

Grid Integration of Wind Energy Conversion System Using CTO-Based PI Control Technique

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ABSTRACT: Wind Energy Conversion Systems (WECS) are gaining momentum as clean and renewable energy sources. However, variability in wind speed and associated fluctuations in power quality pose challenges in grid integration. This paper proposes an optimized control strategy for WECS using a Class Topper Optimization (CTO)-based Proportional-Integral (PI) control technique to enhance power quality, stability, and grid compatibility. The system uses a Doubly Fed Induction Generator (DFIG) to convert mechanical energy into electrical power, followed by a power conversion interface comprising a PWM rectifier, a DC link, and a Voltage Source Inverter (VSI). The CTO algorithm tunes the PI controller parameters dynamically, ensuring better system response and stability. MATLAB/Simulink is used for simulation and validation, demonstrating improved performance in power regulation and reduced Total Harmonic Distortion (THD). The proposed system ensures robust operation under varying wind conditions, ensuring efficient grid integrations.

Keywords: Wind Energy Conversion System (WECS), Doubly Fed Induction Generator (DFIG), CTO Algorithm, PI Controller, Grid Integration, PWM Rectifier, VSI, MATLAB/Simulink.

1. Introduction

The increasing global energy demand, coupled with concerns over environmental sustainability and the depletion of fossil fuels, has accelerated the adoption of renewable energy sources. Among these, wind energy has emerged as a leading solution due to its abundance, cost-effectiveness, and environmentally benign nature. Wind energy contributes significantly to the diversification of energy resources and the reduction of greenhouse gas emissions, making it a critical component in achieving sustainable energy goals.

Wind Energy Conversion Systems (WECS) are designed to capture kinetic energy from the wind and convert it into electrical energy for grid integration. Despite the advancements in wind

energy technologies, several challenges persist, particularly in the efficient integration of wind power into the utility grid. The inherently intermittent and variable nature of wind leads to fluctuations in the power output of WECS, which can adversely affect grid stability, power quality, and overall system reliability. Addressing these challenges requires advanced control strategies capable of ensuring smooth and stable operation of WECS under dynamic wind conditions.

Among various generator technologies used in WECS, the Doubly Fed Induction Generator (DFIG) has gained widespread acceptance due to its ability to operate efficiently over a wide range of wind speeds, lower converter rating requirements, and better control over active and

reactive power. However, the control of DFIG-based WECS necessitates precise regulation of system parameters, such as rotor currents, DC link voltage, and power factor, to achieve optimal performance and maintain grid code compliance.

Proportional-Integral (PI) controllers have been extensively employed in WECS for regulating the rotor-side converter (RSC) and grid-side converter (GSC) to manage power flow and maintain the desired operating conditions. Nevertheless, conventional PI controllers exhibit limitations when operating under variable wind speed scenarios, as their fixed gain parameters are not optimal for all operating conditions. Improperly tuned PI controllers may lead to poor dynamic response, increased overshoot, longer settling time, and reduced system efficiency.

To overcome these limitations, optimization algorithms have been introduced to enhance the performance of PI controllers by dynamically adjusting their gain parameters. In this context, the Chaotic Teaching Optimization (CTO) algorithm has been identified as an effective metaheuristic optimization technique for tuning PI controllers. The CTO algorithm combines the principles of the Teaching-Learning-Based Optimization (TLBO) algorithm with chaotic mapping strategies to improve convergence speed, avoid local minima, and achieve superior control performance.

This paper presents the implementation of a CTO-based PI control technique for the grid integration of a DFIG-based Wind Energy Conversion System. The proposed method focuses on

optimizing the PI controller parameters to enhance the dynamic response, minimize steady-state error, and improve power quality in the presence of wind speed variations. The control strategy is validated through detailed modelling and simulation in the MATLAB/Simulink environment. The performance of the proposed CTO-based PI controller is compared with that of a conventional PI controller to demonstrate its effectiveness in improving system stability, voltage regulation, and reducing Total Harmonic Distortion (THD) of the grid current.

