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WHALE OPTIMIZATION-BASED PI CONTROL FOR DFIG WIND ENERGY SYSTEMS WITH MODULAR MULTILEVEL GRID-SIDE CONVERTER

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ABSTRACT

As wind energy continues to play a key role in the transition to sustainable power, optimizing the performance of Doubly Fed Induction Generator (DFIG) systems is becoming increasingly essential. Traditional control strategies for DFIG-based wind energy systems often struggle with challenges such as limited adaptability to changing wind conditions, suboptimal power quality, and inefficiencies in grid integration. These issues are further complicated by the complexities of grid-side converters, which are crucial for maintaining stable operation and improving power quality. This paper introduces an innovative control strategy for DFIG wind energy systems, utilizing a Whale Optimization Algorithm (WOA)-based Proportional-Integral (PI) controller in combination with a Modular Multilevel Converter (MMC) for grid-side applications. The proposed approach aims to enhance the dynamic performance and stability of DFIG systems, while effectively managing power flow between the rotor and the grid. By taking advantage of the adaptive nature of the WOA, the PI controller is optimized in real-time, allowing it to adjust to varying wind conditions and maximize energy extraction. The integration of the MMC improves power quality, reduces harmonic distortion, and ensures better grid compliance. Simulation results show that the WOA-optimized PI controller significantly outperforms traditional control strategies in terms of response time, tracking accuracy, and overall system efficiency. This work contributes to the advancement of renewable energy technologies, supporting the effective integration of wind energy into modern power grids. The project is implemented using MATLAB Simulation 2021a.

Keywords: multilevel converter, grid, whale optimization, induction generator.

I. INTRODUCTION

Doubly Fed Induction Generators (DFIG) have gained significant traction in the renewable energy sector, especially for wind power generation. This technology effectively converts the kinetic energy of the wind into electrical energy, offering a flexible and efficient solution for integrating renewable energy sources into the power grid. The operation of a DFIG is based on the principles of electromagnetic induction, where the rotor is supplied with currents at variable frequencies, enabling precise control over both active and reactive power output. A key component of the DFIG is the wound rotor induction machine, coupled with a power electronic converter that facilitates variable speed operation—an essential feature for adapting to fluctuating wind speeds. Unlike traditional synchronous generators, DFIGs can operate over a broad range of wind speeds, maximizing energy capture and improving overall system efficiency. The rotor circuit connects to a back-to-back converter that interfaces with the grid, providing the ability to control both active and reactive power. This feature is critical for maintaining grid stability and reliability.

One of the key advantages of DFIG technology is its ability to operate at variable speeds while still maintaining a stable frequency output to the grid. This ensures enhanced efficiency in energy generation and greater adaptability to changing environmental conditions. As wind speeds fluctuate, the DFIG adjusts its rotor speed to optimize energy capture without affecting grid synchronization. Seyed Reza Mosayyebi et al. (2022) focused on improving Fault Ride-Through (FRT) capability in Doubly-Fed Induction Generator (DFIG)-based wind turbines through the use of Modified Active Disturbance Rejection Control (ADRC). This research addresses a critical issue in renewable energy systems, as DFIG-based wind turbines are vulnerable to grid faults. Enhancing FRT capability ensures their stable operation during voltage sags and other grid disturbances. The Modified ADRC has shown potential in managing both internal and external disturbances without requiring an exact system model. According to the literature, the use of Modified ADRC improves system robustness by dynamically compensating for disturbances, resulting in

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better response time and maintaining the turbine's connection to the grid during faults. Key benefits include enhanced stability, reduced reliance on precise system modeling, and improved dynamic performance under grid faults. However, challenges include the complexity of tuning ADRC parameters, higher computational demands, and difficulties in implementing this approach on large-scale wind farms.

