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GRID INTEGRATED DUAL WIND TURBINE SYSTEM USING WHALE OPTIMZED PI CONTROLLER WITH SEPIC CONVERTER

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Abstract: The grid-integrated dual wind turbine system using a whale-optimized PI controller with a SEPIC converter aims to efficiently convert variable wind energy into stable grid-compatible power. Existing systems face challenges such as inefficient energy conversion, poor grid stability, and complex control strategies. The proposed approach addresses these issues by integrating advanced control techniques and optimizing power conversion with improved voltage regulation. This project proposes a wind energy conversion system (WECS) that utilizes doubly fed induction generators (DFIG) integrated with a dual DC wind turbine (DCWT) configuration. The system employs a pulse width modulation (PWM) rectifier and a DC-DC SEPIC converter to effectively manage the conversion of variable wind energy into stable DC voltage. Each DCWT is equipped with a whale-optimized proportional-integral (PI) controller to regulate the DC voltage, ensuring efficient energy transfer to a common DC bus. The architecture also features a three-phase voltage source inverter (VSI) connected to the AC grid, enhanced with an LC filter for improved power quality. The PI controller on the AC side enables precise control of active and reactive power flow into the grid, thereby maximizing energy utilization and grid stability. This integrated approach aims to enhance the performance and reliability of renewable energy systems, contributing to sustainable energy solutions while addressing the challenges of grid integration. This project is implemented by Matlab simulation 2021a.

Keywords: Renewable Energy Sources; Doubly fed induction generators (DFIG); Voltage Source Inverter (VSI); Electric Vehicles (EV)

1. INTRODUCTION

A wind turbine is a device that converts the kinetic energy of the wind into electricity. The main components of a wind turbine include the rotor blades that capture the wind and the hub that connects the blades to the main shaft. The main shaft transfers power to the gearbox, which increases the rotation speed of the generator. The generator then converts mechanical energy into electrical energy. The system also includes a yaw machine that allows the machine to work with the wind, a sound system to control the angle, and a command and control function. The turbines are supported by towers that allow the maximum power to be seen to capture the wind, as well as generators that send out the electricity produced.

Through this process, wind turbines provide a sustainable and eco-friendly source of power by harnessing wind energy. Wind turbine systems consist of several devices that work together to convert wind energy into electricity. The rotor blades capture the kinetic energy of the wind, causing the blades to spin. This rotational power is sent through the hub and main shaft to the gearbox, which turns the generator. The generator then converts the mechanical energy into electrical energy. A yaw mechanism aligns the turbine with the wind, while a pitch system adjusts the blade angle for efficiency. The turbines are supported by tall towers, allowing stronger winds to be captured at higher altitudes. The **braking system** safely stops the turbine when needed, and the **electrical system tr**ansmits the generated electricity. The **controller** monitors and regulates the entire system to ensure safe and efficient operation.

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Wind turbine system innovation focuses on increasing the efficiency, effectiveness, and sustainability of wind energy. Over the years, advances in technology have changed the way wind turbines capture wind energy and convert it into electricity. One major innovation is the development of larger, more efficient turbines, especially those with longer rotors, to capture more wind, even in lower wind areas. Larger turbines can produce more electricity, making them suitable for large-scale energy production. Another major innovation is the use of floating wind turbines, especially in offshore wind farms. These turbines are installed on floating platforms and can be placed in water depths not possible with traditional fixed-base turbines. Offshore wind farms are often located in areas with higher and similar wind speeds, making them ideal for large-scale energy use. Floating wind turbines are a game changer in expanding global wind energy potential. Direct-drive turbines are another innovation that eliminates the need for gearboxes. Traditional wind turbines use gearboxes to increase the speed of the rotor, but direct-drive systems reduce energy consumption and maintenance by connecting the rotor directly to the generator, and increase overall performance and reliability. In addition, smart grid technologies have been integrated into wind turbine systems to improve the management and distribution of wind energy.

2. LITERATURE SURVEY

According to the requirements of wind turbine systems, the performance, features and applications are compared and assessed in this study. Existing studies often overlook DC-link dynamics, crucial for wind turbine applications.

H. Han *et al* [2024] proposed a parallel all-DC wind power system with a novel DC converter, ensuring stable operation through dynamic connection and control strategies, with fault analysis via PSCAD/EMTDC simulations. The system provides better control flexibility, self-starting capability reliability during DC faults, and stable performance in varying conditions.

F. Hans *et al* [2024] Presented is a methodology that involves testing wind turbines for grid code compliance through turbine, nacelle, subsystem, and component tests at Fraunhofer IWES. This process uses simulations and real-time data to ensure the reliability and grid compatibility of the turbines.

R. K. Behara*et al* [2024] developed to predict wind attributes using unsupervised learning, incrementally tuning, and optimizing energy generation for grid stability. Its performance is evaluated based on accuracy and efficiency. The model improves prediction accuracy, adapts to changing wind conditions, enhances grid stability, and increases wind energy efficiency using advanced techniques like a 2-level fused discriminator and self-attention.

G. M. Gomes *et al* [2024] Determined procedures for grid compliance testing involve prototype turbine testing, offline simulations, real-time SIL/HIL simulations for grid performance, and digital twins for dynamic analysis and compliance prediction. Traditional grid compliance testing ensures reliability and regulatory acceptance, while SIL/HIL simulation lowers costs by reducing physical prototypes and enabling diverse testing.