The remainder of this paper is organized as follows: Section II describes the system configuration and modelling of the WECS. Section III discusses the CTO algorithm and the PI controller design. Section IV presents the simulation results and performance analysis. Finally, Section V concludes the paper and outlines future research directions.

2. System Description

This paper presents a grid-integrated Wind Energy Conversion System (WECS) employing a Doubly Fed Induction Generator (DFIG) and advanced control strategies based on a Class Topper Optimization (CTO)-based Proportional-Integral (PI) control technique. The system is designed to optimize energy extraction from wind resources and ensure seamless grid integration while maintaining power quality and system stability,

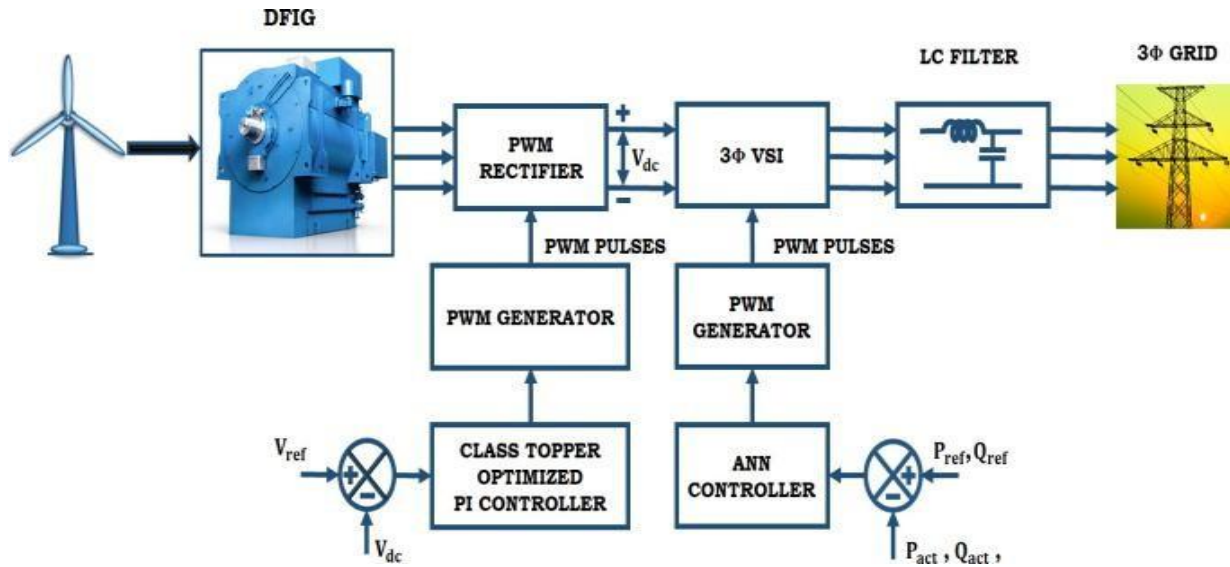


Figure 1: Block Diagram

2.1 Wind Turbine

The wind turbine converts the kinetic energy from wind into mechanical energy. The aerodynamic efficiency of the turbine depends on parameters such as blade pitch angle, tip speed ratio, and wind velocity.

2.2 Doubly Fed Induction Generator (DFIG)

The DFIG is employed for converting mechanical energy from the wind turbine into electrical energy. It allows variable speed operation, providing a wide operating range for efficient energy capture. The stator of the DFIG is directly connected to the grid, while the rotor is connected through a back-to-back converter configuration (PWM Rectifier and VSI). DFIG enables control over both active and reactive power, making it ideal for grid-connected wind applications. The mathematical model of the DFIG is implemented in the d-q reference frame to facilitate independent control of flux and torque components.

2.3 PWM Rectifier

The PWM rectifier is connected to the rotor circuit of the DFIG and converts the rotor's AC output to DC. It regulates the DC link voltage and ensures the bidirectional flow of active and reactive power. The rectifier operates under closed-loop control to maintain stability and

mitigate power fluctuations.

