Scholarly Research Journal for Interdisciplinary Studies
Online ISSN 2278-8808, SJIF 2025 = 8.486
https://www.srjis.com/issues_data/276
Peer Reviewed & Refereed Journal, NOV-DEC 2025, Vol- 14/92

PERFORMANCE ENHANCEMENT OF DFIG-BASED WIND ENERGY CONVERSION SYSTEMS USING AN IMPROVED PERTURB AND OBSERVE MPPT STRATEGY

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Paper Received On: 20 NOVEMBER 2025

Peer Reviewed On: 24 DECEMBER 2025

Published On: 01 JANUARY 2026

Abstract

Wind energy has become one of the most widely adopted renewable energy resources due to its scalability and environmental benefits. The performance of a wind energy conversion system (WECS) largely depends on its ability to extract maximum available power under varying wind conditions. This work presents a DFIG-based wind energy conversion system employing an improved Perturb and Observe (P&O) maximum power point tracking (MPPT) strategy. A detailed MATLAB/Simulink model incorporating a DFIG wind turbine, rotor-side converter, grid-side converter, and DC–DC buck–boost converter is developed. The MPPT controller generates the switching signals required to regulate converter operation and improve energy extraction. Simulation results obtained from the developed model demonstrate stable active and reactive power characteristics and improved tracking capability. The study confirms that integrating an improved P&O controller with a DFIG system provides an effective and practical solution for maximizing wind energy utilization.

Keywords: *DFIG, Wind Energy Conversion System, MPPT, Perturb and Observe, MATLAB/Simulink, Buck–Boost Converter.*

Introduction

The increasing demand for sustainable energy has accelerated the deployment of renewable energy technologies throughout the world. Among the available renewable resources, wind energy has emerged as a commercially viable option because of its abundant availability and low environmental impact [11], [14]. Wind energy generation is one of the most promising methods of producing clean and sustainable electricity. The process begins when moving air transfers its kinetic energy to the blades of a wind turbine, causing the rotor to rotate. This mechanical rotation is converted into electrical energy through a generator, which is then supplied to the power grid. Modern wind energy systems employ advanced control techniques to maximize power extraction under changing wind conditions and improve overall efficiency. Due to its renewable nature, low environmental impact, and growing technological advancements, wind energy continues to play a significant role in meeting future energy demands.Modern wind turbines are required to operate under continuously changing wind conditions, making maximum power extraction a critical requirement.

The Doubly Fed Induction Generator (DFIG) is extensively used in variable-speed wind turbines because it provides flexible speed control, independent active and reactive power regulation, and reduced converter rating requirements [1], [3]. However, achieving maximum energy extraction requires an efficient MPPT strategy capable of responding to wind speed variations.

Among various MPPT approaches, the Perturb and Observe method remains attractive because of its simplicity and ease of implementation [4], [13]. Nevertheless, conventional P&O control may exhibit oscillations around the optimum operating point. Therefore, an improved P&O strategy is implemented in this work to enhance tracking performance and system stability.

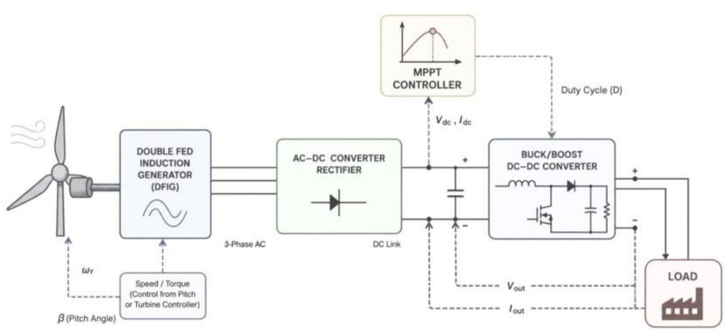

Figure (1) Schematic diagram of Buck converter and Boost converters

Wind Turbine Model

The wind turbine serves as the primary energy conversion component in a wind energy conversion system (WECS). Its main function is to capture the kinetic energy available in the moving air stream and convert it into mechanical energy that can be utilized by the generator. The amount of power extracted from the wind depends on several factors, including wind velocity, air density, turbine blade geometry, and rotor swept area. Because wind speed varies continuously, the operating point of the turbine must be adjusted to ensure maximum energy extraction under changing environmental conditions [2], [13]

The aerodynamic performance of a wind turbine is commonly represented by the power coefficient (C_p), which indicates the fraction of available wind power that can be converted into useful mechanical power. The value of C_p is influenced by the tip-speed ratio (λ) and blade pitch angle (β). For a given wind speed, maximum energy extraction is achieved when the turbine operates at its optimum tip-speed ratio, where the power coefficient reaches its maximum value [13].

