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ANN-CONTROLLED PITCH REGULATION IN A NEW WIND ENERGY SYSTEM FOR EFFECTIVE GRID INTEGRATION

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Abstract: There are a number of difficulties in integrating wind energy into the electrical grid, especially with regard to power quality, efficiency, and stability. Due to varying wind speeds and ineffective pitch control, conventional wind energy systems frequently experience fluctuating power production, which leads to mechanical stress and energy losses. This study suggests a novel wind energy system with pitch adjustment managed by an artificial neural network (ANN) for effective grid integration in order to overcome these problems. By dynamically modifying the pitch angle in response to current wind conditions, the ANN-controlled pitch regulation increases the wind turbine's aerodynamic efficiency and reduces mechanical stress. To ensure smooth power integration, a proportional-integral (PI) controller additionally controls the voltage and current to satisfy grid standards. Traditional power conversion controls combined with ANN-based pitch regulation improve the system's overall efficiency. This novel approach ensures stable, efficient energy delivery to the grid, contributing to the broader goal of integrating renewable energy while minimizing disruptions to grid stability.

***Index Terms* – Artificial Neural Network (ANN); Proportional-Integral Controller (PI); Wind Energy System (WESs); Pulse Grid Integration**

I. INTRODUCTION

Wind energy is a reliable and sustainable source of power derived from the kinetic energy of moving air. Wind power plants operate by converting this kinetic energy into electricity using wind turbines, which consist of key components such as blades, rotors, and generators. As the wind blows, it causes the turbine blades to rotate, transferring energy to the rotor. The rotor, connected to a shaft, drives the generator to produce electricity. Wind turbines are categorized into two main types based on rotor orientation: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). These turbines are deployed on various scales, ranging from small residential applications to large wind farms. The efficiency of wind energy systems is influenced by factors such as wind speed, turbine design, and geographic location. As a clean energy source, wind power generates no greenhouse gas emissions during operation, making it a key component in the global transition to renewable energy and the fight against climate change. Wind turbines harness natural wind motion to generate electricity, serving as an essential element of the shift toward renewable energy [1].

Modern wind turbines, such as direct-drive turbines, eliminate the need for a gearbox, improving efficiency and reducing maintenance costs. Wind energy systems are further classified into onshore and offshore installations. Onshore wind farms are built on land, while offshore wind farms are located in bodies of water, benefiting from stronger and more consistent wind conditions. The performance of wind turbines depends on factors like wind speed, site location, and turbine size. Wind energy is abundant and sustainable, reducing dependence on fossil fuels and mitigating climate change. However, challenges such as high initial costs, material limitations, and potential environmental impacts remain. Despite these hurdles, advancements in smart turbine technology, energy storage, and enhanced turbine designs are improving the efficiency and reliability of wind power, strengthening its role in the global renewable energy transition.

Wind energy plays a crucial role in providing clean, sustainable electricity while reducing greenhouse gas emissions. Wind turbine installations range from small residential setups to large-scale commercial wind farms that contribute significantly to the power grid. These systems are strategically placed in regions with strong, consistent winds to maximize energy production.

Samandar Khan Afridi et al. (2024) conducted an analysis of existing studies on wind energy systems to assess their attributes, advantages, and limitations. The study evaluated the economic, environmental, and social factors associated with three types of wind turbines. A particular focus was placed on floating offshore turbines, which offer higher energy generation potential by utilizing larger turbines. These turbines, situated in deep waters, not only minimize environmental impacts on marine ecosystems compared to fixed installations but also expand the range of viable wind energy locations. However, traditional land-based turbines face challenges, being limited to locations that are often far from areas with high wind potential. These turbines also present significant visual and noise impacts, which may lead to community resistance. Furthermore, the accessibility of remote sites poses additional difficulties [2].