A. A. Bindu*et al* [2024] Proposed repowering for wind farms involves assessing the existing performance using WAsP software, determining the need for more efficient turbines, and presenting the addition of photovoltaic panels between turbines. Established methodologies for evaluating the energy output are applied, and a generated economic feasibility study compares the costs with the increased energy production and financial benefits.

S. Wei *et al* [2023] Established N+ design optimizes wind turbine operation under realistic loads, integrates electrical systems, and balances cost, sustainability, and stakeholder interests. This approach optimizes costs and resources by avoiding over provisioning, enhancing wind energy efficiency, reducing idle equipment, and minimizing environmental impact, while ensuring flexibility and robustness in offshore wind farm operations. The N+ design faces challenges in complexity, underperformance risk, limited redundancy, and difficulty aligning stakeholder objectives.

A. Ouammi*et al* [2023] presented a forecasting model for wind speeds, enabling more accurate predictions to enhance turbine placement and operational efficiency. The objective is to maximize the Net Present Value (NPV) of the wind turbine investment, ensuring the highest possible returns over the project's lifespan.

S. Ghosh *et al* [2023] Presented in this study is a comparison between synchronous machine and wind turbine models, with a focus on damping behavior under post-fault current ramp rate control. The stability boundary is established using a non-autonomous energy function, and the findings are determined through PSCAD simulations, which validate the analysis under various conditions.

Z. Li, H. Han *et al* [2023] Established as the core of this methodology is a simulation of a DC Wind Turbine system, where a control strategy is determined to facilitate energy absorption, voltage stabilization, and reactive power compensation. The idea is to ensure stability during grid failure, allowing wind turbines to maintain their performance even in the event of an outage.

S. Fathallah*et al* [2023] developed adaptive inertia control strategies that adjust gains based on the Rate of Change of Frequency (ROCOF), frequency changes, and wind speed. The controllers were tested under varying conditions, with performance compared to traditional methods, demonstrating improvements in system stability during disturbances. Controllers provide better frequency support under different operating conditions, especially when there are sudden load changes or variations in wind speed.

D. Bustan and H. Moodi*et al* [2022] developed an adaptive interval type-2 fuzzy controller (IT2FC) for a wind turbine, optimizing performance across operational regions without relying on wind speed estimation, to improve power generation, reduce mechanical loads, and enhance turbine reliability. The controller improves power generation by adapting to various wind conditions across different operational regions, ensuring better performance compared to a baseline controller.

Objectives:

- To implement a grid-integrated dual wind turbine system using whale optimized PI controller with Sepic Converter
- To enhance energy conversion efficiency by integrating dual wind turbines with a Sepic Converter and DFIG.
- To enhance voltage regulation by applying whale-optimized PI controllers, ensuring precise control over the DC voltage output from each wind turbine.
- To ensure smooth and reliable DC voltage output by optimizing the PWM rectifier's performance for variable wind speeds and load conditions.

3. MODELING AND CONFIGURATION OF GRID-INTEGRATED DUAL WIND TURBINE SYSTEM

In this proposed system grid integrated dual wind turbine system using whale optimized PI controller with Sepic converter is proposed. The working process begins with wind energy conversion systems (WECS) that utilize doubly fed induction generators (DFIG) to capture wind energy. Each system is equipped with a direct current (DC) bus that connects to a PWM rectifier, converting the variable AC output from the generator into DC. The DC output is then processed by a DC-DC step-up converter, increasing the voltage to the required level. PWM generators create control signals to regulate the inverter operation, ensuring efficient energy conversion. Optimized proportional-integral (PI) controllers fine-tune the PWM signals based on real-time power demands and grid requirements. The system monitors voltage and current levels to maintain stability and efficiency. The generated AC output is filtered through an LC filter to reduce harmonics, producing a clean sinusoidal waveform. This filtered output is then synchronized with the AC grid.