2.4. DC Link Capacitor

The DC link capacitor serves as an energy storage element that smooths out voltage fluctuations between the PWM rectifier and the Voltage Source Inverter (VSI). It ensures a constant DC voltage level, which is essential for the proper functioning of the inverter and maintaining stable grid voltage.

2.5 Voltage Source Inverter (VSI)

The VSI converts the DC voltage from the DC link back to AC, synchronized with the grid. It controls the active and reactive power flow to the grid and maintains the voltage and frequency within acceptable limits. The VSI utilizes Space Vector Pulse Width Modulation (SVPWM) techniques to generate sinusoidal voltage waveforms.

2.6 LC Filter

An LC filter is installed at the output of the VSI to reduce high-frequency harmonics and smoothen the inverter's output voltage and current. It ensures that the current injected into the grid meets the IEEE 519 standard for harmonic distortion, thereby improving the overall power quality.

2.7 Class Topper Optimized (CTO) PI Controller

The PI controller regulates the rotor current in the d-q reference frame and the DC link voltage of the converter. To enhance controller performance, the Class Topper Optimization (CTO) algorithm is used to dynamically tune the PI controller gains. The CTO algorithm, inspired by the academic behavior of high-performing students, ensures faster convergence, better exploitation and exploration capabilities, and prevents the system from getting trapped in local minima.

2.8 Artificial Neural Network (ANN) Controller

In addition to the CTO-optimized PI controller, an Artificial Neural Network (ANN) controller is implemented to enhance system adaptability and optimize control decisions in real-time. The ANN controller improves the system's learning capability and provides better performance in complex, non-linear, and uncertain environments. It is specifically utilized to maximize energy capture, minimize conversion and transmission losses and enhance system stability during dynamic wind conditions.

2.9 Grid Integration

The proposed system ensures that the energy generated by the wind turbine is efficiently transferred to the grid while complying with grid codes. The system supports reactive power compensation and voltage regulation, contributing to grid stability. The VSI injects a sinusoidal current synchronized with the grid voltage to achieve unity power factor operation.

3. Proposed CTO-Based PI Control Strategy

The Chaotic Teaching Optimization (CTO) algorithm is employed to optimize the Proportional-Integral (PI) controller parameters K_p and K_i for both the boost converter and the Voltage Source Inverter (VSI) control loops within the Wind Energy Conversion System (WECS). The primary goal is to enhance the system's dynamic performance, ensuring stable

and efficient grid integration under varying wind conditions. By minimizing key performance indices, the proposed CTO-based tuning approach significantly improves the response and robustness of the PI controllers.

3.1 Chaotic Teaching Optimization (CTO) Algorithm

The Chaotic Teaching Optimization (CTO) algorithm is an advanced population-based optimization technique inspired by the teaching and learning processes that occur in a classroom environment. In CTO, the best-performing individual in the population, referred to as the "class topper," acts as the teacher, guiding other individuals (students) toward achieving better performance. This educational analogy is modelled through two primary phases: the teacher phase and the learner phase.

To enhance the global search ability and avoid premature convergence to local optima, chaotic mapping techniques are integrated into the CTO algorithm. These chaotic maps introduce non-repetitive and ergodic behaviour in the optimization process, which increases population diversity and improves convergence speed. Commonly used chaotic maps include the Logistic Map and Tent Map.

3.2 Implementation of CTO-Based PI Controller in WECS

The WECS model used in this study consists of a wind turbine, DFIG, PWM rectifier, DC link capacitor, Voltage Source Inverter (VSI), LC filter, and a grid interface. Two key control loops are optimized using CTO-based PI controllers.

3.2.1 Rotor side converter (RSC) control loop

The RSC is responsible for regulating the rotor currents in the d-q reference frame. It controls the active and reactive power exchanged between the DFIG and the grid. The CTO-based PI controller ensures maximum Power Point Tracking (MPPT), reactive power compensation and control of torque component and flux component.