Narender Singh et al. (2024) proposed a method for calculating the major loads experienced by various components of a wind turbine. This method involves analyzing the physical stresses and strains on parts such as rotor blades, nacelle, and tower under various operational conditions. The approach ensures that wind power plants (WPPs) can maximize their participation in energy and reserve markets, increasing revenue while preserving the lifespan of turbine components [3].

Muhammad Waleed Raza et al [2024] developed to assess Performance of these control strategies in three-phase symmetrical faults at the point of connection (PCC) of an offshore wind farm. A study on two wind turbines connected to an off-station main switchgear equipped with GFM control confirmed the findings. Reduced sensitivity to system changes and faults. Adjustable frequency response to increase system flexibility. Independence from Phase-Locked Loops (PLLs), simplifying implementation and improving reliability [4].

Manuel Lara et al [2023] developed is an Adaptive Active Generator Torque Control (AGTC) scheme to address the issue of fatigue load reduction in monopile offshore wind turbines. This problem arises from misalignment between wind and wave directions, resulting in lateral loads that compromise the tower's structural lifespan. Both AGTC variants effectively reduce lateral tower fatigue, extending the operational lifespan of the wind turbine. The use of genetic algorithms ensures optimal tuning of control parameters, balancing multiple objectives like fatigue load reduction and power stabilization [5].

F. A. Bourhim et al [2023] developed a model to optimize Wind turbine (WT) design for bus nodes in radial distribution network (RDN). The objective function is to maximize the net present value (NPV) of wind energy revenue. Optimize the present value of wind energy revenue to achieve maximum economic return. Model validated on multiple RDN configurations (IEEE 9 and IEEE 33), demonstrating versatility [6].

D. Bustan et al [2022] developed adaptive IT2FC operates in parallel with the existing baseline controller, enhancing its performance. The baseline controller remains the core controller, while the fuzzy controller serves as an augmentation, providing more precise and adaptive control for improved system performance. The adaptive IT2FC augments the baseline controller, ensuring improved performance without the need for complete replacement of the existing control system. The proposed controller does not rely on wind speed estimation, which reduces the computational burden and eliminates the need for additional sensors or complex algorithms to estimate wind speed [7].

By addressing load impacts, the method helps reduce excessive physical stress on turbine parts, potentially extending their operational lifespan. However, implementing load-aware optimization requires considerable computational resources, advanced algorithms, and expertise, which could pose challenges for smaller operators. Additionally, uncertainties in wind speed, turbine performance, and market conditions complicate accurate load predictions, affecting the reliability of the optimization method.

Objective:

- To implement Innovative Wind Energy System Featuring Ann-Controlled Pitch Regulation for Efficient Grid Integration.
- To develop an innovative wind energy system that uses ANN-controlled pitch regulation for efficient and stable grid integration.
- To optimize power quality and stability through advanced control mechanisms, including PWM rectifiers, VSI, LC filters, and PI controllers.
- To enhance aerodynamic efficiency and energy capture by dynamically adjusting the pitch angle based on real-time wind conditions.

II. CONVENTIONAL WIND TURBINE SYSTEM

Modern urbanization and reducing reliance on fossil fuels. However, designing controllers for wind power generation systems presents significant challenges due to system nonlinearity, variability, external disturbances, and operational constraints. This study tackles these challenges by introducing a Lyapunov-based Model Predictive Control (MPC) framework specifically designed for nonlinear wind power systems.

The research begins by modelling a doubly-fed wind power generation system, which consists of three key components: the wind turbine, the transformation device, and the generator. These physical models serve as the foundation for the proposed control strategy. Given the inherent complexities and external disturbances affecting wind power systems, the study integrates Lyapunov stability theory into the MPC design, ensuring system stability under varying operational conditions.

