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MITIGATION OF POWER QUALITY ISSUES IN WECS USING ADVANCED CONTROLLERS AND STATCOM: A COMPARATIVE STUDY

Archana K^{*1}, Pushparajesh V²

¹Research scholar, Department of Electrical and Electronics Engineering, Jain Deemed University, Bengaluru, India

¹Assistant Professor, Department of Electrical and Electronics Engineering, Cambridge Institute of Technology, Bengaluru, India.

²Professor Department of Electrical and Electronics Engineering, Jain Deemed University, India,

¹<https://orcid.org/0000-0002-0880-1764>, ²<https://orcid.org/0009-0009-6249-4986>

E-mail: *karchanamandya@gmail.com, v.pushparajesh@jainuniversity.ac.in

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ABSTRACT

In recent years, wind power generation has attained significant attention, leading to the installation of numerous wind power plants worldwide. Most wind turbines employ induction generators, which typically absorb substantial reactive power (VARs) from the grid. This reactive power demand can result in voltage drops and may create voltage stability issues for utility operators, particularly during large load variations on distribution feeders. Voltage source converter (VSC) based Flexible AC Transmission System (FACTS) devices are widely utilized for flexible power flow control, secure system loading, and damping of power system oscillations. These devices are also applied to enhance the transient and dynamic stability of wind power generation systems (WPGS). Comparative Analysis is being done with different controllers like PI, PID, Fuzzy, ANN and ANFIS. It was found that implementing an adaptive neuro-fuzzy inference system (ANFIS) controller along with STATCOM and improved kookaburra optimization algorithm (IKOA) will enhance system performance during fault conditions such as voltage sag and swell. The proposed algorithm converges quickly compared to the other optimization algorithms like OOA (Orangutan Optimization Algorithm), SFOA (Star Fish Optimization Algorithm), PSO (Particle Swarm Optimization) techniques. This confirms that ANFIS controller with STATCOM along with proposed IKOA algorithm for WECS gives best result in every aspect, including efficiency, accuracy and reliability for power quality improvement.



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I. INTRODUCTION

Wind plants do not emit air pollutants or greenhouse gases. They are generated and caused by non-uniform warming of the atmosphere and terrestrial irregularities. Compared to other non-conventional energy resources, wind energy requires less conversion equipment, occupies less land, and demands minimal maintenance. Power quality is defined by the consistency, reliability, and stability of electrical power. Maintaining high power quality is crucial, as any deviations can lead to equipment damage, malfunctions, system shutdowns, or data loss. Poor power quality also reduces operational efficiency and increases maintenance costs. Power electronic technology plays an essential contribution in distributed generation and in interfacing renewable energy systems with the electrical grid [1]. Its widespread use continues to expand as more grid-connected renewable systems are developed. In the wind energy sector, India's aggregate wind energy capacity reached 47.96 GW by November 2024 [2]. Wind turbines can be constructed on farms and ranches, allowing landowners to lease land for additional income while still using it for other purposes. This paper is structured as follows: Section I introduces the advantages of wind energy conversion systems (WECS) and the challenges related to their grid integration. A Static Synchronous Compensator (STATCOM) belongs to the family of Flexible AC Transmission Systems (FACTS) devices [3-12]. It provides precise control of power flow, fast dynamic response, and effective voltage regulation. STATCOMs can operate close to their thermal limits and offer rapid power swing suppression, improving overall system stability.

Specialized power technologies offer a comprehensive solution to power distribution systems for the benefit of customers is termed as custom power. These systems enhance power quality by mitigating voltage sags, flickers, and harmonic distortions. Thus, challenges of voltage regulation, harmonics, and reliability faced by utilities and power distributors. A STATCOM [13] is a shunt-connected device in which conventional switched capacitors and reactors are substituted by a Voltage Source Converter (VSC). Compared to traditional reactive power compensators, STATCOM offers faster response, compact design, and modularity. It can also be integrated with real power sources such as batteries, fuel cells, or Superconducting Magnetic Energy Storage (SMES) [14-17] During low-voltage conditions, it maintains constant reactive current and can deliver higher reactive power if rated for transient overload.

II. THEORETICAL REFERENCE

II.1 METHODOLOGY

The proposed system aims to enhance the quality of electrical energy produced by a Wind Energy Conversion System (WECS). The WECS is derived from a variable-speed wind turbine coupled with a Permanent Magnet Synchronous Generator (PMSG). The generator output is converted to DC using a rectifier, and a Voltage Source Inverter (VSI) interfaces the system with the electrical grid. A STATCOM is integrated at the point of common coupling (PCC) to regulate voltage, compensate reactive power, and mitigate harmonics. The control strategy employs an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller to generate suitable reference signals for the STATCOM. To improve the controller's precision, the Improved Kookaburra Optimization Algorithm (IKOA) is applied to fine-tune the ANFIS parameters by minimizing error and enhancing dynamic response [18], [19]. The complete system is modeled and simulated in MATLAB/Simulink. Its performance is evaluated under varying wind conditions and load disturbances.