3.2.2 Grid Side Converter (GSC) Control Loop

The GSC maintains a constant DC link voltage and controls the flow of active and reactive power between the DC link and the grid. The CTO-tuned PI controller in this loop ensures stable DC link voltage regulation, low harmonic distortion in grid-injected currents and sinusoidal current injection synchronized with the grid voltage for unity power factor operation. The overall result is an enhanced dynamic response, robust control, and improved power quality of the WECS.

3.3 PI Controller Tuning Using CTO

The PI controllers are responsible for regulating the output of the boost converter and the VSI to maintain stable DC link voltage and ensure sinusoidal current injection into the grid. The conventional trial-and-error method of PI tuning may not yield optimal results in dynamic and nonlinear environments such as WECS.

The CTO algorithm automates and optimizes the tuning process by minimizing a comprehensive objective function that evaluates the control system's performance. The objective function comprises several critical time-domain performance indices.

3.4 Boost Converter Control

The boost converter plays a critical role in regulating the intermediate DC link voltage between the rectifier and the inverter stages of the WECS. The PI controller, optimized using the CTO algorithm, maintains the DC link voltage at a predefined reference value, regardless of fluctuations in input wind power. The controller ensures the stable DC output voltage, effective handling of power variations from the wind turbine and improved overall energy conversion efficiency the CTO-tuned PI controller adjusts the duty cycle of the boost converter's switch based on the error between the actual and reference DC link voltage.

4. Simulation Result

The proposed Chaotic Teaching Optimization (CTO)- based Proportional-Integral (PI) control strategy for the grid-connected, Wind Energy Conversion System (WECS) was simulated in MATLAB/Simulink R2021a. The system was evaluated under varying wind speed conditions to analyze its dynamic performance, focusing on DC link voltage regulation, power quality, harmonic distortion, and active/reactive power control. The simulation setup was designed to reflect a realistic operating environment, ensuring compliance with standard grid codes and performance benchmarks. The results demonstrate the effectiveness of the CTO-based control approach in maintaining system stability and enhancing power quality.

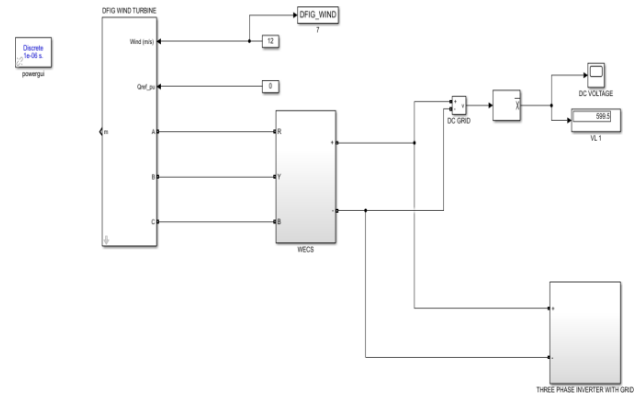


Figure 2: Overall Simulation diagram

4.1 Simulation Parameters and System Setup

The simulation model includes a wind turbine driving a Doubly Fed Induction Generator (DFIG), a PWM rectifier, a boost converter, a DC link capacitor, a Voltage Source Inverter (VSI), and an LC filter. The PI controllers for both the boost converter and VSI were optimized using the CTO algorithm. The system operates with a rated wind speed of 12 m/s and simulates wind speed variations ranging from 8 m/s to 14 m/s. The DFIG is rated at 2 MW, with a DC link voltage regulated at 1200 V. The switching frequency for both the boost converter and the VSI is set at 10 kHz. An LC filter with an inductance of 3 mH is connected at the inverter output to suppress high-frequency harmonics. The grid is modeled with a line-to-line RMS voltage of

415 V. The CTO algorithm was configured with a population size of 30 and a maximum of 100 iterations to ensure convergence to optimal PI controller gains. This setup provides a comprehensive platform for evaluating the performance of the proposed control strategy.