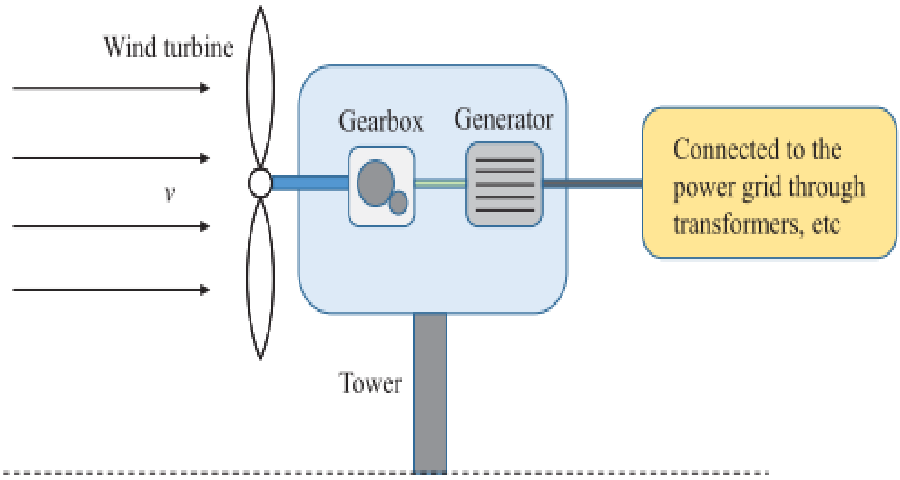


Figure 1. Block Diagram of Existing System

This system represents the flow of materials and energy in a wind turbine shown in figure 1. Wind energy turns the gears connected to the gearbox, which regulates the speed of rotation and transmits it to the generator. The generator then converts mechanical energy into electrical energy for use in the power grid.

(i) Wind Turbine

Wind turbines operate by harnessing wind energy through rotating blades. When the wind blows, it causes the turbine blades to spin, capturing the kinetic energy of the wind. These blades are connected to a gearbox that optimizes the rotational speed to match the generator's requirements. The generator then converts the mechanical energy from the blades into electrical energy. This electricity is transmitted to the power grid through transformers and other necessary equipment, allowing the energy to be distributed for various applications. The entire system is mounted on a tower that provides the necessary height and support to maximize wind capture [8].

(ii) Gearbox

The gearbox plays a crucial role in linking the rotating blades to the generator. As the wind causes the blades to spin, they generate mechanical energy at variable speeds. The gearbox adjusts this rotational speed to a consistent and optimal level suitable for the generator's operation. By stabilizing the speed, the gearbox ensures that the generator receives a steady and efficient flow of mechanical energy, maximizing the turbine's performance and ensuring consistent power generation.

(iii) Generator

The generator is a key component of a wind turbine, responsible for converting mechanical energy into electrical energy. The gearbox optimizes and transfers the rotational speed to the generator. Inside the generator, electromagnetic induction occurs, where mechanical energy moves through a magnetic field, inducing an electric current. This generated electrical energy is then transmitted through transformers and other necessary equipment to the power grid, where it is distributed for various uses.

(iv) Power Grid Connection

The connection to the power grid is a critical step in the wind turbine system, ensuring efficient distribution of the generated electricity. Once the generator converts mechanical energy into electrical energy, it must be transmitted to the power grid for use. This process involves several key components, including transformers that adjust the voltage to levels compatible with the grid.

III. GRID CONNECTED WIND ENERGY SYSTEM

Figure 2. Shows the block diagram of the proposed work. Integrating wind energy into modern power grids requires advanced control systems to ensure stability, reliability, and efficiency. Traditional pitch regulation methods in wind turbines often struggle to adapt to dynamic wind conditions, resulting in suboptimal power output and grid instability.

To address these challenges, this study introduces an innovative wind energy framework utilizing Artificial Neural Network (ANN)-controlled pitch regulation. Leveraging the predictive and adaptive capabilities of ANNs, this system optimizes the blade pitch angle in real time, enhancing energy capture under fluctuating wind conditions. Unlike conventional proportional-integral-derivative (PID) controllers, the ANN approach dynamically adjusts to complex, non-linear environmental inputs, delivering superior performance across diverse operating scenarios. This not only maximizes energy extraction but also reduces mechanical stress on turbine components, extending their operational lifespan [9].