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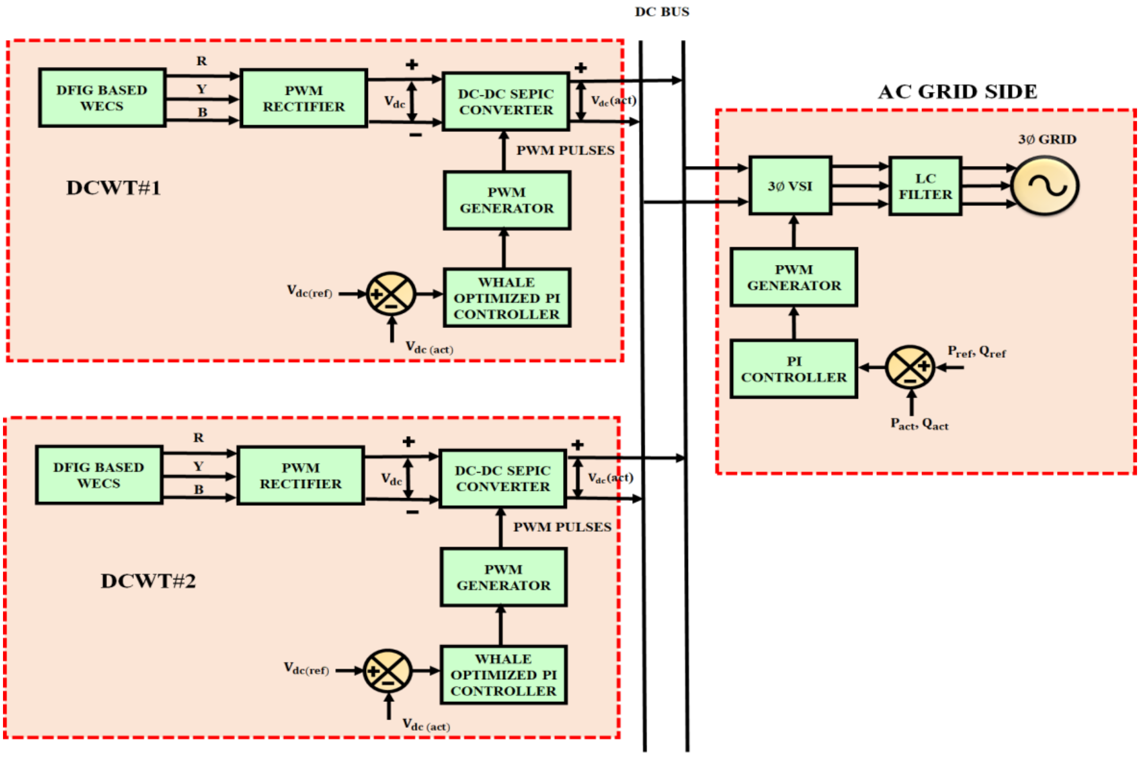

Figure 1. Block Diagram of Grid-Integrated Dual Wind Turbine System

Both DCWT systems operate in parallel, sharing the DC bus, which enhances reliability and power output. Continuous feedback loops allow for real-time adjustments to optimize performance and energy harvesting. The integration of advanced control algorithms ensures the system adapts to varying wind conditions and grid demands. Overall, this process efficiently converts wind energy into grid-compatible electricity, contributing to renewable energy sources.

A. Modeling of the Grid-Integrated Dual Wind Turbine using Whale Optimized PI Controller:

The integration of renewable energy sources, particularly wind energy, into the electrical grid requires sophisticated control techniques to manage the variable nature of wind power generation and ensure that the energy produced is delivered efficiently and reliably to the grid. In this context, the Whale Optimized PI (Proportional-Integral) Controller plays a significant role in optimizing the performance of grid-integrated dual wind turbine systems. When used in conjunction with a SEPIC (Single-Ended Primary Inductor Converter) converter, this advanced control strategy ensures that the variable output from wind turbines is efficiently transformed into stable power that can be fed into the grid while maintaining the integrity of the system and the grid. The Whale Optimized PI controller, which utilizes the Whale Optimization Algorithm (WOA) to optimize the parameters of a conventional PI controller, offers a robust solution to the challenges of controlling wind energy systems. The integration of two wind turbines into a single grid-connected system presents unique challenges due to the inherent variability of wind speeds. Wind turbines typically produce fluctuating electrical power due to changes in wind velocity, which can lead to variations in voltage, frequency, and power output. To manage these fluctuations and ensure that the system remains stable and efficient, precise control of the turbines and their power conversion stages is necessary.

WOA is a meta-heuristic optimization algorithm that is developed from the inspiration of hunting pattern of humpback whales. The hunting behavior of humpback whales is considered the most interesting strategy, as they prefer to prey on swarms or large group of small fish and this behavior is termed as Bubble-Net Feeding method, which is detailed in Figure 2. This method is exhibited by whales in circular motions or “9” shaped patterns in which they release specific bubbles that help them to establish the hunting process.

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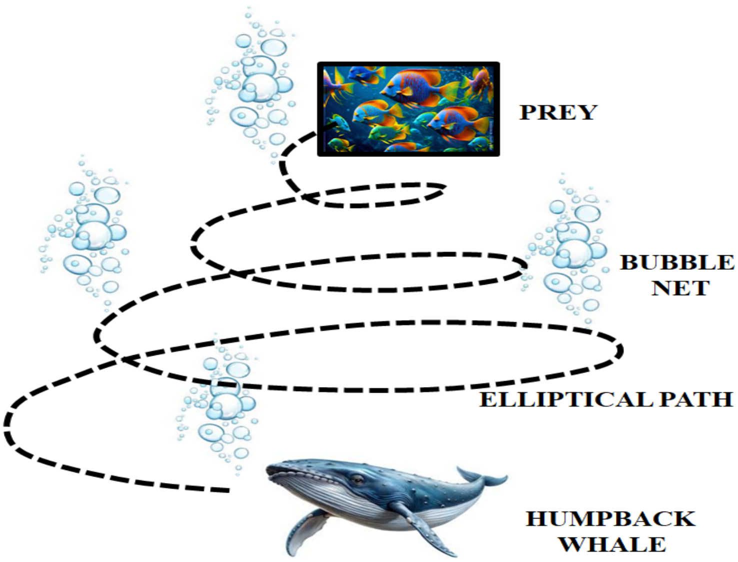

Figure 2 Bubble-Net Feeding method of humpback whales

The hunting pattern of humpback whales comprises three main strategies which are

- Encircling Prey
- Bubble-Net Attack
- Searching for prey

Encircling Prey :