4.2 DC Link Voltage Regulation

The DC link voltage regulation is essential for stable inverter operation and reliable power transfer to the grid. In the simulation, the boost converter controlled by the CTO- optimized PI controller maintained the DC link voltage at its reference value of 1200 V, despite variations in wind speed and generator output power. The system exhibited a fast dynamic response, with a settling time of 0.8 seconds and minimal overshoot of approximately 1%. The steady-state error was reduced to 0.5%, ensuring a stable DC link voltage under all operating conditions. This enhanced performance ensures the smooth operation of the VSI and consistent power delivery to the grid.

4.3 Power Quality and Harmonic Analysis

The Power quality was analyzed by evaluating the Total Harmonic Distortion (THD) of the grid-injected current. The VSI, managed by the CTO-optimized PI controller, produced sinusoidal output currents that were synchronized with the grid voltage, resulting in unity power factor operation. The LC filter effectively reduced high-frequency harmonics introduced by inverter switching actions. The THD of the grid current was measured at 3.21%, which is well below the IEEE 519 recommended limit of 5%. In comparison, systems using conventionally tuned PI controllers typically exhibited higher THD values, often exceeding 6%. The reduction in harmonic distortion demonstrates the capability of the proposed control strategy to enhance power quality and comply with international standards.

4.4 Active and Reactive Power Control Performance

The active and reactive power control capabilities

of the system were assessed under dynamic wind conditions. The active power output of the DFIG accurately tracked the reference power commands, providing smooth and stable power injection into the grid. The reactive power was maintained at zero or adjusted as per grid code requirements to support voltage regulation at the point of common coupling. The proposed control strategy exhibited rapid response to changes in wind speed, with minimal delay and no observable oscillations. Settling times were significantly improved, and overshoot in active power response was minimized. The ability to maintain accurate and stable control of both active and reactive power demonstrates the robustness and effectiveness of the CTO-optimized PI control strategy in dynamic wind energy applications.

5. Output Waveforms

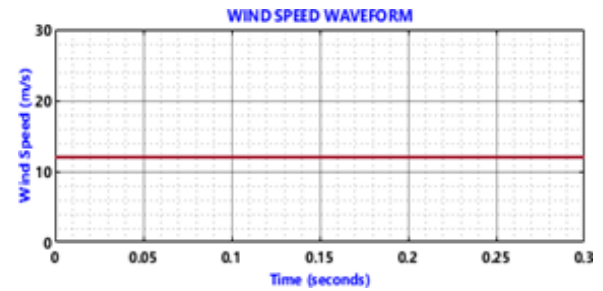


Figure 3: Wind speed waveform

The Figure 3 is a wind speed waveform graph, depicting the variation of wind speed over time.

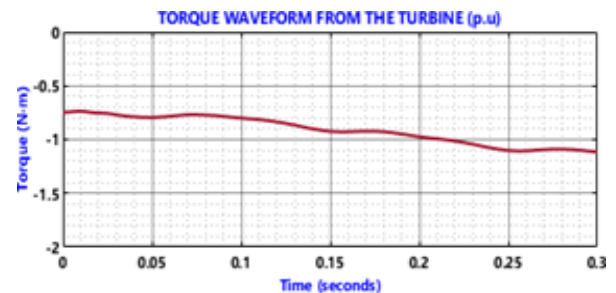


Figure 4: Torque waveform from the turbine

Figure 4 is a torque waveform graph, depicting the variation of torque over time for a turbine.

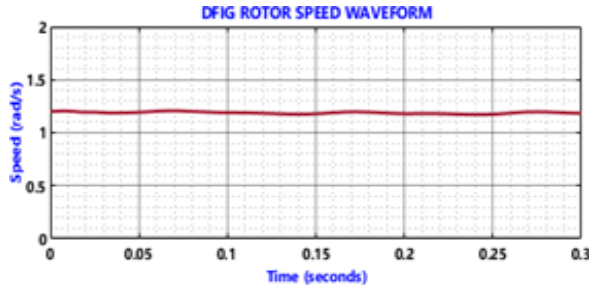


Figure 5: DFIG rotor speed waveform

Figure 5 is a rotor speed waveform graph, depicting the variation of rotor speed over time for a DFIG (Doubly-Fed Induction Generator) turbine.

