ISSN: 2454-9940

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

E-Mail :
editor.ijasem@gmail.com
editor@ijasem.org

www.ijasem.org

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

ISSN 2454-9940

www.ijasem.org

Vol 19, Issue 1, 2025

Enhanced Power Quality in DFIG-Based Wind Energy Systems Using Efficient Control and Five-Level MMC Integration

K. Durga Prasad[1], I. Sai Deepthi[2], G. Satish Kumar[3], Mrs. K. Gowtami[4]

[1]Department of EEE, Godavari Institute of Engineering and Technology(A), prasadkolapati399@gmail.com

[2]Department of EEE, Godavari Institute of Engineering and Technology(A), saideepthiinti@gmail.com

[3]Department of EEE, Godavari Institute of Engineering and Technology(A), gandhamsatishkumar5@gmail.com

[4]Assistant Professor, Department of EEE, Godavari Institute of Engineering and Technology(A), gowthami75.k@gmail.com

Abstract

The integration of Doubly Fed Induction Generators (DFIG) in wind energy systems offers variable speed operation and enhanced energy capture. However, challenges like harmonic distortion, voltage fluctuations, and reactive power management affect power quality. This paper proposes an efficient control strategy with a five-level Multilevel Converter (MMC) to improve power quality in DFIG-based wind systems. The system starts with a three-phase AC source supplying power through a Point of Common Coupling (PCC), incorporating source inductance, a transformer, and an LC filter for voltage stability and harmonic reduction. A five-level MMC converts high-frequency AC to low-frequency AC, enhancing efficiency. A Pulse-Width Modulation (PWM) rectifier transforms AC input to DC, regulated by a PI controller to maintain voltage stability. PWM generators provide control signals for converters, while reference current generation using D-Q theory and a hysteresis current controller ensure precise current regulation. This setup improves the reliability of renewable energy integration, ensuring stable and sustainable power generation. The proposed system is implemented using MATLAB 2021a simulations to validate its effectiveness in enhancing power quality in DFIG-based wind energy systems.

Keywords: Voltage Fluctuations, Multilevel Converter, Photovoltaic System; Pulse Width Modulation (PWM); Renewable Energy Integration

1. INTRODUCTION

Wind energy is a sustainable and renewable power source that harnesses the kinetic energy of moving air to generate electricity. It plays a crucial role in reducing dependence on fossil fuels and combating climate change [1-3]. Wind turbines, the core components of wind energy systems, convert wind flow into mechanical energy, which is then transformed into electrical power. These turbines are classified into two main types based on rotor orientation: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). Wind energy systems operate at various scales, from small residential setups to large wind farms. Their efficiency depends on several factors, including wind speed, turbine design, and site conditions [4]. Offshore wind farms, located in bodies of water, generally experience stronger and more consistent winds than onshore farms, making them more efficient [5]. Advances in turbine technology, such as direct-drive systems that eliminate the need for gearboxes, have improved efficiency and reduced maintenance costs. Additionally, modern aerodynamic blade designs enhance energy capture and ensure greater operational reliability [6-8]. The working principle of wind energy systems is based on converting wind's kinetic energy into mechanical power. When wind flows over the turbine blades, it creates lift and drag forces, causing the rotor to spin. This rotational motion is transferred through a shaft to a generator, which converts mechanical energy into electrical energy [9,10]. Traditional turbines use gearboxes to regulate rotational speed, but modern designs increasingly incorporate direct-drive technology to enhance efficiency and minimize maintenance requirements.

One of the primary advantages of wind energy is its environmental benefits. Unlike fossil fuels, wind power does not produce greenhouse gas emissions during operation, making it a key contributor to global efforts to reduce carbon footprints [11]. Wind is an abundant and inexhaustible resource, ensuring long-term energy security and sustainability. Moreover, wind farms help diversify the energy mix, reducing reliance on non-renewable sources.

Despite its benefits, wind energy faces several challenges. One major issue is the intermittency of wind supply, as energy generation depends on wind speed and weather conditions. This variability requires the integration of energy storage systems or backup power sources to ensure a stable electricity supply [12.13]. Additionally, high initial investment costs for wind farm development, including turbine manufacturing, installation, and grid connection, can be a barrier to widespread adoption. Environmental concerns also arise, such as the impact of wind farms on bird and bat populations, as well as noise and visual disturbances for local communities. To address these challenges, ongoing research and technological advancements are improving wind energy's efficiency and reliability [14]. Innovations in smart turbine technology, predictive maintenance, and enhanced energy storage solutions are helping to optimize power generation. Hybrid renewable systems that integrate wind power with solar and battery storage are also being developed to ensure a consistent energy supply. As global energy demand rises, wind energy continues to play a vital role in the shift toward sustainable power generation [15]. With continuous improvements in turbine technology and energy infrastructure, wind power is set to become an increasingly important component of the renewable energy landscape, reducing carbon emissions and securing a cleaner future.