During this phase, whales locate the position of their prey to encircle them, similarly, in search phase the selected position is encircled as the finest position. The mathematical representation of this phase is given as,

$$\vec{H} = \left|\vec{E}.\overrightarrow{Y^p}(i) - \vec{Y}(i)\right| \quad (1)$$

$$\vec{Y}(i+1) = \overrightarrow{Y^p}(i) - \vec{D}.\vec{H} \quad (2)$$

Where, i denotes the present iteration, $\vec{Y}$ indicates the present best position vector and $\overrightarrow{Y^p}$represents the finest position vector respectively. The vector coefficients $\vec{D}$ and $\vec{E}$ are evaluated using,

Bubble-Net Feeding Method :

In this phase, two feeding strategies are exhibited by the humpback whales, which are the shrinking encircling method and spiral position updation method. The shrinking method is executed by minimizing the value of $\vec{d}$ whereas, the spiral method is achieved by upgrading the position, that is expressed as,

$$\vec{Y}(i+1) = \vec{F}.b_{el}(2\pi r) + \overrightarrow{Y^p}(i) \quad (3)$$

Furthermore, to upgrade the whale position, 50% probability is considered for the above mentioned two methods which are given as,

$$\vec{Y}(it+1) = \{\overrightarrow{Y^p}(i) - \vec{D}.\vec{H} \qquad p < 0.5\, \vec{F}.b_{el}(2\pi r) + \overrightarrow{Y^p}(i) \;\; p \geq 0.5 \quad \} \quad (4)$$

Where, $\vec{F}$ denotes the finest position between the whale and the prey.

Searching for prey :

The search for prey is performed based on the vector deviations and the best position is selected on a random basis. The optimal global position is determined as,

$$\vec{F} = \left|\vec{D}.\overrightarrow{Y^{rand}} - \vec{Y}(i)\right| \quad (5)$$

$$\vec{Y}(i+1) = \overrightarrow{Y^{rand}} - \vec{D}.\vec{H} \quad (6)$$

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Where, $\overrightarrow{Y^{rand}}$ represents the vector position randomly selected by the whales. However, optimization techniques require random solutions for optimized parameter hence, PI controller is utilized for attaining parameters tuning for WOA and to obtain the equivalent objective function J.

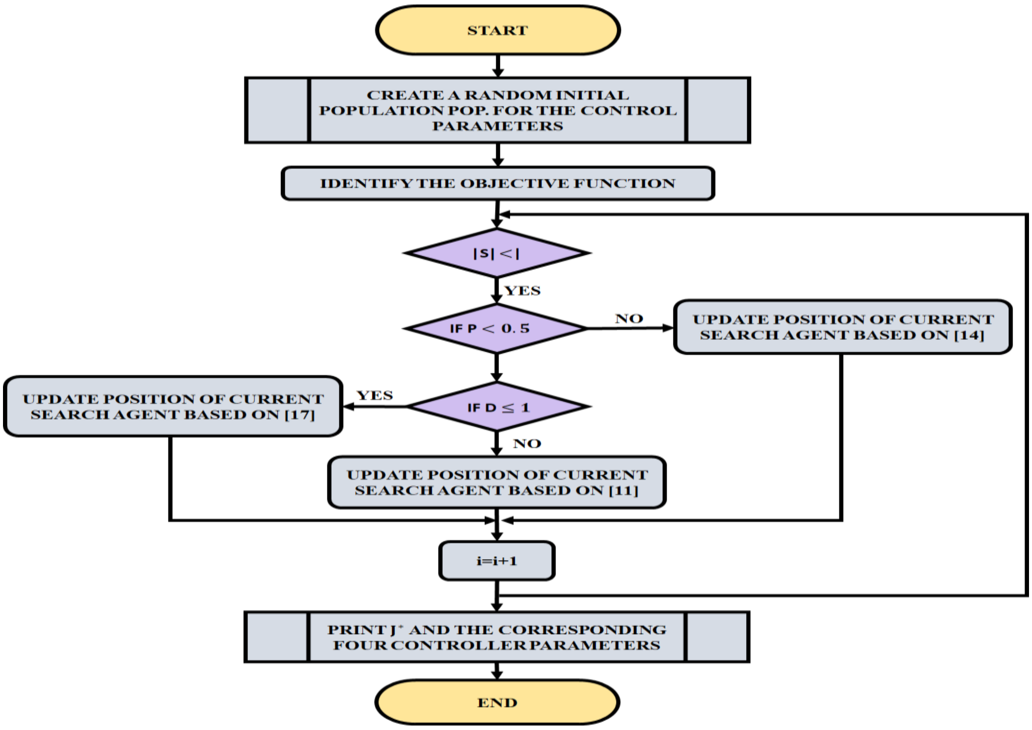

Figure 3 Flowchart of WOA Optimized PI controller

The search agent is used in WOA for determining the updated position and these updated positions are utilized for determining the objective functions. These steps are looped until they find the best suitable position and the flowchart of WOA optimized PI controller is depicted in Figure 3 Furthermore, the perfect grid synchronization is achieved by using a PI controller.

4. RESULTS AND DISCUSSIONS

The proposed work is implemented in MATLAB simulation and the following results are obtained.