The mechanical power captured by the wind turbine is expressed as

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_w^3$$

where P_m represents the mechanical power developed by the turbine, ρ is the air density, A is the rotor swept area, V_w is the wind speed, and C_p is the power coefficient

DFIG-Based Wind Energy Conversion System

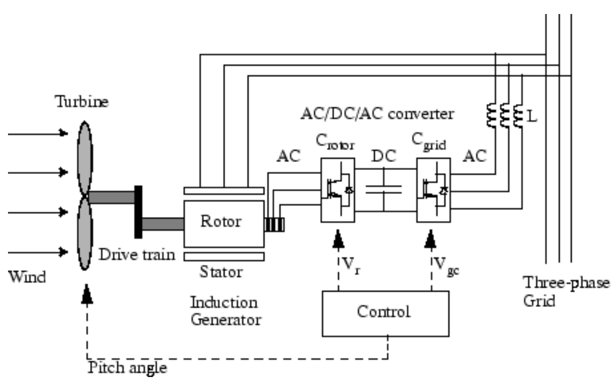

Fig2 DFIG block diagram

The Doubly Fed Induction Generator (DFIG) has become one of the most widely adopted generator technologies in modern variable-speed wind turbines due to its high efficiency, flexible operating range, and reduced converter rating requirements. Unlike conventional induction generators, the DFIG allows independent control of active and reactive power while maintaining synchronization with the utility grid. This characteristic makes it particularly suitable for large-scale wind farm applications where grid stability and power quality are critical requirements [1], [3].

A typical DFIG-based wind energy conversion system consists of a wind turbine, gearbox, doubly fed induction generator, rotor-side converter (RSC), grid-side converter (GSC), DC-link capacitor, and associated control systems. The wind turbine captures kinetic energy from the wind and converts it into mechanical torque. Through the gearbox, this mechanical energy is transmitted to the generator shaft, where electrical energy is produced.

The stator winding of the DFIG is directly connected to the grid, whereas the rotor winding is connected through back-to-back voltage source converters. This configuration enables bidirectional power flow and allows the generator to operate efficiently under sub-synchronous and super-synchronous speed conditions [19]. The rotor-side converter primarily regulates electromagnetic torque and reactive power, while the grid-side converter maintains DC-link voltage stability and ensures proper power exchange with the utility network [18].

The mechanical power available from the wind turbine is determined by the wind speed and aerodynamic characteristics of the rotor blades. Since wind power is proportional to the cube of wind velocity, small variations in wind speed can result in significant changes in power output. Therefore, maintaining operation near the optimum power coefficient becomes essential for maximizing energy extraction [13].

The active and reactive powers generated by the DFIG are represented as

$$P_s = \frac{3}{2}\left(V_{ds}I_{ds} + V_{qs}I_{qs}\right)$$

$$Q_s = \frac{3}{2}\left(V_{qs}I_{ds} - V_{ds}I_{qs}\right)$$

where

P_s= Stator active power (W)

Q_s=Stator reactive power (var)

V_{ds} ,V_{qs}=d-q axis stator voltages (V)

I_{ds}, I_{qs} = d-q axis stator currents (A)

Maximum Power Point Tracking (MPPT) Controller

Maximum Power Point Tracking (MPPT) is an essential control technique employed in renewable energy systems to maximize energy extraction under varying environmental conditions. In wind energy conversion systems, the available wind power changes continuously due to fluctuations in wind velocity. Therefore, an efficient MPPT controller is required to ensure that the wind turbine operates close to its optimum operating point and delivers maximum possible power to the electrical network [4], [13].

