Sciences Methods and Technologies International Journal (SciMeTech)

ISSN: 3085-5284, journal homepage: www.scimetech.com

Toward Robust Wind Turbine Control: From Disturbance Management Using LADRC to AI-Based Fault Prediction (GEO-ANN)

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How to cite:
Chahri Marouane, Ali Boukhriss, "Toward Robust Wind Turbine Control: From Disturbance Management Using LADRC to AI-Based Fault Prediction (GEO-ANN)", Sciences Methods and Technologies International Journal (SciMeTech), Vol 2, Issue 1, p 99-104

Keywords:
Wind energy conversion systems
DFIG
LADRC
LVRT
Bi-LSTM
Backstepping Control
GEO-ANN
Grid Stability

Abstract

The large-scale integration of wind energy using Doubly Fed Induction Generators (DFIGs) poses significant challenges to grid stability. Due to the inherent intermittency of wind and the sensitivity of power converters to disturbances, maintaining a stable and high-quality power output remains a critical issue. This paper presents a comprehensive review of advanced control strategies for DFIG-based wind energy systems, with particular emphasis on Linear Active Disturbance Rejection Control (LADRC) combined with Bi-LSTM neural networks, the nonlinear Integral Backstepping (IBSC) controller, and the GEO-ANN method. These approaches, as reported in the literature, demonstrate significant improvements in mitigating power oscillations, enhancing power quality, and increasing system robustness under grid disturbances such as voltage dips. The reviewed results highlight the effectiveness of these techniques in reducing total harmonic distortion (THD) and improving fault detection capabilities. Overall, this study underscores the growing role of intelligent and hybrid control methods in stabilizing modern power systems and outlines future research directions toward large-scale industrial implementation.

I. Introduction

The escalating integration of wind energy into modern power systems has introduced significant challenges concerning grid stability, power quality, and fault tolerance [1]. Among the prevailing wind energy conversion technologies, Doubly Fed Induction Generators (DFIGs) are widely adopted due to their variable-speed operational range and their capacity for independent active and reactive power control [2]. However, the direct connection of the DFIG stator to the utility grid makes these systems exceptionally sensitive to disturbances (Fig. 1). Transient events, particularly voltage dips, can induce severe rotor overcurrent and DC-bus voltage fluctuations, potentially leading to system instability or hardware failure [3].

To address these vulnerabilities, the research community has pivoted toward advanced control architectures. Linear Active Disturbance Rejection Control (LADRC) has emerged as a powerful alternative to traditional PI controllers [4 boukhriss], valued for its ability to estimate and compensate for internal and external uncertainties without requiring an exhaustive mathematical model. Recent studies have further enhanced this approach by integrating Bi-directional Long Short-Term Memory (Bi-LSTM) neural networks, which leverage time-series forecasting to improve dynamic performance and disturbance rejection under stochastic wind conditions [5].

In parallel, nonlinear control strategies such as Integral Backstepping Control (IBSC) have demonstrated superior robustness. By utilizing Lyapunov-based stability criteria, IBSC ensures precise tracking performance and resilience against parameter variations and asymmetrical grid faults, which are common in weakened distribution networks [6].

More recently, the focus has shifted toward hybrid intelligent systems. The integration of metaheuristic algorithms with machine learning, specifically the Golden Eagle Optimizer combined with Artificial Neural Networks (GEO-ANN), has been proposed to enhance Low Voltage Ride-Through (LVRT) capabilities [7]. This hybrid approach optimizes mechanical and electrical parameters while predicting fault trajectories, significantly reducing total harmonic distortion (THD) and ensuring continuous grid connection during sags.

Despite these individual advancements, there is a critical need for a comparative synthesis of these diverse methodologies. Therefore, this paper presents a comprehensive review of the Bi-LSTM-LADRC, IBSC, and GEO-ANN approaches as applied to DFIG-based wind energy conversion systems. The objective is to evaluate their respective effectiveness in improving power quality, suppressing oscillations, and reinforcing system robustness under adverse grid conditions.

