimization. The method employs small step size perturbations for slow light changes to improve steady-state accuracy and large step size perturbations for rapid light changes to increase tracking speed [8]. As depicted in Fig. 2, the curve illustrates the impact of the number of iterations on the learning factor.

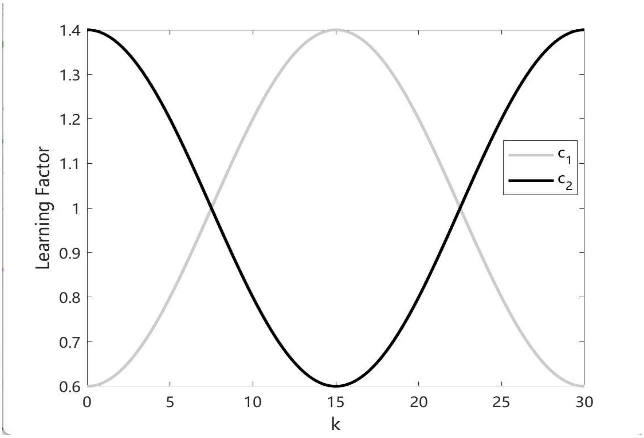

Fig. 2. Influence curves of iteration times on learning factors[8]

(2) Fuzzy PID Control Method: The fuzzy PID control method adjusts the working state of PV cells through a fuzzy reasoning system. By establishing a fuzzy PID controller, this method can handle strong nonlinear variations in light and temperature without relying on precise mathematical models. Ma Mingyue et al. designed a fuzzy PID controller, determining the fuzzy output and control rules to effectively manage the system [9].

2.4 Discussion

MPPT simulation technology offers significant advantages in PV power generation systems. It enhances power generation efficiency, adapts to various environmental conditions, and relies on mature and cost-effective traditional algorithms such as perturbation, observation, and incremental conductance. However, traditional algorithms suffer from inadequate dynamic response and misjudgment under rapid light changes. Improved algorithms, such as neural networks and fuzzy control, are computationally complex and require high hardware performance and design complexity. Future developments could optimize algorithm design by integrating artificial intelligence and big data technologies to improve the dynamic response and adaptability of MPPT, promoting the efficient and intelligent development of PV power generation systems.

3 Wind Power Generation Simulation Technology

Wind turbines are primarily categorized into doubly-fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG) based on generator type. DFIG-based wind turbines are widely used in grid-connected wind farms due to their low cost and flexible control. Their simulation models, grid-connection models, and optimized control models effectively enhance unit performance and operational reliability, making them a current research hotspot.

3.1 Simulation Model of Doubly-Fed Wind Turbines

The simulation model of DFIG-based wind turbines covers three main components: the mechanical transmission system, the generator itself, and the power electronic converter. The mathematical model is constructed based on the mechanical, generator, and converter models. It enables maximum wind energy capture and DC bus voltage stability on the basis of a simplified model. Xiao Xiao developed a structural diagram of a DFIG-based wind turbine. This diagram integrates grid dispatch and local unit control to simulate the entire system. It facilitates the study of each component's characteristics and allows for linearization of the model to establish the unit's state-space model [10].

3.2 Grid-Connection Characteristics of Doubly-Fed Wind Turbines

The grid-connection characteristics of DFIG-based wind turbines significantly impact wind power integration quality and grid stability. Key issues include the following: During grid voltage dips, the unit must maintain grid connection through dynamic reactive power compensation to avoid disconnection. This requires strong low-voltage ride-through (LVRT) capability. The rotor-side converter regulates the direct-axis component of the rotor current to provide reactive power output, thereby supporting grid voltage stability. Additionally, the unit's operation introduces higher-order harmonics, which must be suppressed through filters or improved modulation strategies to reduce harmonic distortion. Tan ZhuKui et al. developed a complete model of a DFIG wind turbine and its control system. They studied grid-connection control strategies for DFIG wind turbines in modern power systems. The strategy constructs a mathematical model in the dq reference frame and uses Park transformation to further decouple active and reactive power. It enables stable variable-speed constant-frequency operation under different wind speeds by tracking power command values [11].The simulation model for the calculation of the current control loop is illustrated in Fig. 3.

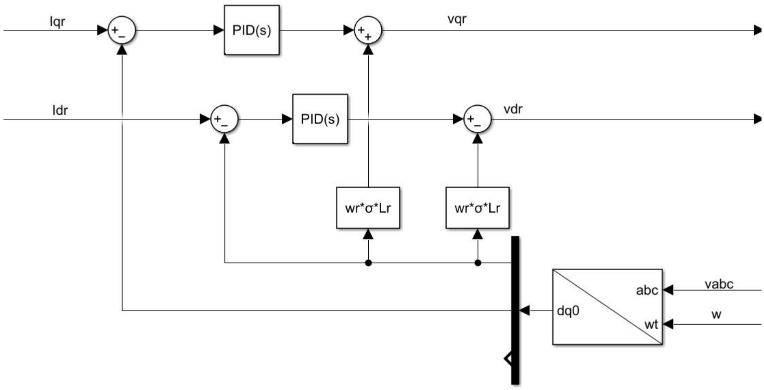

Fig. 3. Current control loop with cross term feedforward compensation[11]