2. SYSTEM DESCRIPTION

This paper presents an advanced control strategy incorporating a five-level Multilevel Converter (MMC) to enhance power quality in a DFIG-based wind energy system. The system operates with a three-phase AC source delivering voltage and current to a load via a Point of Common Coupling (PCC). Key components include source inductance, a transformer, and an LC filter, which ensure voltage stability and mitigate harmonic distortions. At the core of the system, a five-level MMC efficiently converts high-frequency AC to low-frequency AC, optimizing energy conversion and system performance. The AC input undergoes conversion to DC through a Pulse-Width Modulation (PWM) rectifier, followed by a PI controller that regulates DC voltage levels. PWM generators produce precise control signals for the converters, ensuring stable operation. To achieve accurate current regulation, reference currents are generated using D-Q theory, while a hysteresis current controller manages the system's current flow with high precision. This configuration significantly improves the reliability and efficiency of the wind energy system, ensuring stable power generation and integration into the grid with minimal power quality disturbances.

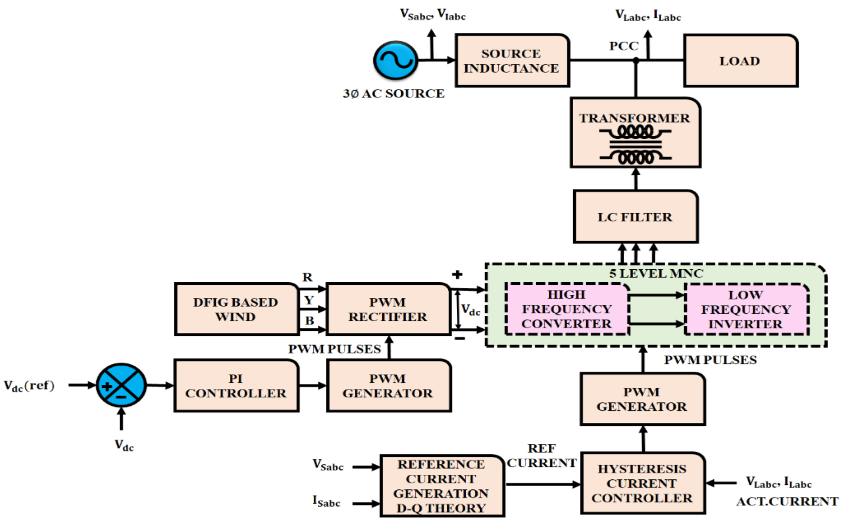


Figure 1. Block Diagram of Proposed system

2.1 DFIG BASED WIND

A Doubly Fed Induction Generator (DFIG) wind energy system efficiently converts wind energy into electrical power using a rotor and stator. The wind turbine captures kinetic energy, transferring it to the rotor shaft, which connects to the rotor side of the DFIG, while the stator is directly linked to the grid. This design allows variable-speed operation, maximizing energy capture across different wind speeds.

A back-to-back converter system, consisting of a rotor-side converter and a grid-side converter, regulates power flow. The rotor-side converter adjusts the rotor current's frequency and amplitude, while the grid-side converter ensures synchronization with the grid. Additionally, a partially rated power converter enhances efficiency and stability.

By maintaining steady performance despite wind fluctuations, DFIG technology is widely used in large-scale wind farms. Its dual connection to the grid via both rotor and stator ensures reliable, high-efficiency energy generation, making it a preferred choice for modern wind energy applications.

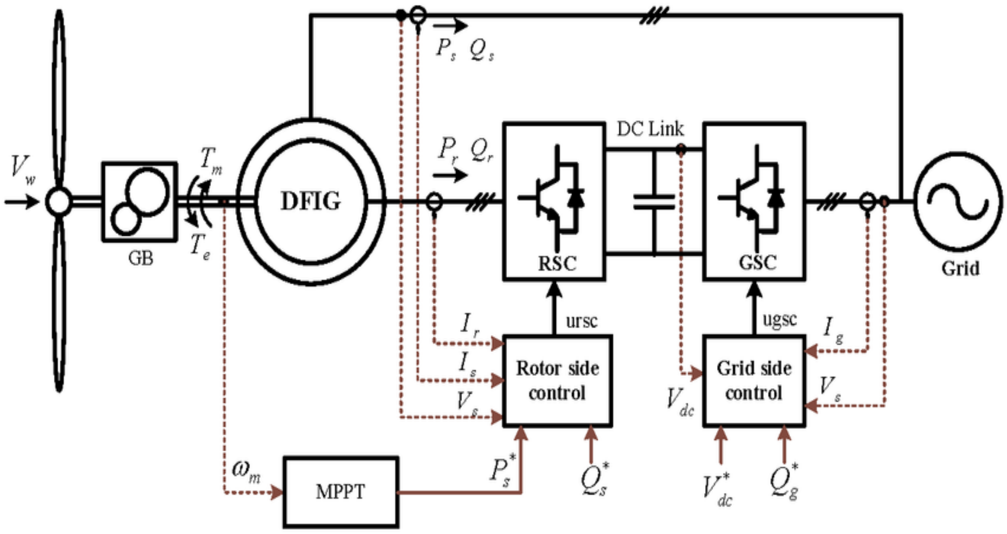


Figure 2 Doubly Fed Induction Generator (DFIG) based Wind

2.2 LEVEL MNC

A 5-level Multilevel Converter (MNC) is a power converter that generates multiple voltage levels, producing a smoother output waveform compared to conventional two-level inverters. Widely used in high-power applications such as motor drives, grid integration, and renewable energy systems, it enhances efficiency, reduces harmonic distortion, and improves overall power quality.