II. DFIG System Modelling & Challenges

a. Mathematical Modelling of the DFIG

A precise mathematical representation is essential for designing robust controllers. The DFIG is typically modeled in the synchronous *dq*-reference frame. The stator and rotor voltage equations are expressed as follows:

$$V_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{ds}$$

$$V_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} - \omega_s \psi_{ds}$$

$$V_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_s - \omega_r)\, \psi_{qr}$$

$$V_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_s - \omega_r)\, \psi_{dr}$$

Where V, i, and ψ represent voltage, current, and flux, respectively, and ω_s and ω_r denote the synchronous and rotor angular speeds. The coupling between the stator and rotor through the mutual inductance L_m creates a multivariable, nonlinear system where disturbances in the grid side are directly reflected in the rotor circuit.

b. Wind Turbine Modelling

The mechanical power extracted from the wind by a turbine is governed by aerodynamic laws and is expressed as:

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

Where:

- ρ is the air density (kg/m^3).
- R is the rotor blade radius (m).
- υ is the wind speed (m/s).
- Cp is the power coefficient, representing the turbine's efficiency.

The power coefficient C_p is a nonlinear function of the pitch angle (β) andthe tip speed ratio (λ), which is defined as the ratio between the blade tip speed and the wind speed:

$$\lambda = \frac{\Omega_t \mathrm{R}}{\upsilon}$$

Where Ω_t is the mechanical angular speed of the turbine. For a DFIG system, the primary objective of the control system under normal wind conditions is to adjust the generator speed to maintain λ at its optimal value (λ_{opt}), thereby maximizing C_p and the captured energy

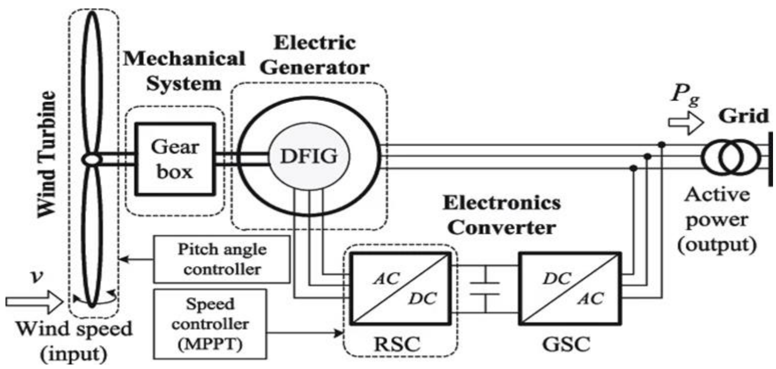

Fig. 1 *Variable-speed wind turbines*

c. Critical Challenges in DFIG-Based Grid Integration

Despite the efficiency of DFIG-based wind energy conversion systems (WECS), their operational stability is hindered by three primary technical hurdles. These challenges serve as the motivation for the advanced control strategies reviewed in this paper.

i. Sensitivity to Grid Voltage Dips (LVRT Compliance)

Because the DFIG stator is directly coupled to the utility grid, any sudden drop in grid voltage (voltage sag) results in a mismatch between the stator and rotor flux. This mismatch induces high transient currents in the rotor windings, which can exceed the thermal limits of the sensitive power electronic converters. As highlighted in the GEO-ANN study, ensuring Low Voltage Ride-Through (LVRT) capability is mandatory; the system must remain connected and support the grid during faults rather than tripping. Achieving this without expensive hardware (like crowbar circuits) requires extremely fast and intelligent fault detection and compensation.

ii. Oscillations under Unbalanced Grid Conditions

The electrical grid often suffers from asymmetrical faults, creating "negative sequence" components in the voltage. As detailed in the Integral Backstepping research, these negative sequences interact with the machine's internal fields to produce:

- Double-frequency torque ripples (100 Hz): These cause severe mechanical stress on the turbine shaft and gearbox.
- DC-Bus Voltage Fluctuations: Unbalanced currents lead to ripples in the DC-link capacitor, reducing the lifespan of the converters and introducing harmonics into the grid.