Several MPPT approaches have been reported in the literature, including Tip Speed Ratio (TSR) control, Optimal Torque (OT) control, Power Signal Feedback (PSF) control, and Perturb and Observe (P&O) control. In addition, advanced intelligent control techniques such as Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC), Particle Swarm Optimization (PSO), and hybrid optimization methods have been developed to improve tracking accuracy and dynamic performance [13], [18]. Although intelligent techniques offer enhanced performance, they generally require greater computational resources and more complex controller structures.

Among the available methods, the Perturb and Observe (P&O) algorithm remains one of the most widely adopted MPPT techniques because of its simple implementation, low computational burden, and satisfactory performance in practical applications [4]. For this reason, the present work utilizes the P&O algorithm to control the DFIG-based wind energy conversion system.

Perturb and Observe MPPT Control Method

Perturb and Observe method determines the maximum power operating point by introducing a small perturbation to the system operating variable and monitoring the resulting change in output power. The controller continuously compares the present power value with the preious measurement and adjusts the contrl signal accordingly. If the perturbaton leads to an increase in generated power, the operating point continues to move in the same direction. Conversely, if the output power decreases, the perturbation direction is reversed to drive the system back toward the maximum power region [4], [13].

In a DFIG-based wind energy conversion system, the generated electrical power is closely related to rotor speed and electromagnetic torque. Consequently, the MPPT controller indirectly regulates the operating condition of the generator by modifying the converter duty cycle. The controller receives voltage and current measurements from the system and calculates the corresponding output power. Based on the variation in measured power, the duty ratio of the buck–boost converter is updated through a PWM switching signal.

The generated PWM pulses regulate the switching operation of the converter, which in turn influences the DC-link voltage and rotor operating conditions. By continuously adjusting the duty cycle, the controller drives the wind turbine toward the optimum operating point corresponding to maximum energy extraction. This control strategy enables effective utilization of available wind energy while maintaining stable operation of the DFIG and associated power electronic converters

Buck–Boost Converter

The performance of a DFIG-based wind energy conversion system can be significantly influenced by the effectiveness of its power electronic interface. In the proposed system, a DC–DC buck–boost converter is employed between the converter stage and the DC-link to regulate voltage levels and support maximum power extraction. The converter operates under the supervision of the Perturb and Observe (P&O) MPPT controller, which continuously adjusts the converter duty ratio according to the available wind energy.

Unlike conventional buck or boost converters that can only decrease or increase voltage respectively, the buck–boost converter provides both operating modes within a single topology. This flexibility enables the system to maintain stable operation even when wind speed variations cause fluctuations in generator output voltage. As a result, the converter assists the MPPT controller in maintaining the operating point near the maximum power region.

MATLAB/Simulink Model Development:

