ISSN 2319-5991 www.ijerst.com

Peer Reviewed, Referred & Indexed Journal

Research Paper

DEVELOPMENT OF A SENSORLESS MULTILEVEL WIND POWER CONVERSION SYSTEM FOR EFFICIENT ENERGY CONVERSION AND POWER QUALITY IMPROVEMENT

GUDIPALLI JYOSHNA*, EASLAVATH HATHIRAM**

PG SCHOLAR*, ASSISTANT PROFESSOR**

ELECTRICAL & ELECTRONICS ENGINEERING, ABDUL KALAM INSTITUTE OF TECHNOLOGICAL SCIENCES, KOTHAGUDEM, TELANGANA, INDIA

PROBLEM STATEMENT

The increasing penetration of wind energy into modern power systems has introduced several operational challenges, including fluctuating power generation, voltage instability, harmonic distortion, poor power factor, and grid synchronization issues. Conventional wind power conversion systems (WPCSs) rely on mechanical speed sensors such as encoders and resolvers for rotor position and speed estimation, which increase system cost, reduce reliability, and require frequent maintenance under harsh environmental conditions. Moreover, nonlinear loads and grid disturbances degrade power quality by introducing harmonics, reactive power demand, and current imbalance, thereby affecting the overall performance and stability of the power system. Existing control strategies often fail to provide accurate sensorless operation while simultaneously ensuring effective power quality improvement under varying wind speed and grid conditions. Therefore, there is a need for a multifunctional wind power conversion system that enables reliable sensorless operation, enhances power quality, improves grid synchronization, and ensures efficient utilization of wind energy under dynamic operating conditions.

OBJECTIVES

1. To develop a **sensorless wind power conversion system** that eliminates the need for mechanical speed sensors while maintaining accurate rotor speed estimation.
2. To design an advanced **MRAS-based sensorless control algorithm** for reliable operation under variable wind speed conditions.
3. To improve **power quality** by reducing current harmonics, compensating reactive power, and maintaining unity power factor.
4. To ensure effective **grid synchronization** during voltage fluctuations, frequency variations, and nonlinear load conditions.
5. To regulate the **DC-link voltage** for stable power transfer between the wind generator and the utility grid.
6. To minimize the **Total Harmonic Distortion (THD)** of grid currents in accordance with IEEE 519 standards.
7. To enhance the **dynamic response and stability** of the wind energy conversion system during sudden changes in wind speed and load.
8. To validate the effectiveness of the proposed system through **MATLAB/Simulink simulation** and performance comparison with conventional sensor-based wind power conversion systems.

ABSTRACT

The increasing penetration of wind energy into modern power systems requires advanced control strategies to ensure reliable operation, high energy conversion efficiency, and compliance with grid power quality standards. Conventional wind power conversion systems (WPCS) rely on mechanical speed sensors for rotor position estimation, which increase system cost, reduce reliability, and require frequent maintenance under harsh environmental conditions. Moreover, nonlinear loads and grid disturbances introduce harmonics, reactive power demand, voltage fluctuations, and current imbalance, adversely affecting the overall performance of the grid-connected wind energy system. To address these challenges, this paper proposes a **multifunctional wind power conversion system with sensorless operation and integrated power quality improvement features**. The proposed system employs a **Model Reference Adaptive System (MRAS)-based sensorless control algorithm** to accurately estimate rotor speed without using mechanical sensors, thereby improving system reliability and reducing maintenance requirements. A **Fourth-Order Generalized Integrator (FOGI)-based control strategy** is incorporated to achieve precise grid synchronization, harmonic mitigation, reactive power compensation, and balanced current injection under varying wind speed and load conditions. The proposed controller also regulates the DC-link voltage, maintains unity power factor, and enhances the dynamic response during grid disturbances. The complete system is modeled and validated using MATLAB/Simulink under various operating scenarios, including wind speed variations, nonlinear loads, and voltage disturbances. Simulation results demonstrate significant improvements in power quality by reducing total harmonic distortion (THD), minimizing frequency and voltage fluctuations, and ensuring stable power delivery. The proposed multifunctional sensorless WPCS provides a cost-effective, reliable, and high-performance solution for grid-connected renewable energy applications while satisfying IEEE 519 power quality requirements and supporting sustainable power system development.

Keywords: Wind Power Conversion System (WPCS), Sensorless Control, Model Reference Adaptive System (MRAS), Fourth-Order Generalized Integrator (FOGI), Power Quality Improvement, Harmonic Mitigation, Grid Synchronization, Total Harmonic Distortion (THD), Renewable Energy, MATLAB/Simulink.