The primary advantage of a 5-level MNC is its ability to generate a low-harmonic voltage waveform, making it ideal for systems requiring high power quality. By using five distinct voltage levels instead of simple on-off switching, it produces a smoother output, reducing the need for complex filtering. The MNC utilizes power semiconductor switches like IGBTs and advanced modulation techniques to achieve this.

Key benefits include reduced Total Harmonic Distortion (THD), lower electromagnetic interference (EMI), and improved system efficiency due to lower switching frequencies. The 5-level MNC is particularly valuable in renewable energy systems, ensuring stable and efficient grid integration.

2.3 HIGH AND LOW FREQUENCY CONVERTER

High-frequency converters operate between a few kHz and MHz, making them ideal for compact applications like mobile devices, laptops, and electric vehicles. Their higher frequencies reduce the size and weight of passive components like capacitors and inductors, improving efficiency while minimizing switching and conduction losses. These converters are widely used in telecommunications, renewable energy systems, and switched-mode power supplies (SMPS), where low electromagnetic interference (EMI) is crucial. However, they require advanced control techniques to manage switching losses and heat dissipation.

In contrast, low-frequency converters operate below 1 kHz and are used in large-scale applications like motor drives, power grids, and industrial machinery. They are more robust and simpler in design but require larger inductors and capacitors, making them bulkier. Additionally, they generate higher harmonic distortion,

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT
ISSN 2454-9940
www.ijasem.org
Vol 19, Issue 1, 2025

necessitating additional filtering. While high-frequency converters prioritize efficiency and compactness, low-frequency converters excel in high-power applications requiring durability and simplicity.

2.4 PWM GENERATOR

A Pulse Width Modulation (PWM) generator regulates power delivery to a load, such as a motor or LED, by adjusting the width of pulses in a periodic signal. It operates by modulating the duty cycle—the percentage of time the signal remains "high" (on) during each cycle—based on the desired output voltage or power level. For example, a 50% duty cycle means the signal is on for half the cycle, delivering half of the maximum voltage. By varying pulse duration relative to the total period, PWM achieves precise power control without excessive energy dissipation as heat. This makes it highly efficient for applications like motor drives, voltage regulation, and audio amplification. PWM enables smooth control over power output, allowing for fine-tuned adjustments to the load's behavior. Its efficiency and versatility make it an essential technique in modern electronic and electrical systems.

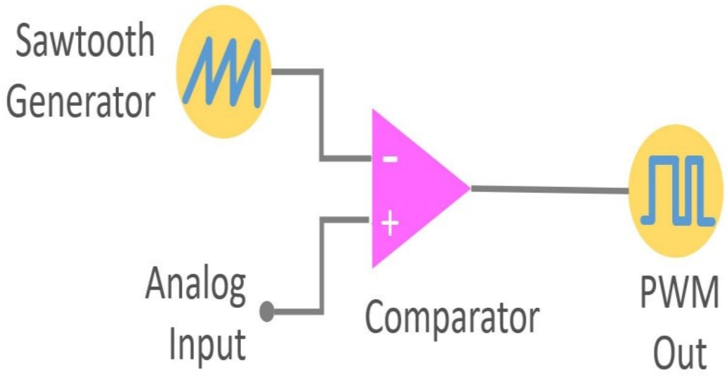
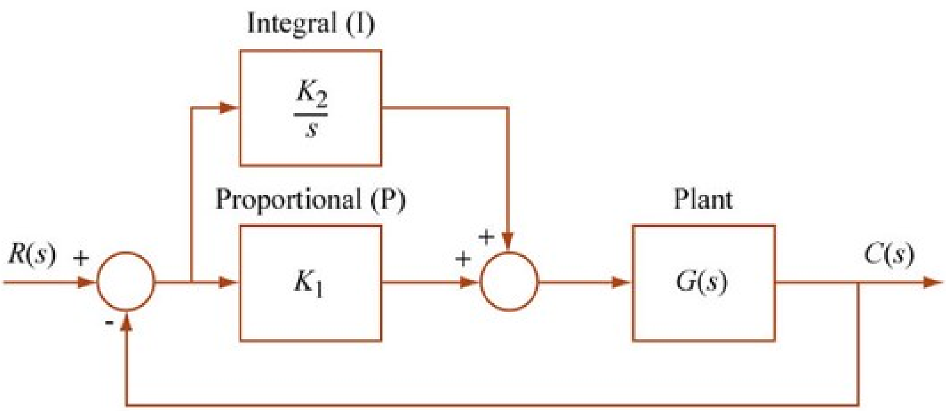


Figure 3 PWM Generator

2.5 PI CONTROLLER

A Proportional-Integral (PI) controller combines both proportional and integral actions to regulate a system's output. The process begins when the controller receives an error signal, which is the difference between the desired setpoint and the actual process variable (PV). The proportional term produces an output that is directly proportional to the current error, meaning that larger errors result in stronger corrective actions. The integral term sums past errors over time, helping to eliminate any accumulated error (offset) that the proportional control alone cannot address. Together, these actions enable the PI controller to correct both immediate errors and long-term offsets, ensuring that the system efficiently reaches and maintains the desired setpoint. PI controllers are widely used in applications such as temperature regulation, motor speed control, and power systems, offering a balance between fast response and steady-state accuracy.



