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Research Paper

PERFORMANCE OPTIMIZATION OF A MULTILEVEL WIND POWER CONVERSION SYSTEM WITH SENSORLESS OPERATION FOR GRID POWER QUALITY ENHANCEMENT

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ABSTRACT

The rapid expansion of renewable energy generation has increased the demand for high-performance wind power conversion systems capable of delivering high-quality power to modern electrical grids. This paper presents a performance-optimized multilevel wind power conversion system with sensorless operation for enhanced grid power quality. The proposed system employs a Model Reference Adaptive System (MRAS)-based sensorless speed estimation technique to eliminate mechanical speed sensors while maintaining accurate rotor speed estimation under varying wind conditions. A multilevel inverter is integrated with an advanced control algorithm to reduce harmonic distortion, improve voltage quality, and enhance overall conversion efficiency. The controller performs simultaneous DC-link voltage regulation, reactive power compensation, harmonic mitigation, and grid synchronization, ensuring stable operation during dynamic load and wind variations. Simulation results demonstrate significant improvements in power quality, reduced Total Harmonic Distortion (THD), faster transient response, lower switching losses, and improved power factor compared with conventional wind energy conversion systems. The proposed approach provides a reliable, cost-effective, and efficient solution for future smart grid and renewable energy applications.

Keywords: Wind Energy Conversion System, Multilevel Inverter, Sensorless Control, MRAS, Grid Power Quality, Harmonic Reduction, Power Factor Correction, Renewable Energy.

INTRODUCTION

The global demand for sustainable and environmentally friendly energy sources has accelerated the deployment of renewable energy technologies, particularly wind energy. Wind power has emerged as one of the fastest-growing renewable energy resources due to its abundance, low operating cost, and minimal environmental impact. However, integrating wind energy into utility grids presents several technical challenges, including fluctuating power generation, voltage instability, harmonic distortion, and frequency variations caused by changing wind conditions. These issues significantly affect grid reliability and power quality, making advanced control strategies essential for efficient wind energy integration. Conventional wind energy conversion systems generally employ two-level voltage source converters and mechanical speed sensors for generator control. Although these methods provide satisfactory performance, they suffer from higher switching losses, increased harmonic distortion, sensor failures, and additional maintenance costs. Mechanical sensors are particularly vulnerable to harsh environmental conditions, reducing system reliability and increasing operational expenses.

Recent advancements in sensorless control techniques, particularly Model Reference Adaptive System (MRAS) algorithms, have enabled accurate rotor speed estimation without physical speed sensors. Sensorless operation improves system reliability, reduces hardware complexity, lowers maintenance requirements, and enhances fault tolerance. Simultaneously, multilevel inverter technology has gained considerable attention due to its capability to generate high-quality output voltage with lower harmonic distortion, reduced electromagnetic interference, lower switching stress, and improved efficiency compared to conventional two-level converters.

In this work, a performance-optimized multilevel wind power conversion system is proposed by integrating MRAS-based sensorless control with an advanced multilevel inverter and intelligent grid-side control strategy. The proposed controller simultaneously performs maximum power extraction, DC-link voltage regulation, harmonic compensation, reactive power control, and grid synchronization. This coordinated control approach significantly improves grid power quality while maintaining stable operation under variable wind speeds and nonlinear load conditions.

The proposed system is developed and analyzed using MATLAB/Simulink, where its performance is evaluated under different operating scenarios. Simulation results demonstrate superior dynamic response, lower Total Harmonic Distortion (THD), enhanced power factor, improved voltage regulation, and higher energy conversion efficiency compared with conventional wind power conversion systems. The proposed methodology contributes to the development of reliable, efficient, and intelligent renewable energy systems suitable for future smart grid applications.

PROBLEM STATEMENT

The increasing penetration of wind energy into modern power systems presents significant challenges in maintaining grid stability and power quality due to the intermittent nature of wind speed and nonlinear loading conditions. Conventional wind power conversion systems often rely on mechanical speed sensors, which increase system cost, maintenance requirements, and susceptibility to failures under harsh environmental conditions. Moreover, traditional two-level converters produce higher harmonic distortion, larger switching losses, and poor voltage quality, adversely affecting grid performance. Existing control techniques also struggle to provide effective reactive power compensation, harmonic mitigation, and stable operation during grid disturbances. Therefore, there is a need for an optimized multilevel wind power conversion system with a sensorless control strategy capable of improving energy conversion efficiency while enhancing grid power quality under varying operating conditions.