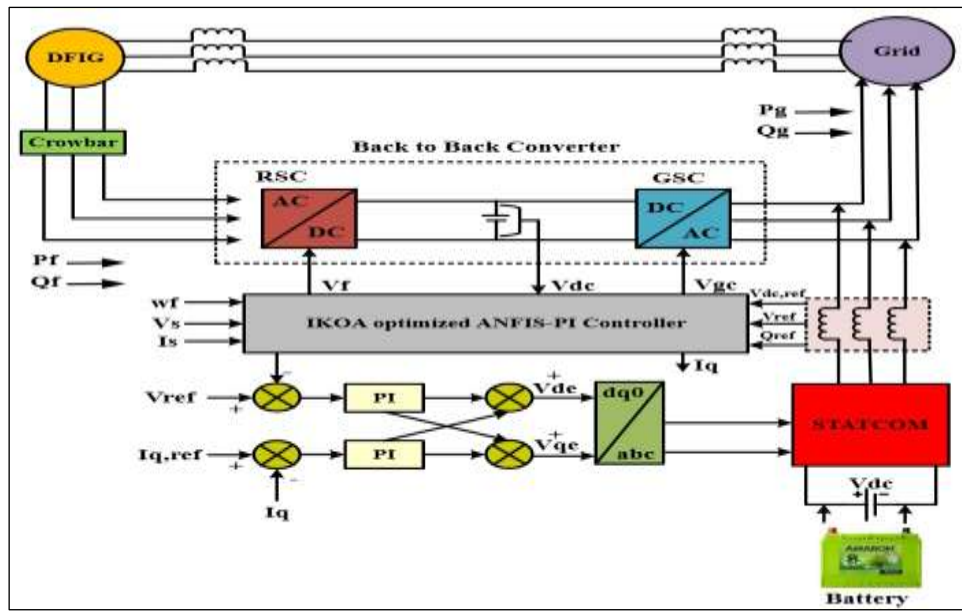


Figure 1: Block diagram for WECS with DFIG.
Source: Authors, (2026).

II.2 DOUBLY-FED INDUCTION GENERATOR (DFIG)

In recent years DFIG has become widely used in the world wide wind turbine industry. It offers an efficient alternative to traditional variable-speed generator systems due to its ability to operate over a range of wind speeds while maintaining grid compatibility. The following equations can be used to express the stator side when it is rotated at an angular velocity of ω and given in an arbitrary frame of reference: The power captured by the turbine can be described using the following equation.

$$Q_s = \frac{1}{2} \rho A_r W_s^3 c_p(\beta, \lambda) \quad (1)$$

In the given equation, the variables are defined as follows: air density (in kg/m³) is denoted by ρ , rotor's swept area (in m²) is represented by A_r , W_s is the wind speed (in m/s), power coefficient is indicated by c_p , which depends on the pitch angle (β) and the tip speed ratio (λ)

$$V_{sbc} = R_s i_{sbc} + j\omega \phi_{sbc} + \frac{1}{\omega_b} \frac{d\phi_{sbc}}{dt} \quad (2)$$

$$V_{rbc} = R_r i_{rbc} + j(\omega - \omega_r) \phi_{rbc} + \frac{1}{\omega_b} \frac{d\phi_{rbc}}{dt} \quad (3)$$

$$\varphi_{sbc} = L_s i_{sbc} + L_m i_{rbc} \quad (4)$$

$$\varphi_{rbc} = L_r i_{rbc} + L_m i_{sbc} \quad (5)$$

In this case, i , V , and Φ stand for current, voltage, and flux. The subscripts s and r , respectively, represent the stator and rotor values. The stator and rotor inductances are denoted by L_s and L_r , the mutual inductance by L_m , the rotor speed by ω , and the rotor sliding frequency by ω . ω_r represents the speed of the reference frame bc , and R_s and R_r represent the stator and rotor resistances, respectively. The DFIG's dynamic characteristics can be modeled in multiple frames of reference, namely the stationary, rotor, and synchronous frames.

$$V_{rbc} = R_r' i_{rbc} + \frac{L_r'}{\omega_b} \frac{di_{rbc}}{dt} + \frac{1}{\omega_b} \frac{L_m}{L_s} \frac{d\varphi_{sbc}}{dt} + j\omega_2 \frac{L_m}{L_s} \varphi_{sbc} \quad (6)$$

$$V_{rbc} = R_r' i_{rbc} + \frac{L_r'}{\omega_b} \frac{di_{rbc}}{dt} + j\omega_2 L_r' i_{rbc} + E_{bc} \quad (7)$$