In a separate study, Mohamed I. Mosaad et al. (2022) examined the issue of Ferro resonance overvoltage in grid-connected Wind Energy Conversion Systems (WECS), which can cause equipment damage and operational instability. The study explores the use of a Static Synchronous Compensator (STATCOM) to mitigate Ferro resonance overvoltage. STATCOM, a Flexible AC Transmission System (FACTS) device, injects reactive power into the grid, helping stabilize voltage fluctuations and dampen Ferro resonance conditions. Within the context of WECS, STATCOM aids in maintaining voltage stability during faults, switching events, or sudden disconnections, thus preventing Ferro resonance. The literature indicates that STATCOM not only mitigates overvoltage but also enhances overall power quality and reliability in wind energy systems. However, the implementation of STATCOM is costly, and its control strategies require careful tuning to handle varying grid conditions effectively.

II. CONVENTIONAL SINGLE MACHINE EQUIVALENT MODEL

Doubly-fed induction generator (DFIG)-based wind turbines have emerged as a leading choice for large-scale wind power generation systems (WPCS) due to their low cost, high efficiency, and scalability. In real-world applications, the integration of modular multilevel converter high-voltage direct current (MMC-HVDC) technology is commonly used to transmit wind energy over long distances, especially in remote areas, helping mitigate transmission challenges faced by wind farms. However, the interaction between DFIG and MMC stations can result in frequent disturbances, which may threaten the stability and power consumption of WPCS. Since the 2014 oscillation incident at a German North Sea wind farm, the stability of DFIG-WPCS connected to MMC-HVDC has become a significant concern in the wind power industry. The phenomenon of one-time input, dual-frequency output (SIDO) is prevalent in power electronic devices and often manifests as dual-frequency resonance in real-world oscillation scenarios. For instance, in a DFIG-WPCS setup, injecting a perturbation voltage with frequency fpf_pfp into the point of common coupling (PCC) can produce two distinct current frequencies: fpf_pfp and fp−2f1f_p - 2f_1fp−2f1, where f1f_1f1 is the frequency of the system's components. The primary cause of this dual-frequency response is the asymmetry in the control structure or parameters, which can manifest as a dual motor phenomenon in the system's connection. Importantly, these dual-frequency disturbances can lead to high-frequency coupling between the DFIG and the MMC, affecting the stability of both the DFIG-WPCS and the MMC-HVDC system