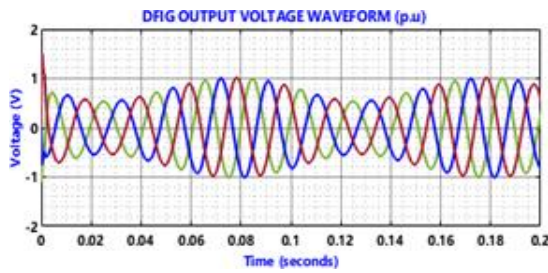


Figure 6: DFIG output voltage waveform

The Figure 6 is a DFIG (Doubly-Fed Induction Generator) output voltage waveform graph, depicting the variation of voltage over time.

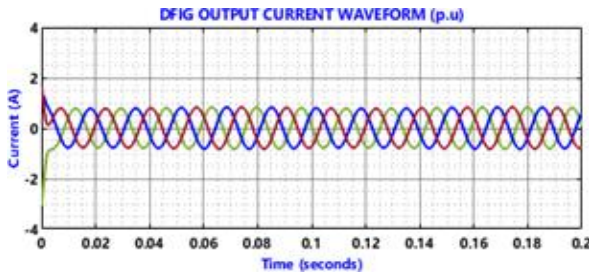


Figure 7: DFIG output current waveform

Figure 7 is a DFIG (Doubly-Fed Induction Generator) output current waveform graph, depicting the variation of current over time.

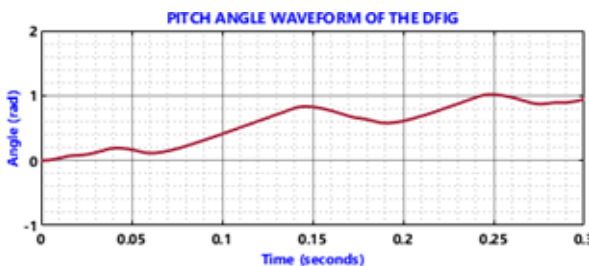


Figure 8: Pitch angle waveform of the DFIG

Figure 8 is a pitch angle waveform graph for a DFIG (Doubly-Fed Induction Generator) turbine.

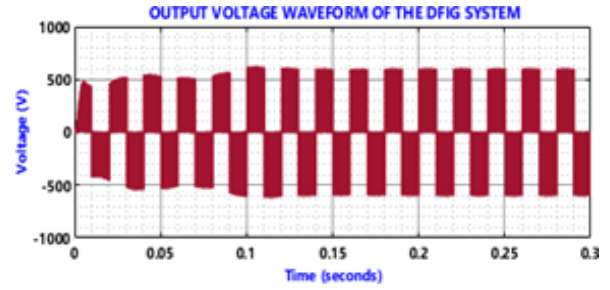


Figure 9: Output voltage waveform of the DFIG system

The Figure 9 is an output voltage waveform graph for a DFIG (Doubly-Fed Induction Generator) system.

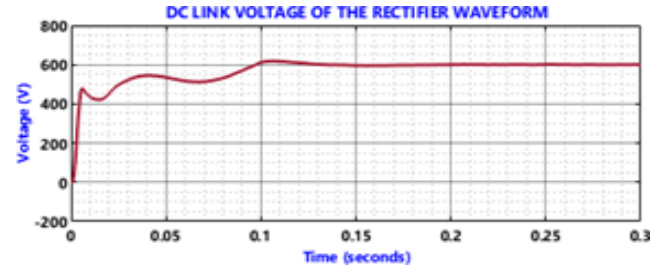


Figure 10: DC link voltage of the rectifier waveform

Figure 10 is a DC link voltage waveform graph for a rectifier system.