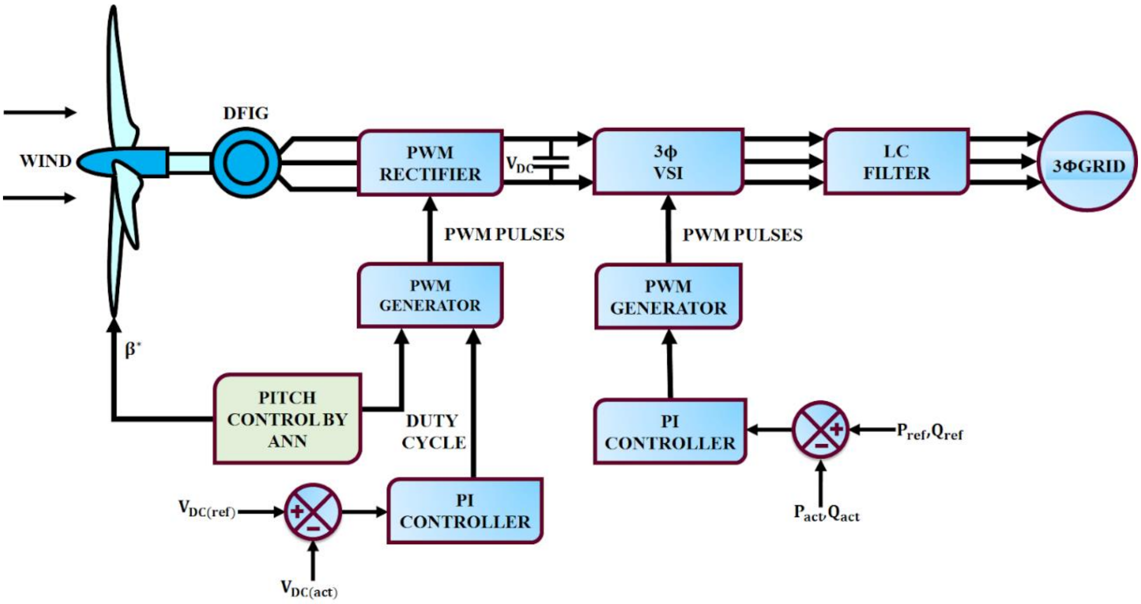


Figure 2. Block Diagram of the Proposed System

In the proposed advanced wind energy system, which incorporates ANN-controlled pitch regulation, the Pulse Width Modulation (PWM) rectifier plays a crucial role in converting the variable AC output from the wind turbine generator into a stable DC voltage. This conversion ensures efficient energy management and seamless integration with the grid. By stabilizing the DC output, the PWM rectifier enhances the overall performance of the system, supporting optimal power conversion and grid compatibility.

A. DFIG Based WECS:

Wind energy converters (WECS) based on doubly-fed induction generators (DFIG) are an important part of new wind energy generation with ANN-controlled noise control. Doubly-fed wind turbine technology is widely used in modern wind turbines due to its excellent efficiency, variable speed operation and good line-connection capacity. In DFIG-based WECS, the wind turbine drives the rotor of an induction generator that is connected to the grid in two ways. The stator is directly connected to the grid, while the rotor is connected back-to-back via a transformer. This converter system consists of a rotor-side converter (RSC) and a grid-side converter (GSC) that provide bidirectional energy flow.

B. Pitch Control by ANN Controller

In the innovative wind energy system, the pitch control mechanism plays a pivotal role in regulating the angle of the turbine blades to optimize energy capture and ensure grid-friendly power generation shown in figure 3. Traditional pitch control systems rely on PID controllers, which are limited in handling the non-linear and dynamic nature of wind conditions. To overcome these limitations, the system employs an Artificial Neural Network (ANN) controller for pitch regulation.