ISSN 2454-9940
www.ijasem.org
Vol 19, Issue 1, 2025

Figure 4 PI Controller

3. RESULTS AND DISCUSSIONS

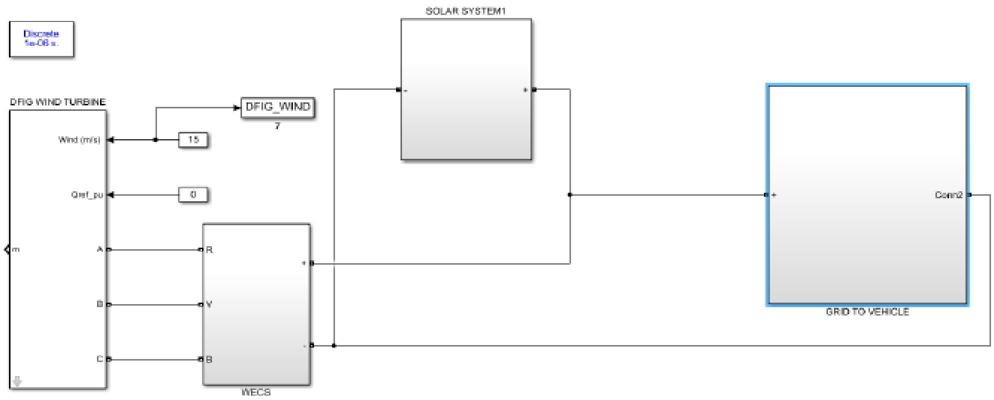


Figure 5. Over All Simulation Diagram

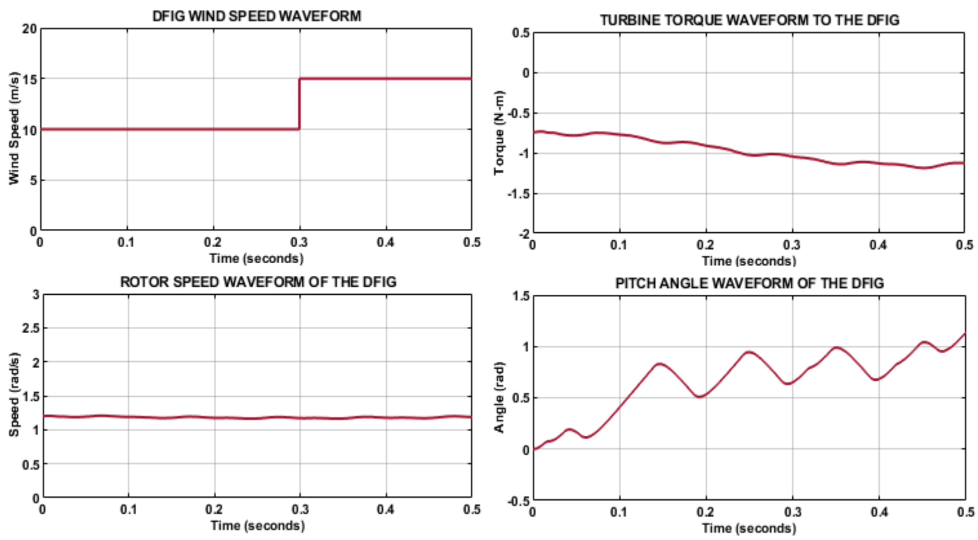


Figure 6 DFIG in Wind System

Figure 6 illustrates the dynamic performance of a Doubly Fed Induction Generator (DFIG) under different operational conditions. The figure consists of four subplots, each showing key parameters: wind speed, turbine torque, rotor speed, and pitch angle. These waveforms, observed over a 0.5-second time period, offer valuable insights into the generator's response to fluctuating conditions, highlighting how the system adapts to changes in wind speed and other operational factors.