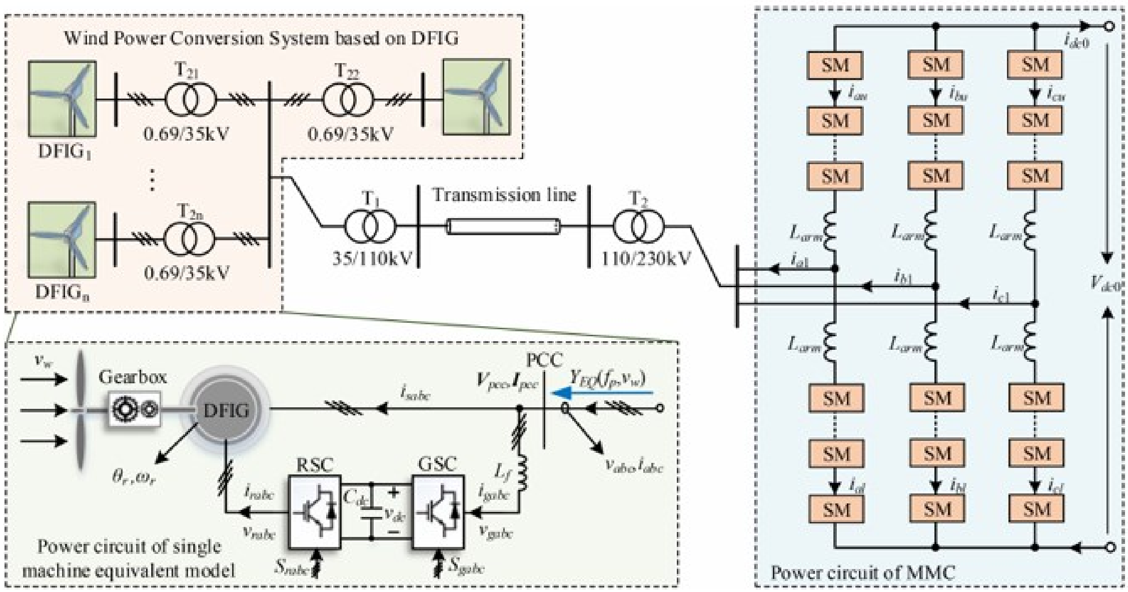

Figure 1. Block diagram of the conventional system

The current system presents the quantification of the fixed wind speed range for small signal sub-synchronous resonance (SSR) in DFIG-based wind energy converters, with a focus on determining frequency coupling. Identifying the fixed wind speed range of small signal SSR is crucial for the efficient planning of agricultural wind supply. However, there are limited methods available to accurately measure the fixed wind speed range of DFIG-WPCS small signal SSR. Additionally, the coupling gap between the DFIG-WPCS and multi-phase high voltage direct current (MMC-HVDC) systems can lead to incorrect measurement results.

III. PROPOSED WHALE OPTIMIZED CONTROLLER

The growing global demand for energy and rising environmental concerns have accelerated the transition to renewable energy sources, with wind energy emerging as a key player. Wind energy systems using Doubly-Fed Induction Generators (DFIGs) have become increasingly popular due to their efficient power generation capabilities and their ability to adapt to fluctuating wind speeds. The integration of advanced control strategies with DFIGs can significantly improve system stability, efficiency, and reliability. A promising approach involves using Proportional-Integral (PI) controllers, which are well-known for their simplicity and effectiveness in regulating system dynamics. However, traditional PI controllers often struggle with the nonlinear and time-varying characteristics of wind energy systems. To address these challenges, optimization algorithms are increasingly being used to fine-tune the parameters of PI controllers. Among these algorithms, the Whale Optimization Algorithm (WOA) has gained recognition for its robustness and efficiency. Inspired by the social hunting behavior of humpback whales, WOA excels at solving complex optimization problems by effectively balancing exploration and exploitation in the search space. By integrating WOA-optimized PI control with DFIG-based wind energy systems, improvements in dynamic response, power quality, and grid stability can be achieved. Additionally, the Modular Multilevel Converter (MMC) is gaining attention as an efficient and highly flexible grid-side converter. MMCs offer benefits such as scalability, reduced harmonic distortion, and high efficiency, making them well-suited for modern power systems. Combining the strengths of WOA-optimized PI control with MMC technology provides a promising solution to the challenges of grid integration and performance enhancement in wind energy systems.