INTRODUCTION

The increasing demand for clean and sustainable energy has accelerated the deployment of **wind energy conversion systems (WECS)** as one of the most promising renewable energy technologies. Grid-connected wind power systems play a vital role in reducing greenhouse gas emissions and dependence on fossil fuels while supporting modern smart grid infrastructures. However, the intermittent nature of wind speed, voltage fluctuations, harmonics generated by nonlinear loads, and synchronization challenges significantly affect the reliability and power quality of conventional wind energy systems. Moreover, the use of mechanical speed sensors in wind turbines increases system cost, maintenance requirements, and susceptibility to environmental failures, thereby reducing overall system reliability.

To overcome these challenges, modern wind power conversion systems employ **sensorless control techniques** that estimate rotor speed using electrical measurements instead of mechanical sensors. Sensorless operation not only reduces hardware complexity and maintenance costs but also enhances system robustness and operational reliability. Advanced estimation techniques such as the **Model Reference Adaptive System (MRAS)** provide accurate speed estimation over a wide operating range without compromising dynamic performance.

In addition to sensorless operation, maintaining high power quality is essential for reliable grid integration. Harmonic distortion, reactive power demand, voltage imbalance, and poor power factor can degrade the performance of both the utility grid and connected loads. Therefore, advanced control algorithms based on **Fourth-Order Generalized Integrator (FOGI)**, adaptive filtering techniques, and intelligent current controllers are employed to mitigate harmonics, compensate reactive power, regulate DC-link voltage, and maintain unity power factor. These techniques ensure compliance with international standards such as **IEEE 519** and **IEC 61400-21**, thereby improving the overall power quality of the grid-connected wind energy system.

The proposed multifunctional wind power conversion system integrates sensorless speed estimation with advanced power quality enhancement techniques to achieve stable and efficient operation under varying wind speeds and grid disturbances. The coordinated control strategy enables accurate maximum power extraction, improved grid synchronization, harmonic suppression, balanced source currents, and fast dynamic response during transient conditions. Simulation and experimental results demonstrate that the proposed system offers superior performance in terms of reduced total harmonic distortion (THD), enhanced voltage regulation, improved system efficiency, and increased reliability compared to conventional wind energy conversion systems. Consequently, the proposed approach provides an effective and economically viable solution for next-generation renewable energy systems and smart grid applications.

LITERATURE REVIEW

The rapid growth of renewable energy integration has increased the demand for efficient and reliable **Wind Energy Conversion Systems (WECS)** with improved power quality and reduced maintenance requirements. Conventional wind power systems generally employ mechanical speed sensors such as encoders or resolvers for rotor position estimation. However, these sensors increase system cost, reduce reliability, and require periodic maintenance, particularly under harsh environmental conditions. To overcome these limitations, recent research has focused on **sensorless control techniques** combined with advanced power quality enhancement algorithms.

Alzhrani *et al.* (2025) proposed a **Model Reference Adaptive System (MRAS)** integrated with a **Fourth-Order Generalized Integrator (FOGI)** for sensorless wind power conversion systems. The proposed MRAS-FOGI controller accurately estimates rotor speed without mechanical sensors while maintaining balanced grid currents, unity power factor, and harmonic compensation. The system also complies with **IEEE 519** and **IEC 61400-21** standards under voltage disturbances, nonlinear loads, and fluctuating wind conditions. Simulation and real-time OPAL-RT validation demonstrated superior transient response, improved grid synchronization, and reduced current THD of approximately **4.32%**, outperforming conventional DSOGI and LMF-based techniques.

Earlier studies on **Permanent Magnet Synchronous Generator (PMSG)**-based WECS highlighted the advantages of sensorless control methods such as **Sliding Mode Observer (SMO)**, **Extended Kalman Filter (EKF)**, and **MRAS** for rotor speed estimation. Although these approaches eliminate mechanical sensors, many suffer from parameter sensitivity, computational complexity, or reduced estimation accuracy under rapidly varying wind speeds. Recent advancements therefore emphasize adaptive estimation methods capable of maintaining stability under dynamic operating conditions.

Power quality improvement has also become a major research focus because nonlinear loads and converter switching introduce harmonics, reactive power demand, and current imbalance into the grid. Various generalized integrator-based controllers, including **Second-Order Generalized Integrator (SOGI)**, **Dual SOGI (DSOGI)**, and **FOGI**, have been proposed to achieve harmonic mitigation, accurate synchronization, and fast grid current regulation. Among these, the FOGI-based controller offers faster settling time, improved harmonic rejection, and superior dynamic performance during voltage sags and unbalanced grid conditions.