ISSN 2454-9940
www.ijasem.org
Vol 19, Issue 1, 2025

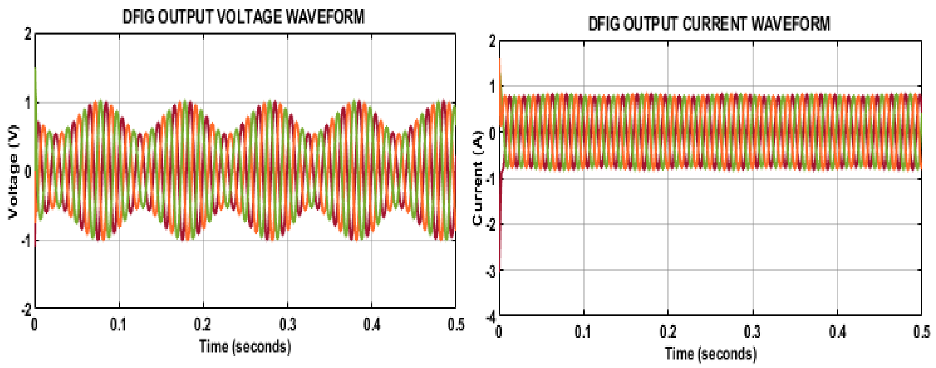


Figure 7 Voltage and Current Output of DFIG System

Figure 7 shows the output voltage and current waveforms of a Doubly Fed Induction Generator (DFIG) over a 0.5-second period. The left subplot depicts the voltage fluctuations, while the right subplot illustrates the corresponding current variations. Together, these waveforms highlight the electrical performance of the generator during operation, emphasizing how voltage and current change in response to varying operational conditions.

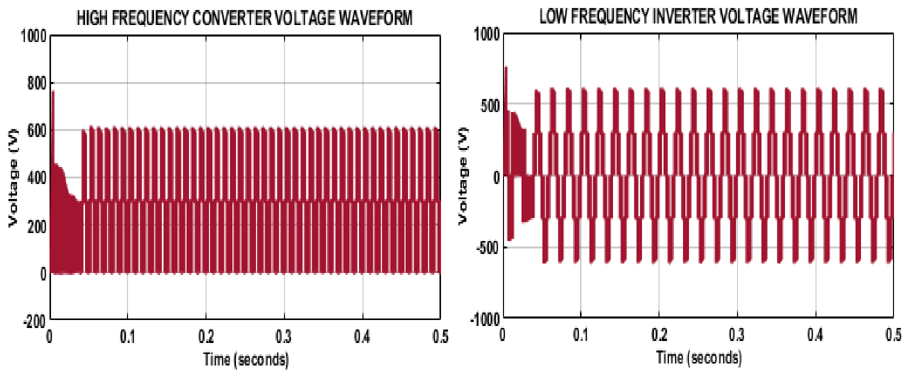


Figure 8 Five Level MMC Waveform

Figure 8 presents the voltage waveforms for both a high-frequency converter and a low-frequency inverter. The distinct characteristics of these waveforms highlight the differences in their operational frequencies and voltage behaviors over time, emphasizing how each type of converter/inverter responds to varying conditions and frequencies in the system.

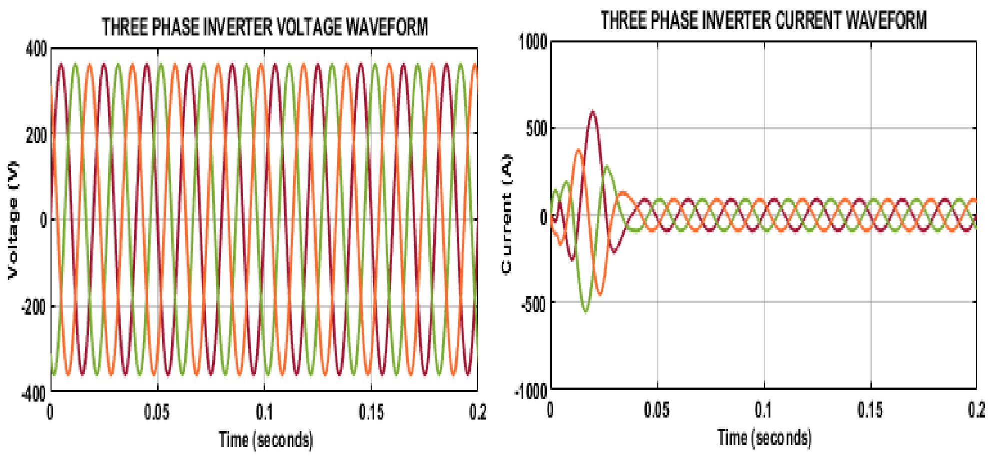


Figure 9 Inverter Characteristics Waveform

Figure 9 illustrates the voltage and current waveforms of a three-phase inverter, providing a detailed analysis of their performance. The figure highlights the relationship between voltage fluctuations and the corresponding current response over time, offering insights into the inverter's behavior and efficiency during operation. This

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

ISSN 2454-9940

www.ijasem.org

Vol 19, Issue 1, 2025

analysis is crucial for optimizing system performance and ensuring stable energy.