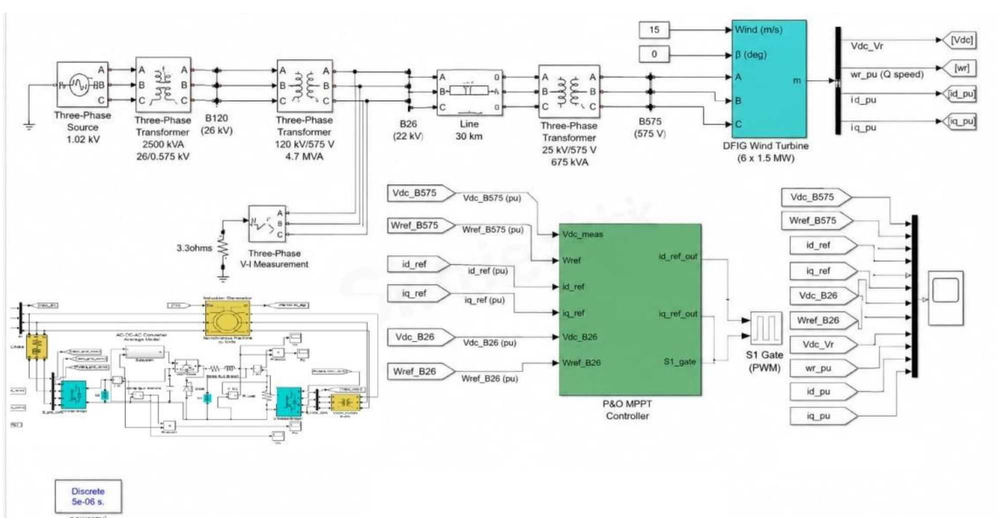

Fig4 Simulink Modal Wind Farm-Dfig Detailed Modal

The wind turbine block receives wind speed and pitch angle inputs and generates the corresponding mechanical torque required for generator operation. The turbine output is connected to the DFIG model, which serves as the primary energy conversion unit. The DFIG subsystem generates electrical output while providing critical feedback signals such as rotor speed, direct-axis current, quadrature-axis current, and DC-link voltage. These parameters are continuously monitored and supplied to the MPPT controller for determining the optimum operating point. A DC–DC buck–boost converter is incorporated between the converter stages to regulate the DC-link voltage and improve energy transfer efficiency. The converter consists of an inductor, switching device, diode, and output capacitor. The switching operation is controlled through pulse width modulation (PWM) signals generated by the MPPT controller.

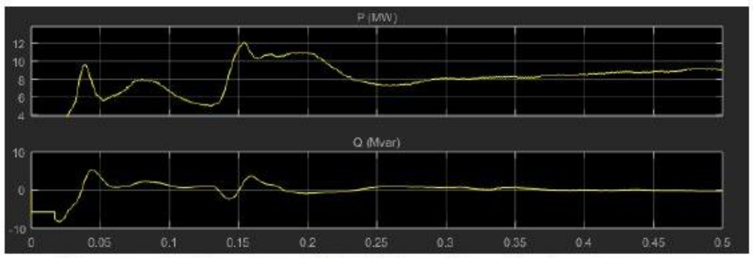

Fig5 Output of P&O by using Buck converter

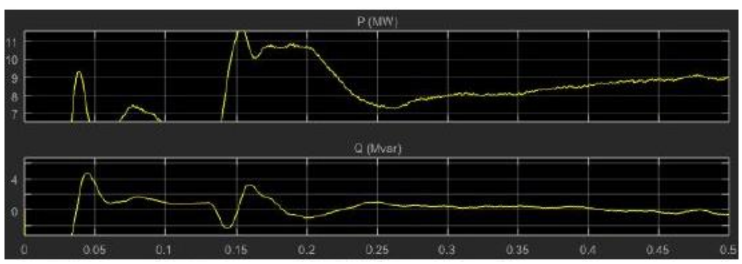

Figure 6 Output of P&O by using Boost converter

Figures 5 and 6 show the active power ((P)) and reactive power ((Q)) responses obtained using buck and boost converter configurations.

In the buck converter case, the active power initially exhibits transient oscillations before settling near the maximum operating region. The reactive power also experiences temporary fluctuations and gradually approaches a stable value. This indicates successful tracking of the maximum power point by the MPPT controller.

For the boost converter configuration, the active power reaches the steady-state condition more smoothly with reduced oscillations. The reactive power variations are also lower compared with the buck converter. The improved response demonstrates better voltage regulation and enhanced utilization of the available wind energy.

From the simulation results, it is evident that both converter configurations enable effective maximum power extraction. However, the boost converter provides improved dynamic performance, faster settling, and reduced steady-state oscillations. Therefore, the proposed P&O MPPT controller combined with the boost converter offers better overall performance for the DFIG-based wind energy conversion system

Conclusion

This paper presented a DFIG-based wind energy conversion system incorporating a Perturb and Observe (P&O) maximum power point tracking technique for improved energy extraction under varying operating conditions. A detailed MATLAB/Simulink model consisting of a wind turbine, DFIG, power electronic converters, and a buck–boost converter was developed to evaluate the effectiveness of the proposed control approach.

The simulation results demonstrated that the MPPT controller was capable of tracking the maximum power operating region and maintaining stable active and reactive power characteristics. Both buck and boost converter configurations achieved satisfactory performance; however, the boost converter exhibited smoother power response and reduced oscillations during steady-state operation. The coordinated operation of the DFIG, converter system, and MPPT controller contributed to improved utilization of the available wind energy and enhanced overall system stability.

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