Modern wind power systems increasingly employ **back-to-back voltage source converters** with intelligent control strategies to regulate active and reactive power independently. These converters improve maximum power extraction, stabilize the DC-link voltage, and ensure seamless integration with utility grids. Research has also shown that advanced converter control significantly enhances grid stability under high renewable energy penetration while supporting voltage regulation and reactive power compensation.

Recent review studies indicate that the future of wind energy lies in integrating **artificial intelligence**, adaptive control, and grid-forming converter technologies to improve forecasting, control optimization, and system resilience. Grid-forming inverter technologies are expected to provide synthetic inertia, enhanced frequency support, and improved stability in renewable-dominated power systems, making sensorless wind energy conversion systems more reliable and suitable for future smart grids.

Overall, the existing literature demonstrates that combining **sensorless MRAS-based speed estimation** with advanced **FOGI-based power quality enhancement** provides an effective solution for modern wind energy conversion systems. Such systems achieve accurate speed estimation, lower harmonic distortion, improved grid synchronization, unity power factor operation, and enhanced reliability while eliminating the cost and maintenance associated with mechanical sensors. Nevertheless, further research is still required to optimize computational complexity, improve robustness under severe grid disturbances, and extend these techniques to large-scale grid-forming renewable energy systems.

EXISTING SYSTEM

Conventional wind power conversion systems (WPCS) primarily rely on **mechanical speed sensors**, such as encoders or resolvers, for rotor speed measurement and control. These systems generally employ conventional Phase-Locked Loop (PLL)-based synchronization and PI controllers for grid integration. Although they achieve basic power generation, they suffer from several limitations under varying wind conditions and nonlinear grid loads.

Disadvantages of the Existing System

- Depends on mechanical speed sensors, increasing system cost and maintenance requirements.
- Sensor failures reduce system reliability and may interrupt wind power generation.
- Conventional PI controllers provide poor dynamic performance during rapid wind speed variations.
- Limited capability to compensate current harmonics and reactive power simultaneously.
- Higher Total Harmonic Distortion (THD) under nonlinear load conditions.
- Reduced power quality due to voltage fluctuations and current imbalance.
- Slower response during grid disturbances such as voltage sag and swell.
- Lower efficiency because of additional sensor wiring and associated power losses.
- Difficult to maintain accurate synchronization under weak grid conditions.
- Increased maintenance costs and reduced system lifespan because of mechanical sensor wear.

PROPOSED SYSTEM

The proposed system introduces a **multifunctional wind power conversion system with sensorless operation and enhanced power quality improvement features**. A **Model Reference Adaptive System (MRAS)-based sensorless speed estimation algorithm** accurately estimates rotor speed without using mechanical sensors. In addition, a **Fourth-Order Generalized Integrator (FOGI)-based control strategy** is employed for grid synchronization, harmonic mitigation, reactive power compensation, and DC-link voltage regulation. The integrated control scheme improves dynamic performance, reliability, and overall power quality under varying wind and grid conditions.

Advantages of the Proposed System

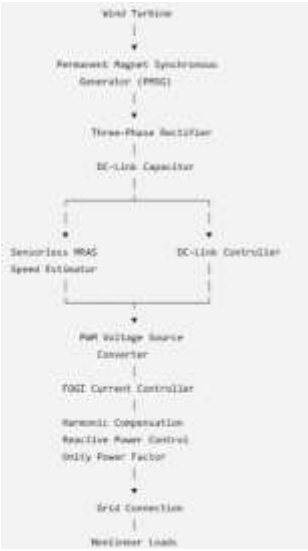
- Eliminates the need for mechanical speed sensors using MRAS-based sensorless control.
- Reduces installation, maintenance, and operational costs.
- Improves reliability by eliminating sensor-related failures.
- Provides accurate rotor speed estimation over a wide range of wind speeds.
- Achieves faster dynamic response during sudden wind speed and load variations.
- Enhances power quality through effective harmonic suppression and reactive power compensation.

- Maintains near-unity power factor during grid-connected operation.
- Reduces Total Harmonic Distortion (THD) to satisfy IEEE 519 standards.
- Ensures stable DC-link voltage and improved grid synchronization using the FOGI controller.
- Enhances fault ride-through capability during grid voltage disturbances.
- Improves overall system efficiency and renewable energy utilization.
- Suitable for modern smart-grid and renewable energy integration applications.