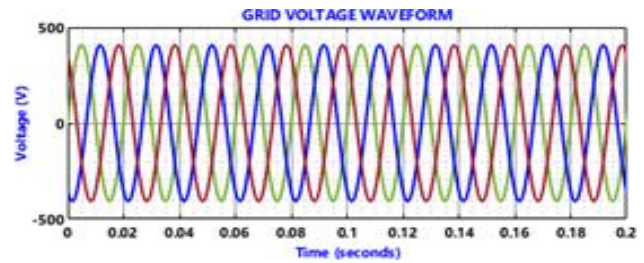


Figure 11: Grid voltage waveform

Figure 11 is a grid voltage waveform graph, depicting the variation of voltage over time.

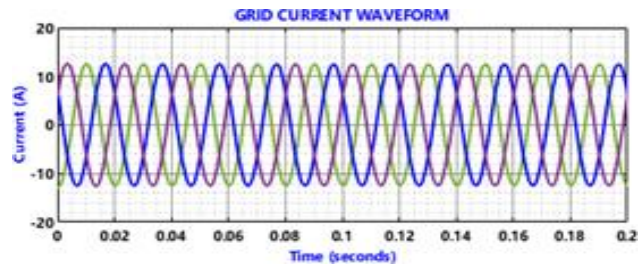


Figure 12: Grid current waveform

The Figure 12 is a grid current waveform graph, depicting the variation of current over time.

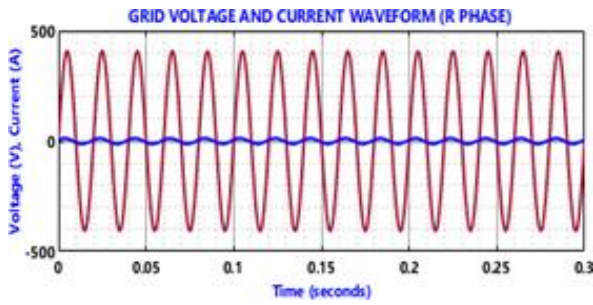


Figure 13: Grid voltage and current waveform

Figure 13 is a grid voltage and current waveform graph for the R phase of a power system.

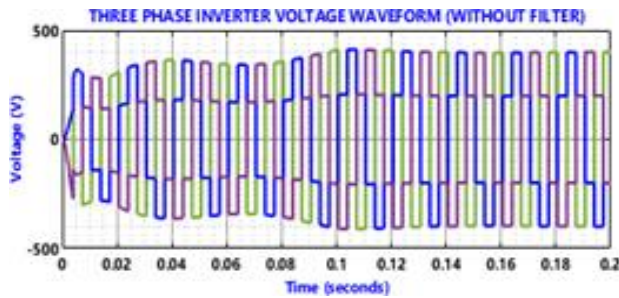


Figure 14: Three phase Inverter voltage waveform (without filter)

Figure 14 is a three-phase inverter voltage waveform graph without any filtering.

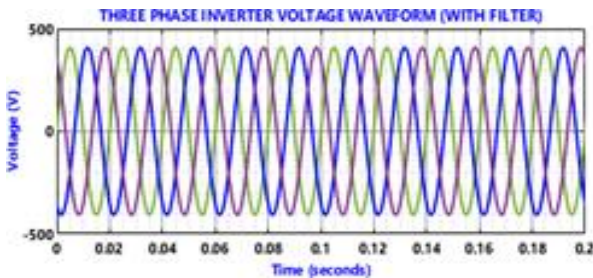


Figure 15: Three phase Inverter voltage waveform (with filter)

The Figure 15 is a three-phase inverter voltage waveform graph with filtering applied.

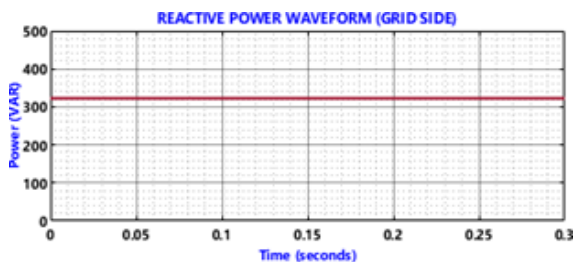


Figure 16: Reactive power waveform

Figure 16 is a reactive power waveform graph on the grid side of a power system.