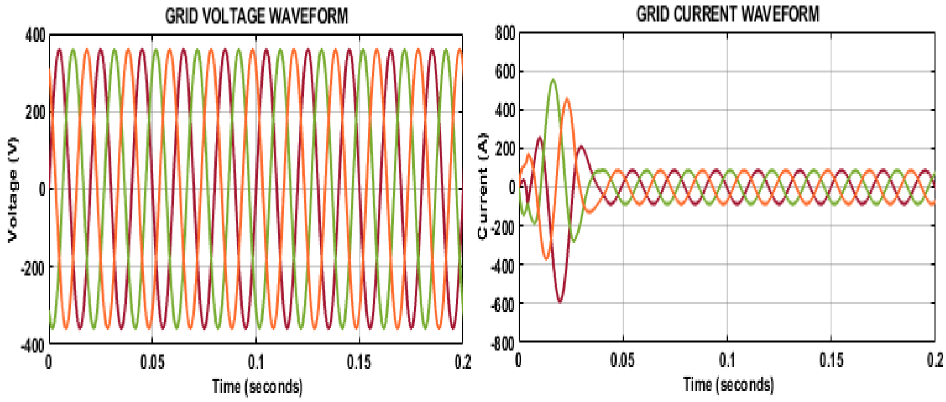


Figure 10 Grid voltage and Current Waveform

Figure 10 shows the grid voltage and current waveforms, illustrating the dynamic behavior of the system over time. These waveforms are crucial for monitoring the stability and efficiency of grid systems, ensuring that voltage and current levels remain within optimal ranges for reliable power distribution and system performance.

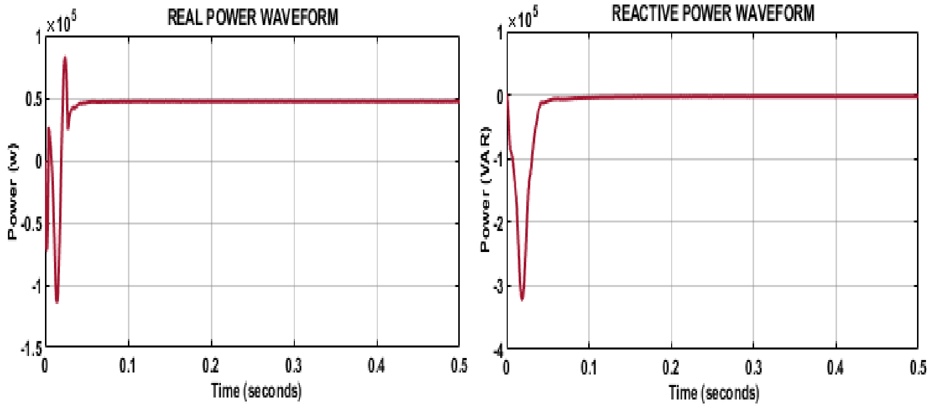


Figure 11 Real and Reactive Power Waveform

Figure 11 presents the real and reactive power waveforms, highlighting their behavior over time. Analyzing both real and reactive power is essential for optimizing the performance and efficiency of power systems. Monitoring these components helps in understanding energy consumption patterns and ensuring the stability of the system, allowing for better management and control of power distribution..

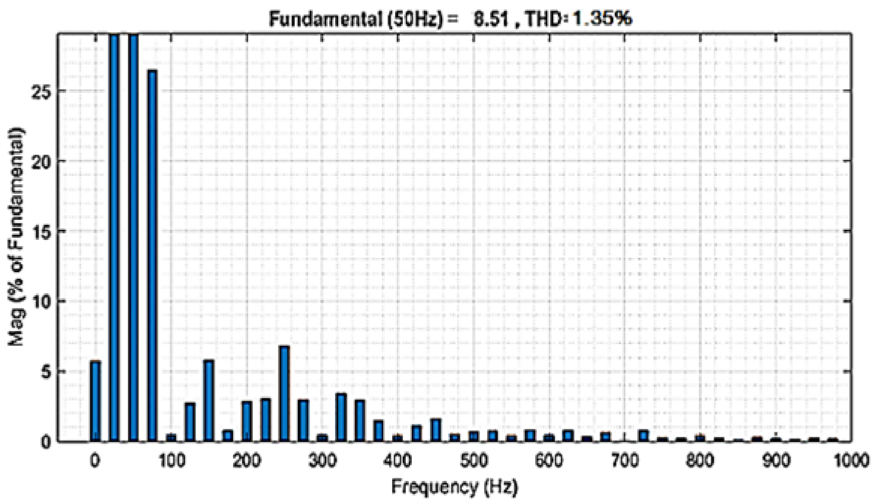


Figure 12 THD Waveform

Figure 12 displays the Total Harmonic Distortion (THD) waveform. The frequency analysis process involves measuring the magnitude of harmonics to assess the quality of electrical signals. By evaluating the THD, engineers can identify potential issues that may affect system performance. The histogram illustrates the frequency distribution, highlighting the fundamental frequency and the corresponding THD value, providing insights into the signal quality and areas for improvement in the system.