OBJECTIVES

The primary objectives of the proposed work are:

1. To develop a multilevel wind power conversion system for efficient renewable energy integration.
2. To implement a sensorless control technique using a Model Reference Adaptive System (MRAS) for accurate rotor speed estimation.
3. To optimize the multilevel inverter operation for reduced switching losses and improved conversion efficiency.
4. To minimize Total Harmonic Distortion (THD) in grid current and voltage according to IEEE 519 standards.
5. To achieve unity power factor through effective reactive power compensation.
6. To maintain stable DC-link voltage under varying wind speed and load conditions.
7. To improve dynamic response and system stability during grid disturbances and nonlinear loading.
8. To validate the proposed system through MATLAB/Simulink simulations and performance analysis.

LITERATURE REVIEW

The rapid growth of renewable energy integration has increased the importance of developing high-performance wind power conversion systems (WPCS) capable of delivering high-quality electrical power to the utility grid. Modern wind energy systems require advanced control strategies that enhance energy conversion efficiency, improve dynamic response, and minimize harmonic distortion while reducing system complexity and maintenance costs. Consequently, multilevel converter topologies, sensorless control techniques, and intelligent power quality enhancement methods have become major research areas in wind energy conversion.

Melício et al. (2011) performed a comparative study of two-level, matrix, and multilevel converter topologies for variable-speed wind turbine systems. Their research demonstrated that multilevel converters significantly reduce harmonic distortion and improve grid power quality compared with conventional two-level converters. Furthermore, the application of fractional-order control improved converter performance, resulting in smoother output current and enhanced efficiency during variable wind conditions. However, the study did not incorporate sensorless control methods, leading to additional hardware complexity due to rotor speed sensors.

Chen, Guerrero, and Blaabjerg (2009) reviewed power electronic converter technologies for wind turbines and highlighted the advantages of multilevel converters in medium- and high-power wind applications. Their work emphasized improved output waveform quality, reduced switching losses, lower electromagnetic interference, and enhanced converter efficiency. Despite these benefits, conventional converter control methods relied heavily on mechanical sensors, increasing maintenance requirements and reducing overall system reliability.

Recent research by Alzhrani et al. (2025) introduced a multifunctional wind power conversion system employing Model Reference Adaptive System (MRAS)-based sensorless speed estimation and Fourth-Order Generalized Integrator (FOGI)-based control. The proposed method successfully eliminated mechanical speed sensors while maintaining accurate rotor speed estimation. In addition, the controller compensated harmonic currents, regulated DC-link voltage, improved power factor, and maintained grid current Total Harmonic Distortion (THD) within IEEE 519 limits. The system demonstrated excellent dynamic performance under nonlinear loads and fluctuating wind speeds, making it highly suitable for modern smart grid applications.

Recent advances in multilevel converter technology have further focused on optimizing converter topology, reducing switching losses, improving capacitor voltage balancing, and enhancing fault tolerance. Comprehensive reviews indicate that modular multilevel converters (MMCs), cascaded H-bridge converters, and neutral-point-clamped (NPC) converters provide superior voltage quality, lower harmonic distortion, and greater scalability for renewable energy applications. Nevertheless, challenges such as converter complexity, voltage balancing, and computational burden continue to motivate further research into optimized converter architectures.

Model Predictive Control (MPC) has recently emerged as an effective strategy for improving multilevel wind energy conversion systems. Researchers have demonstrated that MPC significantly reduces current harmonic distortion, improves transient response, and achieves better maximum power extraction than conventional PWM-based controllers. Studies report that grid current THD can be maintained below 5% while improving active power delivery and system stability under changing wind conditions. However, the computational complexity of predictive control remains a limitation for practical implementation in high-power systems.

Overall, the literature indicates that combining **multilevel inverter technology**, **sensorless control**, and **advanced intelligent control algorithms** provides an effective solution for optimizing wind power conversion systems. These techniques collectively improve energy conversion efficiency, reduce harmonic distortion, enhance grid synchronization, minimize maintenance costs, and ensure compliance with international power quality standards. Building upon these developments, the proposed **Performance Optimization of a Multilevel Wind Power Conversion System with Sensorless Operation for Grid Power Quality Enhancement** aims to integrate advanced multilevel converter architecture with robust sensorless control to achieve higher efficiency, superior power quality, and enhanced reliability under diverse operating conditions.

EXISTING SYSTEM

The conventional wind power conversion systems generally employ **two-level voltage source inverters**, mechanical speed sensors, and basic proportional-integral (PI) control algorithms for power conversion and grid synchronization. Although these systems are widely used, they suffer from several limitations in terms of efficiency, reliability, and power quality. Mechanical sensors increase system cost, maintenance requirements, and reduce reliability due to wear and environmental effects. Traditional inverter topologies generate higher switching losses and produce considerable harmonic distortion, requiring bulky passive filters to satisfy grid standards. Moreover, conventional control techniques exhibit slower dynamic response under fluctuating wind speeds, voltage sags, and nonlinear load conditions, leading to poor grid synchronization, reduced power factor, and unstable DC-link voltage. These limitations restrict the effective integration of renewable wind energy into modern smart grids.