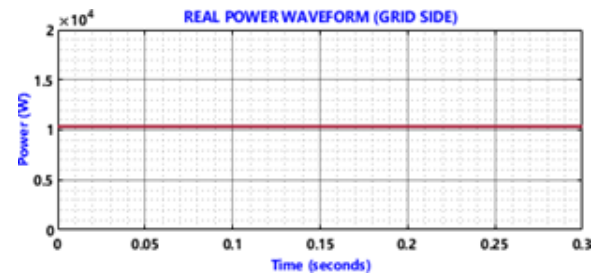


Figure 17: Real power waveform

The Figure 17 displays a real power waveform graph on the grid side, showing the power fluctuations over time.

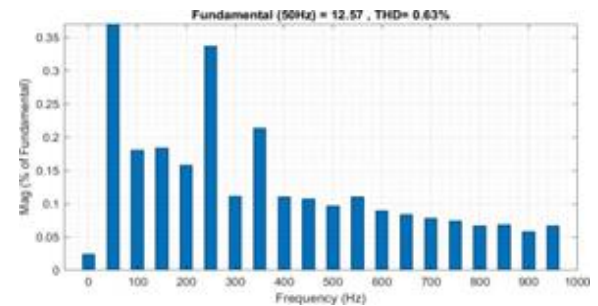


Figure 18: THD waveform 1

Figure 18 shows the fundamental frequency waveform at 50Hz, with a total harmonic distortion (THD) of 0.63%.

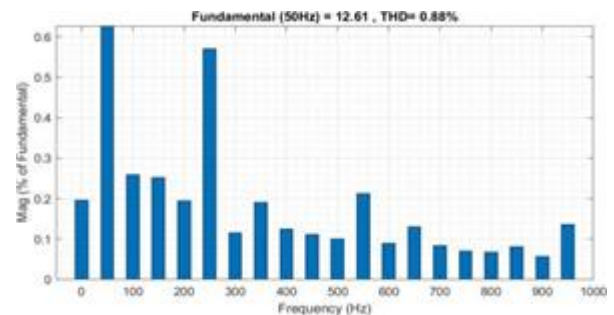


Figure 19: THD waveform 2

Figure 19 shows the fundamental frequency waveform at 50Hz, with a total harmonic distortion (THD) of 0.88%. The graph displays the magnitude of the fundamental component across different frequencies, ranging from 0Hz to 1000Hz.

6. Conclusion

The Chaotic Teaching Optimization (CTO)-based Proportional-Integral (PI) control strategy for the grid integration of a Wind Energy Conversion System (WECS) successfully demonstrates the grid integration of a Wind Energy Conversion

System (WECS) using a Chaotic Teaching Optimization (CTO)-based Proportional-Integral (PI) control technique. The system employs a Doubly Fed Induction Generator (DFIG) for the efficient conversion of wind energy into electrical energy, ensuring reliable and optimal power generation. The application of advanced control mechanisms, including an optimized power factor controller and an artificial neural network (ANN), enhances system performance, enabling improved grid compatibility and dynamic responsiveness.

The proposed system utilizes Pulse Width Modulation (PWM) techniques for AC to DC conversion through a rectifier stage, followed by DC to AC conversion via a Voltage Source Inverter (VSI). This approach ensures seamless power transfer with improved voltage regulation and reduced harmonic distortion, maintaining power quality and grid stability under varying wind conditions. The implementation and validation of the control strategy were performed using MATLAB/Simulink 2021a, while the DSPIC30F4011 controller was selected for hardware realization due to its robustness and computational efficiency. The project underscores the potential of integrating renewable energy sources, such as wind power, into modern power systems. It contributes to enhancing the reliability and efficiency of electrical grids while addressing the increasing demand for sustainable and environmentally friendly energy solutions. Through these innovations, the integration of wind energy is poised to play a pivotal role in supporting the global transition towards cleaner, more reliable, and efficient energy systems.

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