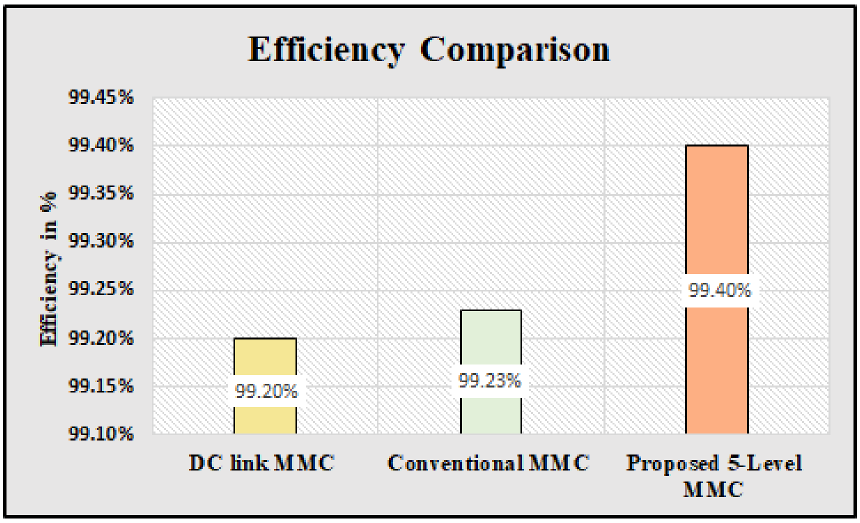


Figure 13 Efficiency Comparison

Figure 13 illustrates the efficiency of various types of Modular Multilevel Converters (MMCs), including the DC link MMC, conventional MMC, and the proposed 5-level MMC. The figure highlights that the proposed 5-level MMC achieves the highest efficiency at 99.40%, demonstrating its superior performance compared to the other configurations. This showcases the advantages of the 5-level MMC in terms of efficiency, making it a promising option for power conversion applications.

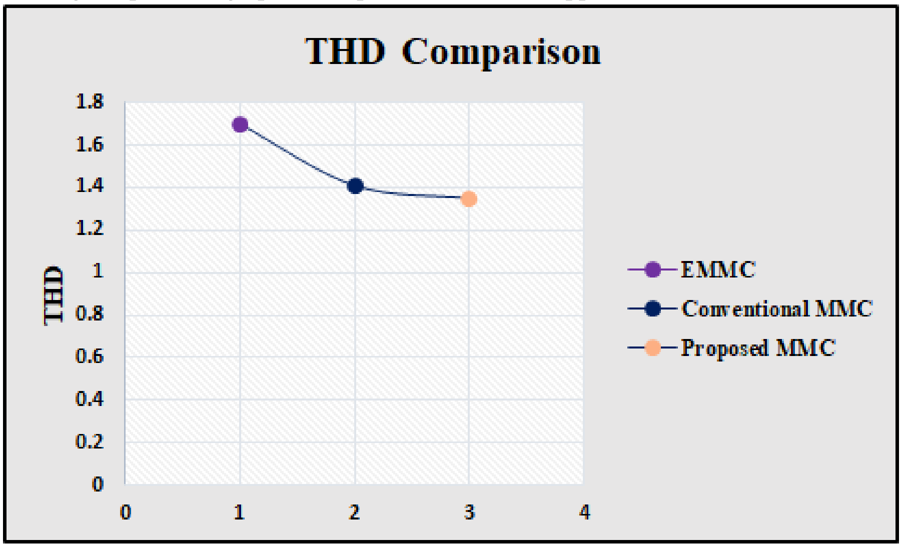
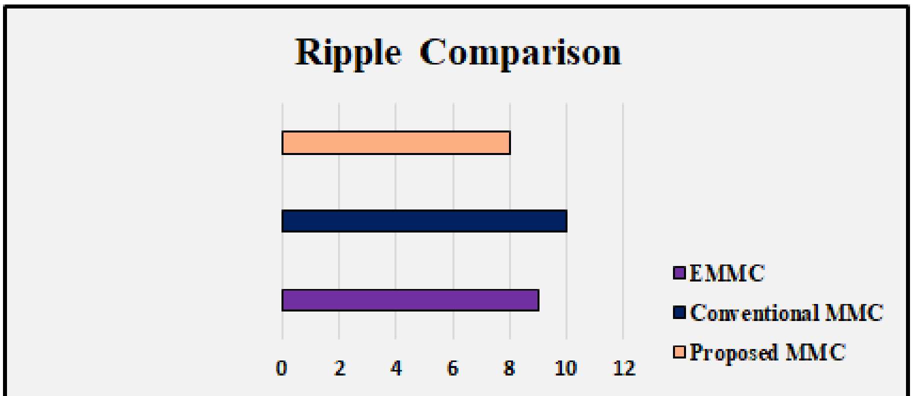


Figure 14 THD Comparison

Figure 14 illustrates the Total Harmonic Distortion (THD) for different Modular Multilevel Converter (MMC) configurations. It compares the performance of the EMMC, conventional MMC, and the proposed MMC under various operating conditions. The proposed MMC demonstrates a lower THD value, indicating improved harmonic performance and superior efficiency in minimizing distortion compared to the other configurations



	EMMC	Conventional MMC	Proposed MMC
Ripple Comparison	9	10	8

Figure 15 Ripple Comparison

Figure 15 presents a visual comparison of ripple values for different Modular Multilevel Converter (MMC) configurations. The figure includes data for the EMMC, conventional MMC, and the proposed MMC, highlighting their respective ripple levels. Notably, the proposed MMC exhibits the lowest ripple value, demonstrating its superior performance in reducing ripple compared to the other configurations. This suggests enhanced stability and efficiency in the proposed MMC design.