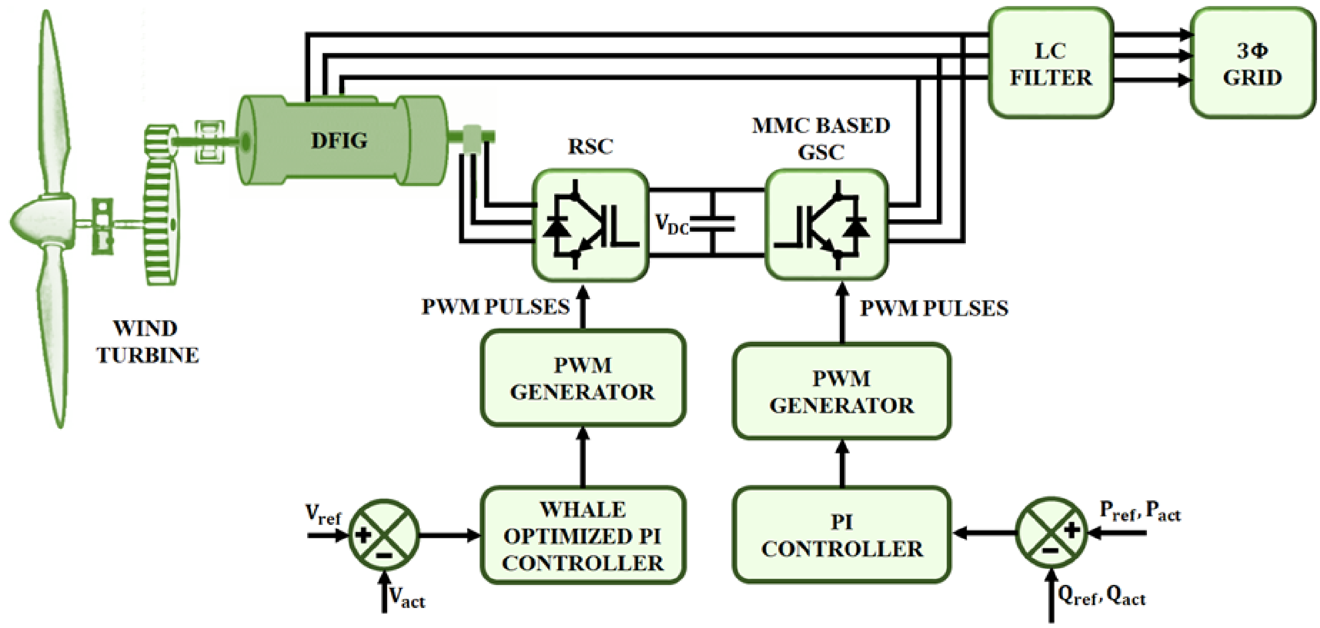

Figure 2. Block diagram of the proposed system

This work proposes an optimization-based PI control strategy for DFIG-based wind energy systems, integrated with a modular multilevel grid-side converter. The process begins with the wind turbine capturing kinetic energy from the wind, converting it into mechanical energy that drives the DFIG rotor. This setup enables the DFIG to operate at variable speeds, optimizing efficiency under varying wind conditions. The rotor is connected to the grid through a pair of back-to-back converters: the Rotor Side Converter (RSC) and the Grid Side Converter (GSC). The RSC converts the rotor's variable output into controlled AC power, regulating rotor currents to maintain optimal slip for maximum power extraction. To enhance system performance, the Whale Optimization Algorithm (WOA) is used to optimize the parameters of the PI controller, improving its ability to track set points and respond more effectively. The optimized PI controller adjusts PWM signals based on the difference between the reference voltage and the actual voltage, ensuring precise voltage regulation. The Modular Multilevel Converter (MMC) plays a key role in efficiently converting DC to AC while minimizing losses. It employs multiple voltage levels to reduce stress on individual devices, and the output is smoothed using an LC filter before being fed into the 3-phase grid. Additionally, the GSC interacts with the grid, providing reactive power support and ensuring system stability

IV. RESULTS AND DISCUSSIONS

MATLAB and SIMULINK are powerful tools for analyzing simulation results, especially in client environments where problems and solutions are represented with well-established codes. MATLAB excels in signal analysis, making it an ideal choice for computational and visualization tasks. For this analysis, tools like PLECS were used to model the grid voltage, PV strings, modulation stages, and power converters. The simulation was designed to match the conditions of a real-world experimental setup to validate the results. It's important to note that the simulation settings were chosen based on a reduced-power prototype experiment. MATLAB is an interactive programming language widely used by researchers and professionals across various fields, including accounting, communications, management, and signal/image processing. It offers an intuitive environment for simulating and representing physical mathematical models. SIMULINK, an extension of MATLAB, simplifies the modeling process by providing a graphical interface for dynamic systems analysis. This is especially useful for studying complex systems' responses quickly, particularly when solving mathematical models analytically is not feasible. SIMULINK enables numerical approximations, using physical laws to create equations that represent specific systems in simulations.