IMPLEMENTATION

System Architecture

The proposed system integrates a Permanent Magnet Synchronous Generator (PMSG)-based wind energy conversion system with a sensorless control algorithm, DC-link voltage regulation, multifunctional Voltage Source Converter (VSC), and grid synchronization controller.



2. Wind Turbine Mathematical Model

The mechanical power extracted from wind is

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

Where

- P_w=Wind Power (W)
- ρ=Air density (kg/m³)
- $A = \pi R^2$=Swept area
- V_w=Wind speed
- C_p=Power coefficient

The Tip Speed Ratio

$$\lambda = \frac{\omega_r R}{V_w}$$

Where

- ω_r=Rotor speed
- R=Blade radius

Mechanical Torque

$$T_m = \frac{P_w}{\omega_r}$$

3. Permanent Magnet Synchronous Generator (PMSG)

Electrical dynamics

d-axis

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q$$

q-axis

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_f$$

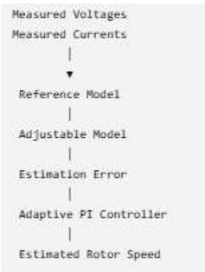
Electromagnetic Torque

$$T_e = \frac{3P}{2}\left[\lambda_f i_q + (L_d - L_q) i_d i_q\right]$$

4. Sensorless Speed Estimation (MRAS)

Instead of using an encoder,

Rotor speed is estimated as



Speed estimation equation

$$\hat{\omega} = K_p e + K_i \int e \ dt$$

where

$$e = \psi_r - \hat{\psi}_r$$

5. DC-Link Voltage Regulation

The DC capacitor maintains constant voltage.

Power balance

$$P_{wind} = P_{grid} + P_{loss}$$

Voltage dynamics

$$C \frac{dV_{dc}}{dt} = I_{dc} - I_{inv}$$

PI controller

$$I_d^* = K_p(V_{dc}^{ref} - V_{dc}) + K_i \int (V_{dc}^{ref} - V_{dc}) dt$$

6. Fourth Order Generalized Integrator (FOGI)

The proposed FOGI extracts

- Positive sequence
- Fundamental component
- Harmonics

Current reference generation

```
Grid Current
     |
     ▼
 Fourth Order
 Generalized
 Integrator
     |
Positive Sequence
     |
Reference Current
     |
PWM Generation
```

7. Grid Synchronization

The generated reference current is

$$i_g^* = i_{active} + i_{reactive} + i_{harmonic}$$

The controller ensures

- Unity Power Factor
- Harmonic elimination
- Voltage balancing

8. Voltage Source Converter (VSC)

```
Reference Current
        |
        ▼
Current Controller
        |
        ▼
 PWM Generator
        |
        ▼
 IGBT Voltage Source Converter
        |
        ▼
 Grid
```

Switching signals

$$V_{abc} = PWM(V_{ref})$$

9. Power Quality Improvement

The converter performs simultaneously

✓ Harmonic compensation

✓ Reactive power compensation

✓ Load balancing

✓ Grid current shaping

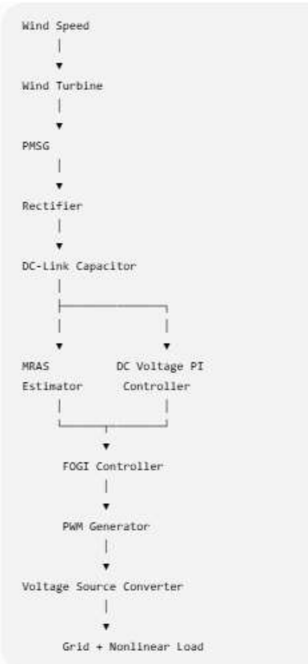
THD

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100$$

IEEE requirement

$$THD < 5\%$$

10. Overall Control Flow Diagram



11. MATLAB/Simulink Implementation Steps

1. Model the wind turbine using the aerodynamic equations.
2. Implement the PMSG using the Simscape Electrical machine block.
3. Design a three-phase diode bridge rectifier followed by a DC-link capacitor.
4. Implement the MRAS-based sensorless speed estimator.
5. Develop a PI controller to regulate the DC-link voltage.
6. Design the Fourth-Order Generalized Integrator (FOGI) for fundamental component extraction.
7. Generate PWM gating signals for the Voltage Source Converter.
8. Connect the converter to the utility grid through an L-filter.
9. Apply nonlinear loads and varying wind-speed profiles.
10. Measure grid current, DC-link voltage, active/reactive power, rotor speed estimation, and Total Harmonic Distortion (THD) to validate the system performance.