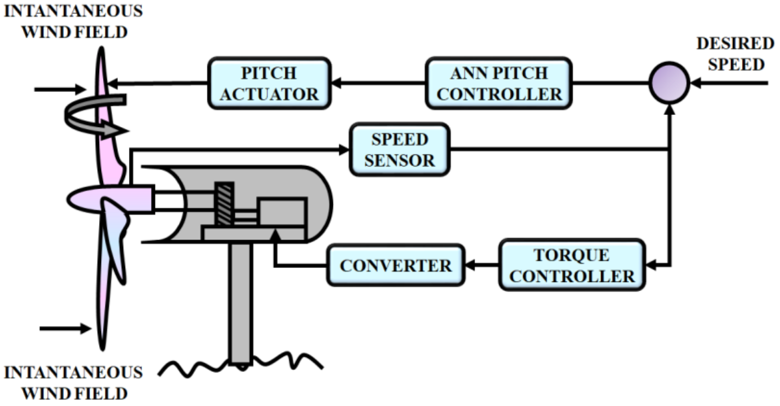


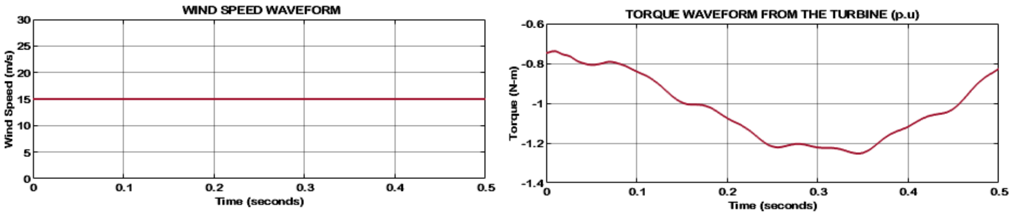
Figure 3. Standard control loops of wind turbine

C. PI Controller

Wind energy system with ANN-controlled pitch regulation for efficient grid integration, the Proportional-Integral (PI) controller is essential for maintaining system stability and optimizing performance. The PI controller is responsible for ensuring that the turbine's output remains consistent and meets the required grid parameters, even under fluctuating wind conditions. The working process begins with the turbine capturing wind energy and converting it into mechanical power. This mechanical power is then transformed into electrical power by the generator and fed through an inverter for grid integration.

IV. RESULTS AND DISCUSSIONS

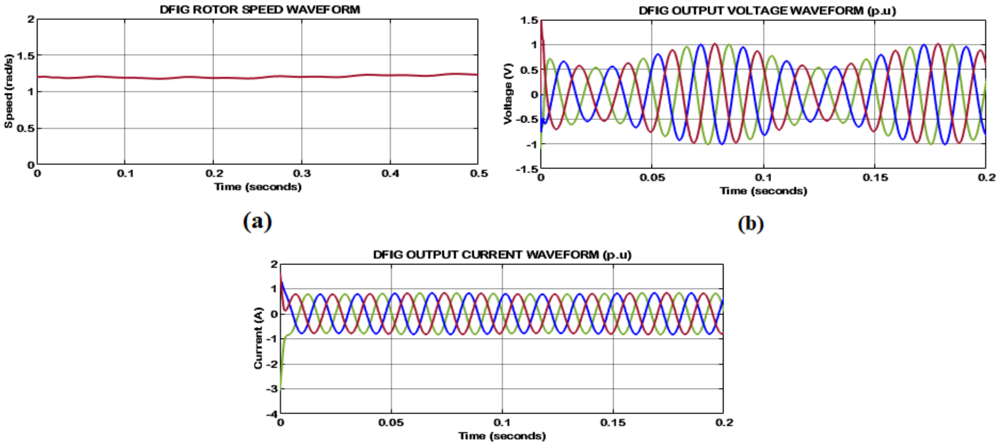
The proposed work is implemented in MATLAB simulation and the following results are obtained.