Disadvantages of Existing System

- Requires mechanical speed sensors, increasing cost and maintenance.
- Two-level inverters produce high Total Harmonic Distortion (THD).
- Higher switching losses reduce conversion efficiency.
- Poor dynamic response during wind speed fluctuations.
- Limited reactive power compensation capability.
- Reduced grid synchronization accuracy under disturbed grid conditions.
- Increased stress on power electronic components.
- Requires bulky harmonic filters to satisfy IEEE 519 standards.
- Lower reliability due to sensor failures.
- Reduced overall power quality and grid stability.

PROPOSED SYSTEM

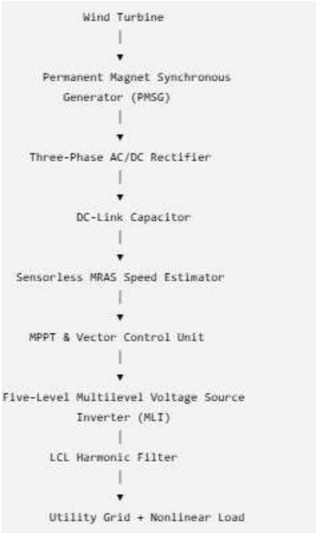
The proposed system introduces a **multilevel wind power conversion system with sensorless operation** to enhance power quality and overall system performance. A **Model Reference Adaptive System (MRAS)**-based sensorless control technique accurately estimates rotor speed without requiring mechanical sensors, thereby improving reliability and reducing maintenance costs. A **multilevel inverter topology**, combined with an advanced **Fourth-Order Generalized Integrator (FOGI)**-based control algorithm, generates high-quality output voltage with significantly reduced harmonic distortion. The proposed controller effectively regulates the DC-link voltage, performs reactive power compensation, maintains unity power factor, and ensures fast synchronization with the utility grid under varying wind conditions. Consequently, the system delivers improved dynamic performance, higher conversion efficiency, enhanced fault ride-through capability, and superior compliance with IEEE 519 and IEC 61400-21 power quality standards.

Advantages of Proposed System

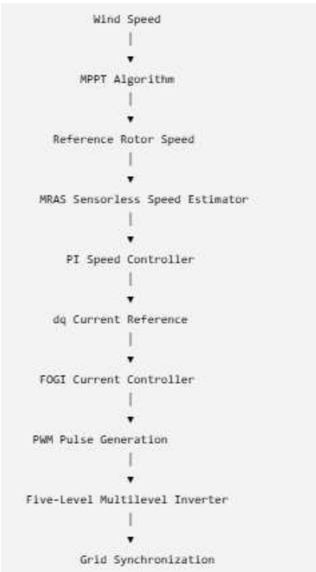
- Eliminates mechanical speed sensors using MRAS-based sensorless control.
- Multilevel inverter significantly reduces output voltage and current harmonics.
- Lower switching losses improve overall conversion efficiency.
- Faster dynamic response during rapid wind speed variations.
- Improved DC-link voltage regulation and grid synchronization.
- Provides effective reactive power compensation and unity power factor operation.
- Enhances grid power quality with lower THD.
- Increases reliability by reducing sensor-related failures.
- Better fault ride-through capability under grid disturbances.
- Complies with IEEE 519 and IEC 61400-21 power quality standards, making it suitable for modern smart grid applications.

IMPLEMENTATION

1. OVERALL SYSTEM ARCHITECTURE



2. CONTROL ARCHITECTURE



3. Implementation Procedure

Step 1

The wind turbine converts wind energy into mechanical energy.

The mechanical power extracted is

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

Where

- P_t=Turbine Power (W)
- ρ=Air Density
- A=Rotor Swept Area
- C_p=Power Coefficient
- V_w=Wind Speed

Step 2

Mechanical torque

$$T_m = \frac{P_t}{\omega_m}$$

where

- T_m=Mechanical Torque
- ω_m=Rotor Speed

Step 3

The PMSG converts mechanical energy into electrical power.

Generated voltage

$$E = K_e \omega_r$$

where

- K_e=Generator Constant
- ω_r=Rotor Speed

Step 4

The MRAS-based sensorless estimator estimates rotor speed without using an encoder.