4. CONCLUSION

In conclusion, this paper presents an efficient control strategy and the integration of a five-level Multilevel Converter (MMC) to enhance power quality in a DFIG-based wind energy system. Key components such as the Point of Common Coupling (PCC), source inductance, transformer, and LC filter ensure voltage stability and minimize harmonics for efficient power distribution. A PWM rectifier, along with a PI controller, regulates the DC voltage, providing precise control over the power conversion. D-Q theory for reference current generation and a hysteresis current controller optimize current management, ensuring system reliability. Simulation results using MATLAB 2021a validate improvements in both efficiency and power quality. This approach not only improves renewable energy integration but also supports sustainable and reliable power generation, advancing green energy technologies.

REFERENCES:

1. H. Shutari, T. Ibrahim, N. B. Mohd Nor, N. Saad, M. F. N. Tajuddin and H. Q. A. Abdulrab, "Development of a Novel Efficient Maximum Power Extraction Technique for Grid-Tied VSWT System," in IEEE Access, vol. 10, pp. 101922-101935, 2022.
2. M. Alzayed, Y. Farajpour and H. Chaoui, "Simplified Current Sensorless Maximum Power Extraction for Wind Energy Conversion Systems," in IEEE Access, vol. 10, pp. 104686-104695, 2022.
3. D. Zhang, Y. Hu and Y. Gao, "Flexibility Improvement of CHP Unit for Wind Power Accommodation," in Journal of Modern Power Systems and Clean Energy, vol. 10, no. 3, pp. 731-742, May 2022.
4. S. Wang, J. Li, Z. Hou, Q. Meng and M. Li, "Composite Model-free Adaptive Predictive Control for Wind Power Generation Based on Full Wind Speed," in CSEE Journal of Power and Energy Systems, vol. 8, no. 6, pp. 1659-1669, November 2022.
5. Y. Zhu and H. Peng, "Multiple Random Forests Based Intelligent Location of Single-phase Grounding Fault in Power Lines of DFIG-based Wind Farm," in Journal of Modern Power Systems and Clean Energy, vol. 10, no. 5, pp. 1152-1163, September 2022.

6. L. Zhang and J. Wei, "Module Lifetime Evaluation Method for the Power Converter of the DFIG Based on the Analysis of the Field Wind Speed Probability and Ambient Temperature," in IEEE Access, vol. 10, pp. 72545-72556, 2022.
7. R. G. Mohamed, M. A. Ebrahim, Z. M. Alaas and M. M. R. Ahmed, "Optimal Energy Harvesting of Large-Scale Wind Farm Using Marine Predators Algorithm," in IEEE Access, vol. 10, pp. 24995-25004, 2022.
8. M. I. Mosaad and N. A. Sabiha, "Ferroresonance Overvoltage Mitigation Using STATCOM for Grid-connected Wind Energy Conversion Systems," in Journal of Modern Power Systems and Clean Energy, vol. 10, no. 2, pp. 407-415, March 2022.
9. K. A. Singh, A. Chaudhary and K. Chaudhary, "Three-phase AC-DC Converter for Direct-drive PMSG-based Wind Energy Conversion System," in Journal of Modern Power Systems and Clean Energy, vol. 11, no. 2, pp. 589-598, March 2023.
10. L. Guo, M. Yin, C. Cai, Y. Xie and Y. Zou, "Optimal Decreased Torque Gain Control for Maximizing Wind Energy Extraction Under Varying Wind Speed," in Journal of Modern Power Systems and Clean Energy, vol. 11, no. 3, pp. 853-862, May 2023.
11. X. Feng, S. Lin, W. Liu, W. Liang and M. Liu, "Distributionally Robust Optimal Dispatch of Offshore Wind Farm Cluster Connected by VSC-MTDC Considering Wind Speed Correlation," in CSEE Journal of Power and Energy Systems, vol. 9, no. 3, pp. 1021-1035, May 2023.
12. W. Chen, W. Yang, H. Qi, Z. Shi and H. Geng, "Coordinated Power Reserve Control of Wind Farm for Frequency Regulation," in IEEE Access, vol. 11, pp. 55465-55473, 2023.
13. B. E. Elnaghi, M. N. Abelwhab, F. E. S. A. Abdel-Kader, A. M. Ismaiel, R. H. Mohammed and M. E. Dessouki, "Experimental Validation of Second-Order Adaptive Fuzzy Logic Controller for Grid-Connected DFIG Wind Power Plant," in IEEE Access, vol. 11, pp. 135255-135271, 2023.
14. H. Chojaa et al., "A Novel DPC Approach for DFIG-Based Variable Speed Wind Power Systems Using DSpace," in IEEE Access, vol. 11, pp. 9493-9510, 2023.
15. T. Wang, J. Zheng, Q. Chen, Y. Liu and W. Song, "Mitigation of Subsynchronous Control Interaction in DFIG-Based Wind Farm Using Repetitive-PI," in IEEE Access, vol. 11, pp. 60807-60816, 2023, doi: 10.1109/ACCESS.2023.