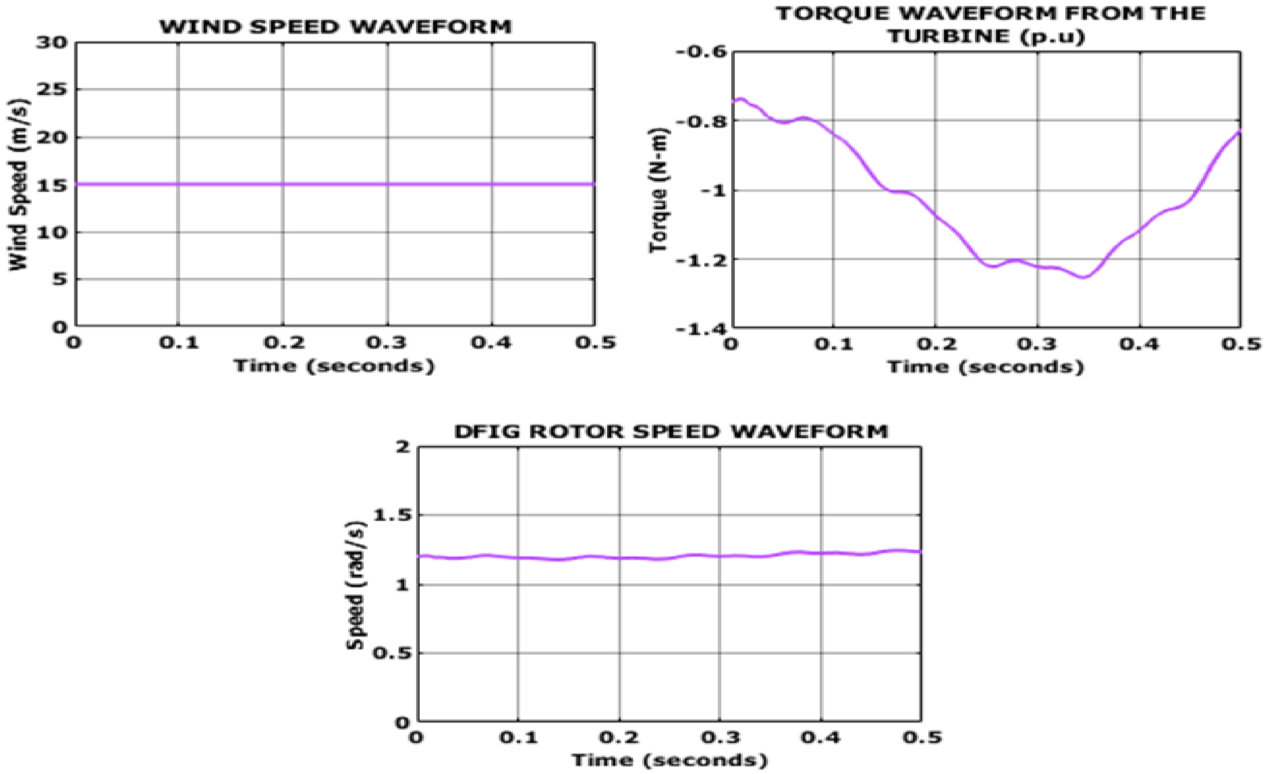

Figure 3. Output waveforms

The top left graph displays a constant wind speed of 25 m/s over time, signifying stable wind conditions. In the top right, the torque waveform from a turbine fluctuates between -0.8 and 0.8 p.u., representing varying operational states. The bottom graph shows the rotor speed of a DFIG, which remains steady at 15 rad/s.

V. CONCLUSION

A DFIG-based Wind Energy Conversion System (WECS) with a WOA-optimized PI controller is proposed for enhanced control. The integration of a Modular Multilevel Converter (MMC) for the grid-side converter ensures superior voltage regulation, harmonic reduction, and overall power quality. By using Whale Optimization Algorithm (WOA) to fine-tune the PI controller parameters, the system achieves improved dynamic performance, effectively handling fluctuations in wind speed and grid disturbances. Simulation results in MATLAB demonstrate significant improvements in system stability, minimizing overshoot and total harmonic distortion (THD), while enhancing transient stability. The combination of the optimized PI controller and MMC-based grid converter leads to a minimized THD of 0.62%, reduced ripples, and faster response times. This approach provides an effective solution to the challenges of intermittent wind energy generation, contributing to the development of more efficient and stable wind power systems for future renewable energy applications

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