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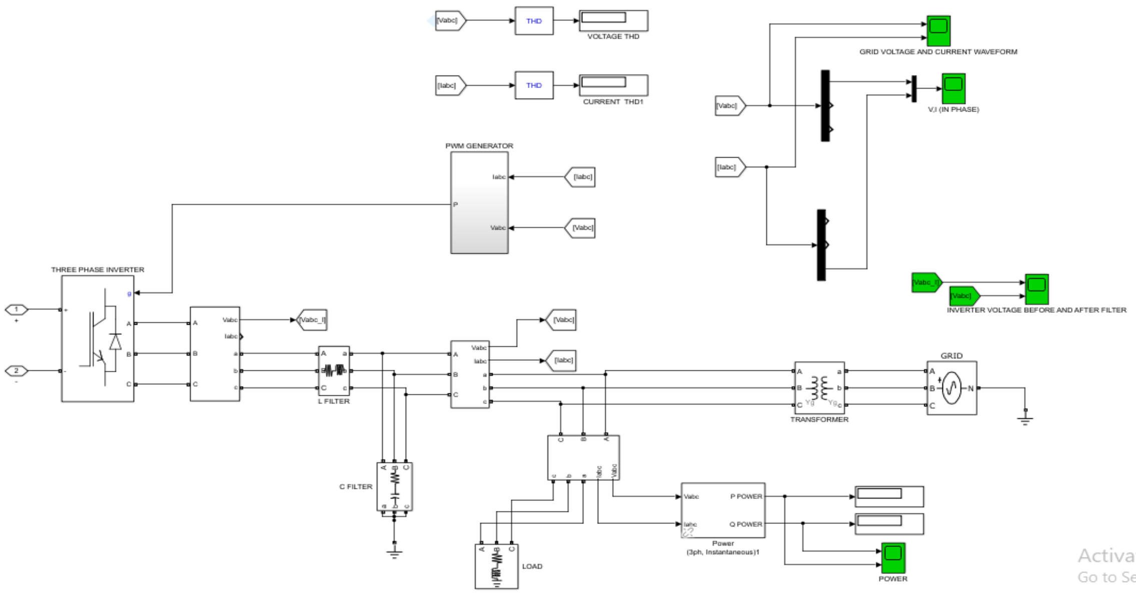

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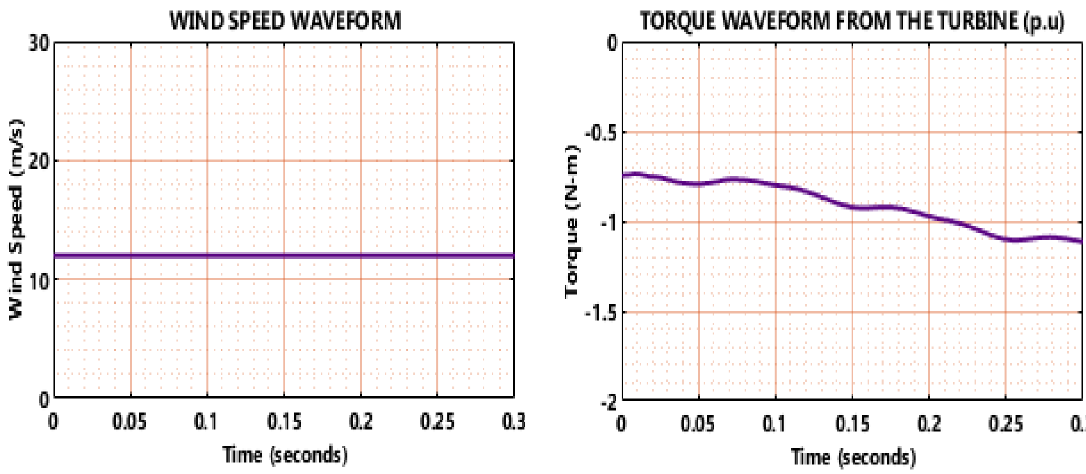

Figure 4.1 Wind speed and Torque Waveform

Figure 4.1 represents two waveforms: the left shows a consistent wind speed of 10 m/s over time, indicating stable conditions. The right illustrates the torque generated by a turbine, which gradually decreases, suggesting a decline in efficiency or power output as the wind conditions remain steady.