3.3 Optimization and Control of Doubly-Fed Wind Turbines

(1) Pitch Angle Optimization: Above rated wind speed, dynamic pitch angle adjustment limits mechanical power to prevent unit overload. Lv Yi analyzed the basic laws of variable pitch control and designed a pitch control system combining fuzzy RBF neural network theory with PID control. By dynamically adjusting the pitch angle, the system achieves optimal control effects, ensuring stable power output and protecting the turbine components from excessive mechanical stress.Considering the multi-variable and nonlinear characteristics of wind turbines, this approach achieves ideal control effects by reasonably adjusting the pitch angle [12].As shown in Fig.4,this is the model of a doubly-fed wind turbine generator in a rotating coordinate system.

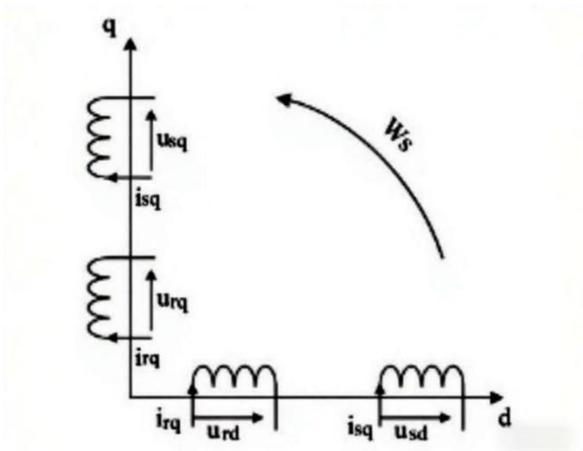

Fig. 4. Double-fed Wind Turbine Generator Model in Rotating dq Coordinate System[12]

(2) Intelligent Control Algorithms: Intelligent control algorithms such as fuzzy control and model predictive control(MPC)replace traditional PI control to enhance system dynamic response and anti-interference capability. Wang Hao et al. proposed a control strategy combining an extended state observer with model predictive direct power control. This strategy effectively mitigates the impact of uncertainties such as motor parameter perturbations and grid voltage fluctuations on the control system.This integrated approach significantly improves the system's dynamic response, robustness, and overall performance, making it a promising solution for enhancing the stability and efficiency of doubly-fed wind turbines [13].

3.4 Discussion

DFIG wind turbine simulation uses high-precision mathematical models to replicate unit dynamics, providing a reliable basis for control strategy design. It supports rapid parameter adjustment, facilitating optimized design and fault analysis. This approach significantly reduces costs and risks while shortening the development cycle. However, simulation errors may arise from model simplification, especially when nonlinear factors are ignored, leading to deviations from actual results. High-precision simulations also have high computational complexity, limiting real-time performance. Moreover, simplified grid interaction makes it difficult to simulate the true characteristics under complex grid conditions.

4 Limitations and Outlook

This review of the latest developments in wind power generation simulation systems, primarily based on doubly-fed induction generator (DFIG) units, and photovoltaic (PV) power generation simulation systems centered on maximum power point tracking (MPPT) algorithms reveals several limitations in current renewable energy system simulations. Simulation models are often based on ideal conditions and fail to fully capture the complex meteorological variations and grid fluctuations encountered in actual operation. The dynamic response characteristics of DFIG units and the nonlinear nature of PV systems are challenging to match precisely in simulations, resulting in actual performance that falls short of expectations. Moreover, existing simulation systems tend to focus on optimizing single energy sources and lack research on coordinated control of hybrid systems, such as wind-solar complementary systems. This limits their application in integrated renewable energy systems. Future simulation systems are expected to evolve towards higher precision, stronger adaptability, and broader application scopes. With the integration of artificial intelligence and big data technologies, the ability of simulation models to replicate complex environments will be enhanced, and algorithm robustness will be improved. Coordinated optimization of hybrid wind-solar systems will become a key focus, with multi-energy coordinated control aimed at achieving more efficient utilization. The application of edge computing and cloud computing technologies will increase the computational efficiency of simulation systems, supporting large-scale real-time simulations. As the proportion of renewable energy increases, simulation systems will play a more significant role in smart grids and energy internet applications.

5 Conclusion

Simulation systems have provided essential support for the technical optimization and system design of renewable energy generation. This study investigated MPPT technology for PV power generation systems and simulation of DFIG-based wind power generation systems. The results demonstrate that optimized MPPT algorithms can significantly enhance the power generation efficiency of PV systems, while accurate DFIG models effectively improve the operational stability and control performance of wind power systems. These research findings hold positive implications for advancing renewable energy generation technologies and promoting their large-scale application. They also provide theoretical and practical guidance for the simulation design and performance optimization of renewable energy generation systems. Future research can further explore multi-energy coordinated simulation and intelligent optimization control to achieve efficient integration and stable operation of renewable energy systems.

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