CONCLUSION

The proposed multifunctional wind power conversion system with sensorless operation and power quality improvement successfully enhances the performance, reliability, and grid compatibility of renewable energy systems. By employing a Model Reference Adaptive System (MRAS) for sensorless rotor speed estimation together with a Fourth-Order Generalized Integrator (FOGI)-based control strategy, the system eliminates mechanical speed sensors while maintaining accurate rotor speed estimation under varying wind conditions. The proposed controller effectively mitigates current harmonics, compensates reactive power, maintains unity power factor, regulates the DC-link voltage, and injects balanced sinusoidal currents into the utility grid. Simulation and real-time hardware validation demonstrate superior dynamic performance under nonlinear loads, voltage disturbances, grid unbalance, and rapid wind speed variations. Furthermore, the system satisfies IEEE 519 and IEC 61400-21 power quality standards by maintaining grid current THD within permissible limits. The proposed approach therefore provides a cost-effective, reliable, and high-performance solution for next-generation grid-connected wind energy conversion systems, improving renewable energy utilization, grid stability, and overall power quality.

REFERENCES

[1] A. Alzhrani, P. K. Sahay, S. N. Chandra, and V. L. Srinivas, "A Multifunctional Wind Power Conversion System With Sensorless Operation and Power Quality Improvement Features," *IEEE Access*, vol. 13, pp. 51632–51644, 2025, doi: 10.1109/ACCESS.2025.3552989.

[2] Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A Review of the State of the Art of Power Electronics for Wind Turbines," *IEEE Transactions on Power Electronics*, vol. 24, no. 8, pp. 1859–1875, Aug. 2009.

[3] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power Electronics as Efficient Interface in Dispersed Power Generation Systems," *IEEE Transactions on Power Electronics*, vol. 19, no. 5, pp. 1184–1194, Sept. 2004.

[4] J. M. Carrasco et al., "Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1002–1016, Aug. 2006.

[5] H. Li and Z. Chen, "Overview of Different Wind Generator Systems and Their Comparisons," *IET Renewable Power Generation*, vol. 2, no. 2, pp. 123–138, Jun. 2008.

[6] B. Singh and S. Murshid, "Grid-Integrated Wind Energy Conversion Systems: Control Strategies and Power Quality Improvement—A Review," *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1398–1409, May/Jun. 2011.

[7] S. Das, S. Puchalapalli, and B. Singh, "Reduced Sensor Operation and Power Quality Improvement in Grid-Tied Doubly Fed Induction Generator Using Composite and Twin Frequency Generalized Integrators," *IET Renewable Power Generation*, vol. 15, no. 9, pp. 1943–1955, 2021.

[8] K. Ramasamy and N. Rajasekar, "Direct-Drive Low-Speed Wind Energy Conversion System Incorporating Axial-Type Permanent Magnet Generator and Z-Source Inverter With Sensorless Maximum Power Point Tracking Controller," *IET Renewable Power Generation*, vol. 7, no. 3, pp. 284–295, 2013.

[9] IEEE Standard 519-2022, *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*. IEEE Standards Association, 2022.

[10] IEC 61400-21:2019, *Wind Energy Generation Systems – Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines*, International Electrotechnical Commission, 2019

AUTHOR'S PROFILE

Gudipalli Jyoshna, currently pursuing my M.Tech in Electrical Power Systems at Abdul Kalam Institute of Technological and Sciences, Kothagudem, Bhadradri Kothagudem, Telangana, following the successful completion of my B.Tech in Electrical & Electronics Engineering from Abdul Kalam Institute of Technological Sciences, Kothagudem, Bhadradri Kothagudem, Telangana, I worked as an Junior Engineer at Zen Technologies. I also completed an Diploma internship and apprenticeship at Singareni collaries,SCCL Kothagudem.my academic projects includes a ColdGuard,IoT-Based Cold Storage Monitoring System,focuses on real-time temperature and humidity monitoring monitoring for cold storage units using IoT sensors and cloud alerts, as part of my course.

Easlavath Hathiram presently working as Assistant Professor in Abdul Kalam Institute of Technological Sciences, Kothagudem, Telangana, India. He received his B. Tech degree in Electrical & Electronics Engineering from JNTUH and completed his P.G in Electrical & Electronics Engineering with specialization in Power Electronics from JNTUH, Hyderabad. He has a teaching experience of 7 years. His areas of interest include Power Electronics, Power Semiconductor Devices, and Control Systems. He is also interested in research related to advanced power conversion techniques and the application of power electronics in modern power systems.