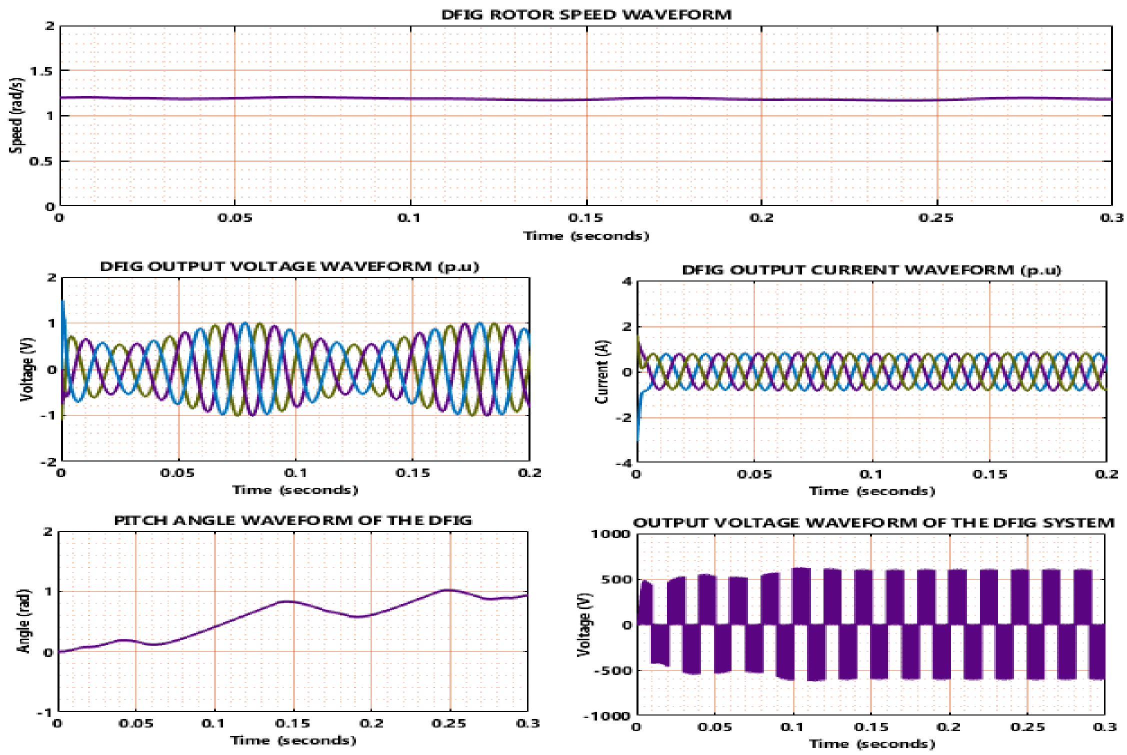

Figure 4.2DFIG 1 Performance Waveforms

Figure 4.2 represents the four waveforms related to a Doubly Fed Induction Generator (DFIG) system. The top shows a stable rotor speed. The second and third sections display fluctuating output voltage and current, respectively. The bottom illustrates a gradual increase in pitch angle, while the final waveform indicates a pulsed output voltage pattern.

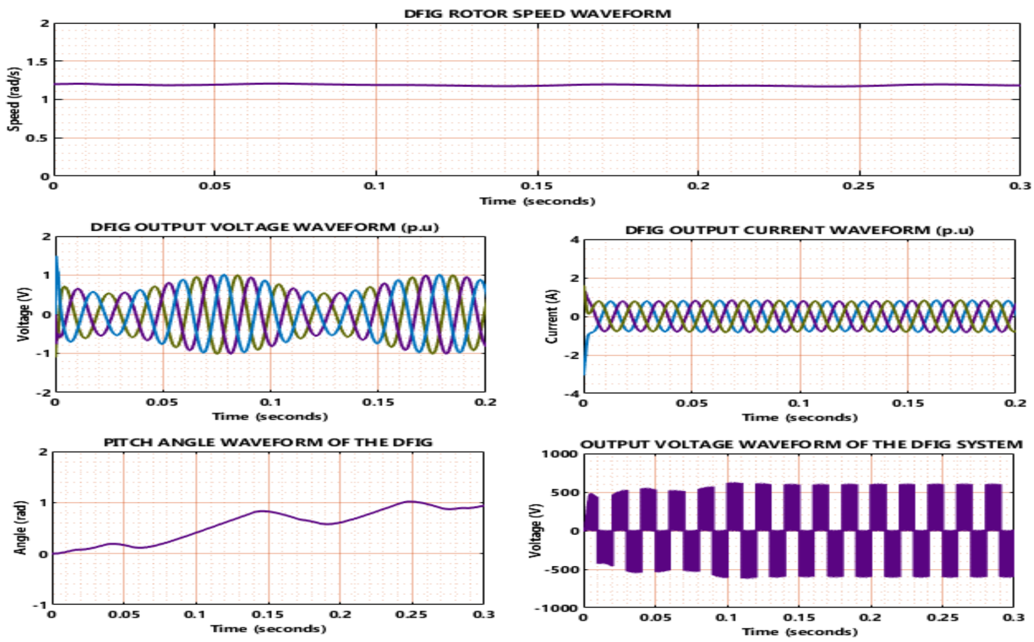

Figure 4.3 DFIG 2 Performance waveforms

Figure 4.3four waveforms related to a Doubly Fed Induction Generator (DFIG). The top shows a constant rotor speed. The second and third sections depict the fluctuating output voltage and current. The bottom illustrates a gradually increasing pitch angle, while the final waveform shows a pulsed output voltage pattern.