(a) (b)

Figure 4. Waveforms representing (a) Wind speed and (b) Wind turbine torque

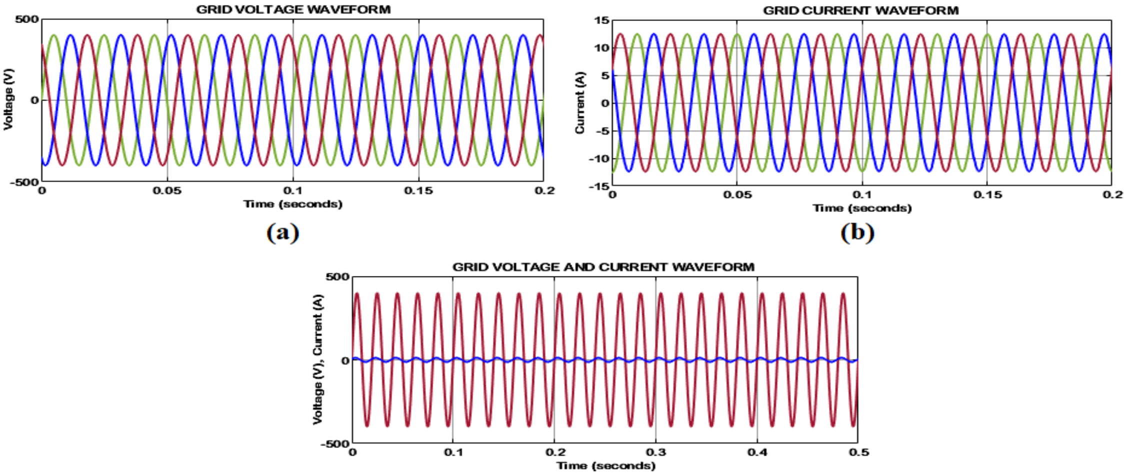
In figure 4, The waveforms of (a) wind speed and (b) wind turbine torque are shown. The first graph presents a steady wind speed of 25 m/s, while the second graph displays fluctuating torque values in per unit (piu.) over time, reflecting variations in turbine performance.



(c)

Figure 5. DFIG waveforms representing (a) rotor speed (b) output voltage and (c) output current

Figure 5. represent as the performance of a Doubly-Fed Induction Generator (DFIG). Graph (a) shows a steady rotor speed, while graph (b) illustrates the fluctuating output voltage in per unit (p.u.) over time. Graph (c) represents the corresponding output current waveform, highlighting the DFIG's dynamic response to operational conditions.



(c)

Figure 6. Waveforms representing (a) Grid voltage (b) Grid current and (c) single phase of grid parameters

Figure 5.6 represent as the figure presents three waveforms: (a) grid voltage, (b) grid current, and (c) combined grid voltage and current. Each waveform oscillates over 0.5 seconds, indicating their sinusoidal nature. The voltage and current waveforms are crucial for analyzing power quality and system performance in electrical grid applications.

V. CONCLUSION

In summary, the proposed innovative wind energy system, incorporating ANN-controlled pitch regulation, effectively tackles key challenges in wind power integration, including stability, efficiency, and power quality. By utilizing ANN-based pitch control, the system dynamically optimizes the turbine's aerodynamic performance, maximizing energy capture even in fluctuating wind conditions. Furthermore, advanced power conversion technologies—such as PWM rectifiers, a DFIG, a VSI, and an LC filter—ensure stable, high-quality power output that meets grid standards. The addition of a PI controller enhances voltage and current regulation, facilitating seamless grid integration. This approach reduces mechanical stress, minimizes energy losses, and supports the broader transition to renewable energy with minimal disruption to grid operations. Ultimately, this system marks a significant advancement in the efficient and reliable harnessing of wind energy for sustainable power generation.

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