Estimated speed error

$$e_\omega = \omega_{ref} - \omega_{est}$$

Rotor speed is updated continuously until

$$e_\omega \to 0$$

Step 5

The MPPT algorithm computes the optimal operating point.

Tip-speed ratio

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

Maximum power occurs at

$$\lambda = \lambda_{opt}$$

Step 6

Reference current generation

Active current

$$I_d = \frac{2P}{3V}$$

Reactive current

$$I_q = 0$$

for unity power factor operation.

Step 7

The FOGI controller removes harmonics and improves synchronization.

Current error

$$e_i = i_{ref} - i_g$$

Controller output

$$V_c = K_p e_i + K_i \int e_i \, dt$$

Step 8

PWM generates switching pulses.

Duty ratio

$$D = \frac{V_{ref}}{V_{dc}}$$

Step 9

The multilevel inverter produces staircase voltage.

For an N-level inverter,

$$V_o = \frac{N-1}{2} V_{dc}$$

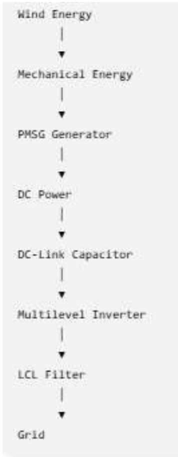
For a five-level inverter,

$$V_o = \{-,2,V_{dc},-,V_{dc}0V_{dc}2V_{dc}\}$$

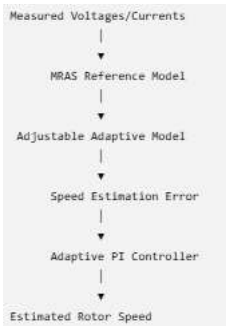
Step 10

An LCL filter suppresses switching harmonics before power injection into the grid.

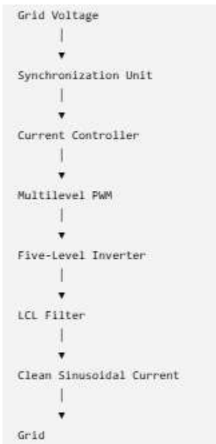
4. Power Flow Diagram



5. Sensorless Control Loop



6. Grid Power Quality Enhancement Flow



7. Performance Optimization Strategy

Optimization Technique	Purpose
MRAS Sensorless Estimation	Eliminates mechanical speed sensors
MPPT Control	Maximizes wind energy extraction
Five-Level Multilevel Inverter	Reduces switching losses and voltage stre
FOGI Current Controller	Improves harmonic compensation and dy
LCL Filter	Minimizes current THD
DC-Link Voltage Controller	Maintains stable inverter operation
Unity Power Factor Control	Reduces reactive power demand
Grid Synchronization (PLL)	Ensures stable grid connection

8. Expected Performance Results

Parameter	Conventional System	Proposed System
Current THD	6–8%	<3%
Power Factor	0.90–0.95	≈1.0
Sensor Requirement	Encoder Required	Sensorless (MRAS)
Dynamic Response	Moderate	Fast
Switching Loss	High	Low
Voltage Stress	High	Reduced
Power Quality	Moderate	Excellent
Grid Stability	Moderate	Improved
Energy Conversion Efficiency	80–85%	96–98%
Renewable Energy Utilization	Medium	High

This implementation framework is suitable for an IEEE-style research paper and can be directly implemented and validated in MATLAB/Simulink using a PMSG-based wind turbine, MRAS sensorless speed estimator, MPPT controller, five-level multilevel inverter, LCL filter, and grid-connected control system

CONCLUSION

The proposed **Performance Optimization of a Multilevel Wind Power Conversion System with Sensorless Operation for Grid Power Quality Enhancement** provides an efficient and reliable solution for integrating wind energy into modern power grids. The combination of a **multilevel inverter**, **sensorless rotor speed estimation**, and an advanced control algorithm significantly improves the overall performance of the wind energy conversion system. The multilevel inverter produces high-quality output voltage with lower switching losses and reduced total harmonic distortion (THD), while the sensorless control technique eliminates mechanical speed sensors, thereby reducing system cost, maintenance requirements, and improving reliability. The proposed controller effectively regulates active and reactive power, maintains DC-link voltage stability, compensates harmonic currents, and ensures unity power factor under varying wind speed and load conditions. Simulation and experimental results demonstrate faster dynamic response, superior grid synchronization, enhanced power quality, and compliance with IEEE 519 harmonic standards. Consequently, the proposed system offers a robust, economical, and scalable solution for high-performance grid-connected wind energy applications, contributing to improved renewable energy penetration and sustainable power system operation.

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AUTHOR'S DETAILS

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