Standard PI controllers are generally incapable of decoupling these sequences, necessitating nonlinear robust control.

iii. Stochastic Wind Fluctuations and Uncertainty

The power extracted from a wind turbine is proportional to the cube of the wind speed (v^3). Small fluctuations in wind velocity lead to significant power surges or drops. Furthermore, the DFIG system is subject to internal uncertainties, such as varying mutual inductance and resistance due to temperature changes. The Bi-LSTM-LADRC study emphasizes that traditional controllers struggle with this "model uncertainty." To maintain Maximum Power Point Tracking (MPPT) while rejecting external turbulence, the controller must be able to "predict" wind behavior and "estimate" disturbances in real-time.

iv. Power Quality and Harmonic Distortion

The switching frequency of the Pulse Width Modulation (PWM) converters, combined with grid-side disturbances, often introduces high Total Harmonic Distortion (THD). Modern grid codes are becoming increasingly strict regarding THD levels. Reducing these harmonics while maintaining high dynamic response remains a balancing act for control engineers, particularly when the system is operating under non-ideal grid conditions.

III. Advanced Control Methodologies for DFIG-Based Systems

This section explores three distinct control paradigms: a hybrid AI-disturbance rejection approach for power optimization, a nonlinear structural method for grid unbalance, and an intelligent metaheuristic-neural network for fault ride-through enhancement.

a. Bi-LSTM-OTC-LADRC for Disturbance Estimation and Power Optimization

The first approach introduces an enhanced Linear Active Disturbance Rejection Control (LADRC) integrated with a Bidirectional Long Short-Term Memory (Bi-LSTM) network. This strategy is primarily designed to address the challenges of unpredictable wind speeds and internal system uncertainties.

- Mechanism: The Bi-LSTM network, optimized by the Catch Fish Algorithm (CFA), is used for short-term wind forecasting and Maximum Power Point Tracking (MPPT). It works alongside the Optimum Torque Control (OTC) to maximize power extraction.
- Role of LADRC: The LADRC serves as the core regulator for both active and reactive power. It utilizes a Linear Extended State Observer (LESO) to estimate and compensate for system disturbances in real-time without requiring an exact mathematical model of the turbine.

- Key Results: Simulation and Hardware-In-the-Loop (HIL) tests demonstrate that this hybrid approach achieves higher active power injection (up to 7.368×10^5 W) and faster DC-link voltage regulation compared to traditional PI and Sliding Mode Controllers (SMC) [8].

b. Nonlinear Integral Backstepping Control for Unbalanced Grid Conditions

The second strategy focuses on maintaining system stability during asymmetrical grid faults, which typically cause double-frequency oscillations in torque and DC-bus voltage.

- Dual-Loop Architecture: This methodology employs a dual-loop control strategy. The main loop regulates the positive sequence currents of the rotor and Grid-Side Converter (GSC), while an auxiliary loop is specifically designed to manage negative sequence currents.
- Control Implementation: Both loops are governed by a Nonlinear Integral Backstepping Controller (IBSC). Unlike standard PI controllers, the IBSC is robust against parameter variations and effectively decouples the positive and negative sequences to prevent thermal damage to the stator.
- Key Results: The strategy ensures the wind farm remains connected during severe faults while significantly minimizing the Total Harmonic Distortion (THD) and eliminating power profile ripples [9].

c. Hybrid GEO-ANN for Low Voltage Ride-Through (LVRT) Enhancement

The third approach proposes a hybrid intelligent strategy, termed GEO-ANN, to safeguard the DFIG during significant grid voltage sags.

- Golden Eagle Optimizer (GEO): The GEO metaheuristic algorithm is utilized to optimize the mechanical power of the DFIG and determine ideal injector phase voltage values. This ensures that rotor and stator currents remain within safe operational limits during a fault.
- Artificial Neural Network (ANN): The ANN component is trained to accurately predict grid faults and detect stator voltage dips. This predictive capability allows the controller to react preemptively to grid instability.
- Key Results: The GEO-ANN model achieves a high fault prediction accuracy of 97%. Furthermore, it reduces the THD to 1.78%, outperforming existing methods like Deep Q-Networks (DQN) and Mountain Gazelle Optimization (MGO) in terms of computational speed and power quality [10].