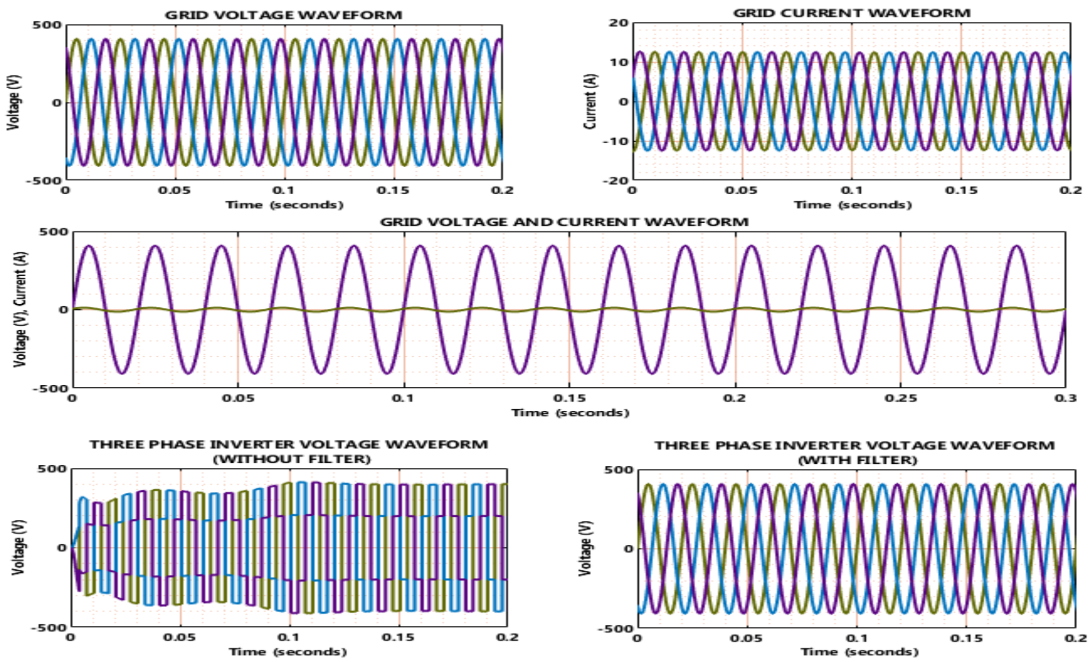

Figure 4.4 Grid and Three-phase inverter waveform

Figure 4.4 represent as features five waveforms related to grid voltage and current. The top two sections display periodic grid voltage and current waveforms. The middle section combines both for comparison. The bottom two sections show the three-phase inverter voltage waveforms, one without a filter and the other with a filter applied.

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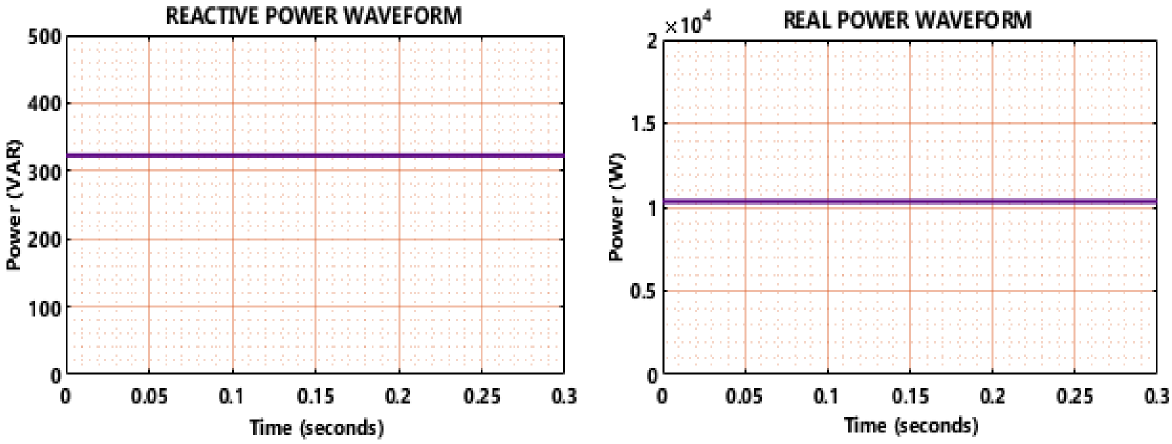

Figure 4.5 Reactive and Real Power Waveform

Figure 4.5represent as two power waveforms. On the left, the reactive power waveform is constant at 300 VAR, indicating steady reactive power flow. On the right, the real power waveform shows a consistent output of approximately 10,000 W, reflecting stable real power consumption over the observed time period.

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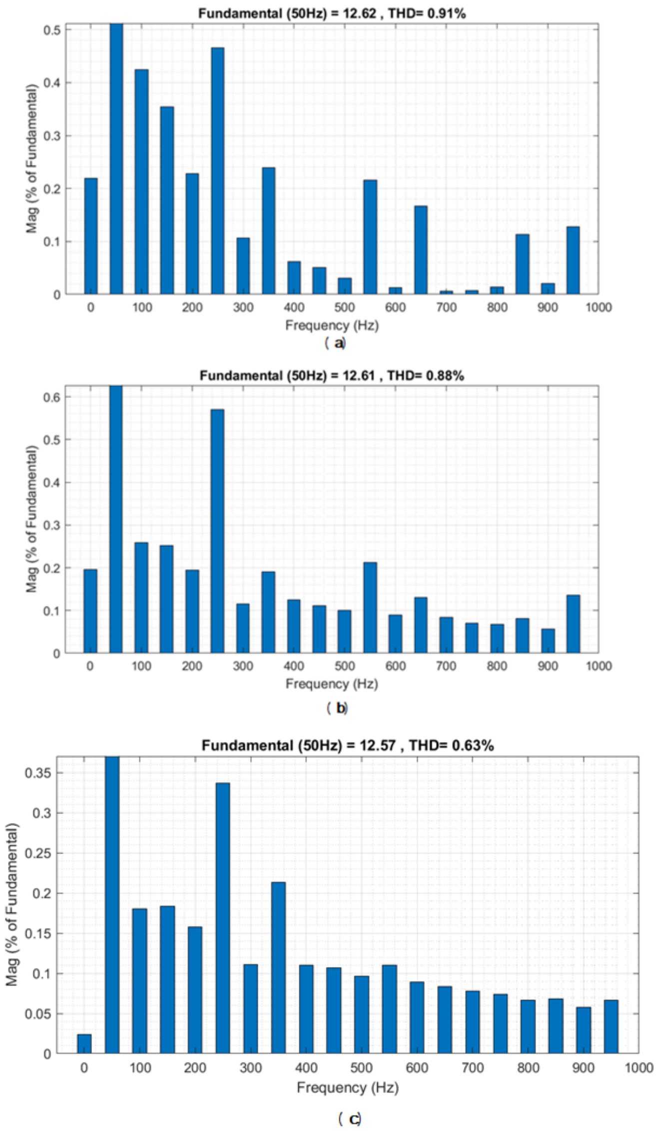