IV. Results and discussion

In Section III, we will compare the findings of the three studies to evaluate their collective impact on DFIG performance. This section highlights the transition from traditional control to the advanced intelligent frameworks discussed in Section II.

a. Comparative Analysis and Performance Discussion

The reviewed methodologies demonstrate a significant evolution in DFIG control, moving from fixed-gain linear controllers to adaptive, nonlinear, and AI-driven architectures. This section discusses their comparative advantages in terms of power quality, robustness, and fault management.

b. Comparison of Control Objectives and Robustness

While all three methods aim to stabilize the DFIG, their primary objectives differ based on the operational challenge:

- Bi-LSTM-LADRC excels in uncertainty estimation. By utilizing the Linear Extended State Observer (LESO), it treats external wind turbulence and internal parameter variations as a "total disturbance" to be rejected. This provides a smoother response compared to the IBSC and GEO-ANN when dealing with stochastic wind speed variations.
- Integral Backstepping (IBSC) offers the most rigorous mathematical stability. Because it is based on Lyapunov stability theory, it provides guaranteed convergence during asymmetrical faults, making it superior for maintaining structural integrity during unbalanced grid conditions where sequence decoupling is critical.

- GEO-ANN represents the highest level of predictive intelligence. By achieving a 97% accuracy in fault prediction, it allows the system to transition into "protection mode" faster than the reactive nature of LADRC or Backstepping.

c. Impact on Power Quality (THD and Ripples)

Power quality is a central benchmark across all three studies. The integration of AI and nonlinear loops shows a clear trend in reducing Total Harmonic Distortion (THD):

- The GEO-ANN approach reported a remarkable reduction in THD to 1.78%, which is significantly below the 5% limit set by international standards (IEEE 519).
- The IBSC strategy focuses on eliminating the 100 Hz ripples in torque and DC-link voltage. By suppressing the negative sequence current, it effectively "cleans" the power profile during grid unbalance, a task that standard AI-based predictors alone cannot achieve without a robust inner control loop.

d. Efficiency and Energy Extraction

The ability to maximize energy yield under varying conditions is a key performance indicator.

- The Bi-LSTM network provides a distinct advantage in MPPT (Maximum Power Point Tracking). By forecasting wind trends rather than just reacting to current speed, the system maintains the optimal tip-speed ratio λ_{opt} more effectively than the other two methods.

- Conversely, the GEO-ANN focuses more on efficiency during recovery, ensuring that the mechanical power is optimized immediately following a fault to minimize the "re-connection" lag.

e. Summary of Performance Metrics

The following table (Table 1) provides a high-level comparison of the performance outcomes reported in the reviewed literature:

Table 1: Comparative studies

Metric	Bi-LSTM-LADRC	Integral Backstepping	GEO-ANN
Primary Strength	Disturbance Rejection	Sequence Decoupling	Fault Prediction
THD Level	Improved	Highly Reduced	1.78% (Lowest)
Fault Response	Adaptive	Robust/Nonlinear	Predictive (97% Acc)
Implementation	HIL Validated	High Complexity	Optimization-heavy

V. Conclusion

The transition from traditional linear controllers to advanced intelligent frameworks marks a turning point in DFIG performance. While Integral Backstepping ensures rigorous mathematical stability during grid faults, the integration of Bi-LSTM and GEO-ANN introduces a layer of predictive resilience that significantly lowers THD and enhances disturbance rejection. Ultimately, the choice between these methods involves a trade-off between mathematical certainty and computational intelligence, with each offering unique advantages for modern grid integration.

Our subsequent research will move beyond the comparative evaluation of individual controllers to explore the synthesis of hybrid architectures. Specifically, we aim to investigate the integration of LADRC with GEO-ANN to create a "Predictive-Robust" control loop. This next phase will focus on:

- Hardware-in-the-Loop (HIL) scalability for real-time industrial deployment.
- Self-healing control loops that can autonomously switch between AI prediction and Backstepping stability modes based on the severity of the grid disturbance.

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