Figure 4.6THD waveform

Figure 4.6 represent as three histograms illustrating frequency spectra at a fundamental frequency of 50 Hz. Each histogram displays the magnitude of harmonics across varying frequencies. The total harmonic distortion (THD) values are 0.91%, 0.88%, and 0.63% for the respective plots, indicating decreasing harmonic distortion in higher frequency ranges.

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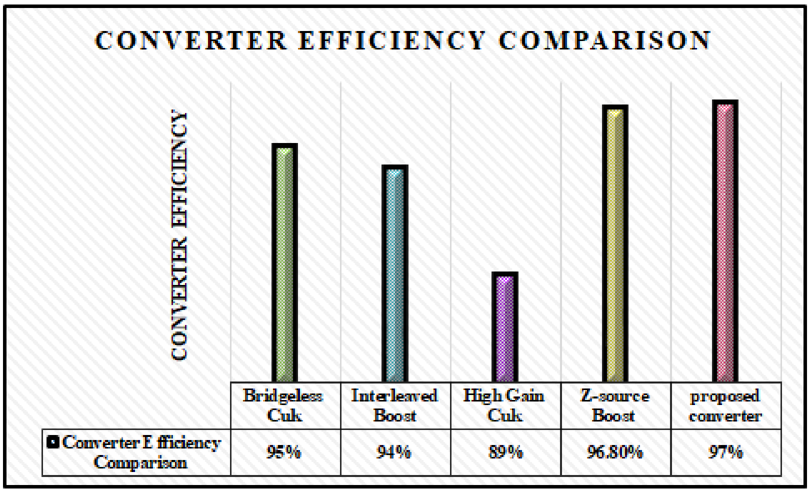

Figure 4.7 Efficiency Comparison

Figure 4.7 represent as compares the efficiency of various converters. It features five categories: Bridgeless Cuk (95%), Interleaved Boost (94%), High Gain Cuk (89%), Z-Source Boost (96.80%), and a proposed converter (97%). The proposed converter exhibits the highest efficiency, highlighting advancements in converter technology for improved performance.

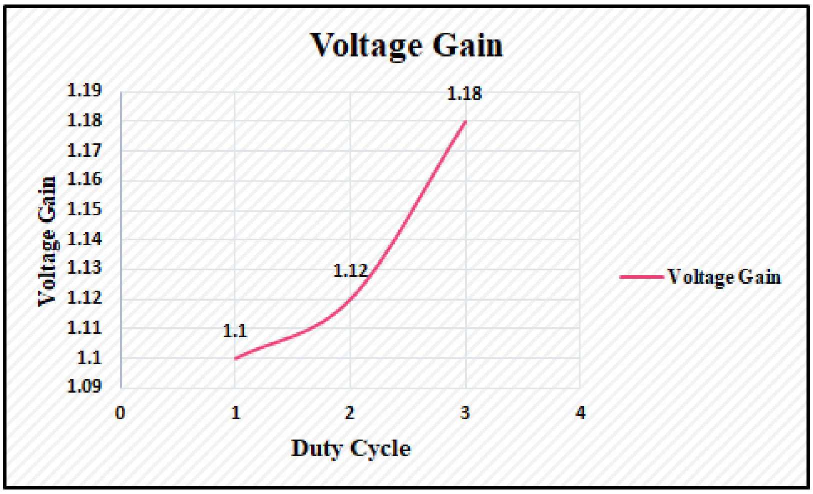

Figure 4.8 Voltage Gain comparison

Figure 4.8 represents the illustrates the relationship between voltage gain and duty cycle. As the duty cycle increases from 0 to 4, the voltage gain rises from approximately 1.1 to 1.18. This indicates a positive correlation, demonstrating how adjustments in duty cycle can enhance voltage gain in the system.

5. CONCLUSION

In conclusion, the proposed wind energy conversion system (WECS) utilizing doubly fed induction generators (DFIG) integrated with a dual DC wind turbine (DCWT) configuration offers an efficient and reliable solution for converting variable wind energy into stable DC voltage. The use of a pulse width modulation (PWM) rectifier and DC-DC SEPIC converter, combined with whale-optimized proportional-integral (PI) controllers, ensures effective voltage regulation and energy transfer. The three-phase voltage source inverter (VSI) with an LC filter and the precise PI control of active and reactive power flow contribute to enhanced power quality, grid stability, and energy utilization. This integrated system provides a promising approach to improving the performance and reliability of renewable energy systems, addressing key challenges in grid integration. The Matlab simulation

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2021a implementation confirms the viability and effectiveness of this approach, supporting its potential for sustainable energy solutions in the future.

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