R_r' and L_r' represent the transient resistance and transient inductance associated with the rotor current dynamics, respectively in Equations (8) and (9).

$$R_r' = R_r + \left(\frac{L_m}{L_s} \right)^2 R_s \quad (8)$$

$$L_r' = L_r - \frac{L_m^2}{L_s} \quad (9)$$

Furthermore, E_{bc} in Equation (10) denotes the induced back EMF voltage of the rotor windings, capturing how stator dynamic s affect the behavior of the rotor current. This term is critical in understanding phenomena such as rotor inrush current, DC link overvoltage, and torque spikes during voltage dips. The value of E_{bc} depends on both the stator flux and stator voltage, and can be mathematically expressed as:

$$E_{bc} = \frac{L_m}{L_s} (V_{sbc} - j\omega_r \varphi_{sbc} - \frac{R_s}{L_s} \varphi_{sbc}) \quad (10)$$

The following mathematical formulas are used to compute the stator's active and reactive power components.

$$P_s = R_e \{V_{sbc} i_{sbc}^*\} = \{V_{sb} i_{sb} + V_{sc} i_{sc}\} \quad (11)$$

$$Q_s = R_e \{V_{sbc} i_{sbc}^*\} = \{V_{sc} i_{sb} - V_{sb} i_{sc}\} \quad (12)$$

In steady state real and reactive powers of the stator are given by:

$$P_s = R_s |I_s|^2 - \frac{L_m}{L_s} (V_{sb} i_{rb} + V_{sc} i_{rc}) \quad (13)$$

$$Q_s = \frac{L_m}{L_s} (V_{sb} i_{rc} - V_{sc} i_{rb}) \quad (14)$$

As shown in Equations (13) and (14), Both the b-axis and c-axis components of the rotor current have an impact on the stator's active and reactive power.

II.2.1. Anfis And Koa Algorithm

ANFIS (Adaptive Neuro-Fuzzy Inference System) is an intelligent controller formed by combining the learning capabilities of **Artificial Neural Networks (ANNs)** with the reasoning approach of **Fuzzy Logic Systems (FLS)**. This hybridization enables ANFIS to learn from data, adapt to system changes, and handle nonlinearities efficiently. The neural network component provides **adaptive learning and parameter tuning**, while the fuzzy logic component introduces **human-like reasoning** through linguistic rules and membership functions. [19-25]. The Kookaburra is a, carnivorous bird and belongs to the Coraciiformes and Alcedininae families. A dark brown patch sits just behind each eye, and together with the unique shape of their feathers, it gives the bird an appearance of looking angry. Kookaburras measure between 28 and 47 cm in length and weigh about 300 g. Among the Kookaburra's natural behaviors in the wild, its hunting approach is especially noteworthy. The bird knocks its prey against a tree to deliver a fatal blow to the prey. These intelligent hunting behaviors are implemented in the design of the proposed KOA approach [26]. Fitness graph with different algorithms like PSO (Particle Swarm Optimization), COA (Coati Optimization Algorithm), POA (Pelican Optimization Algorithm) is compared with the proposed algorithm (Kookaburra optimisation Algorithm) KOA and found that KOA converges quickly. The comparison graph is indicated in the figure.2. Table 1 shows THD Analysis With Different Loads With And Without Statcom.

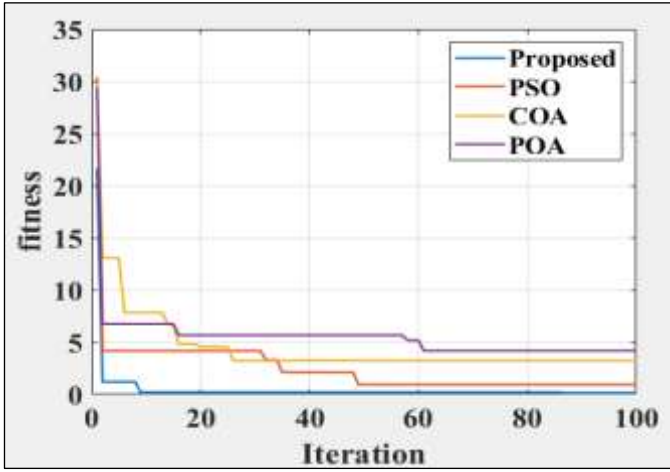


Figure 2: Comparison graphs of different controllers.
Source: Authors, (2026).

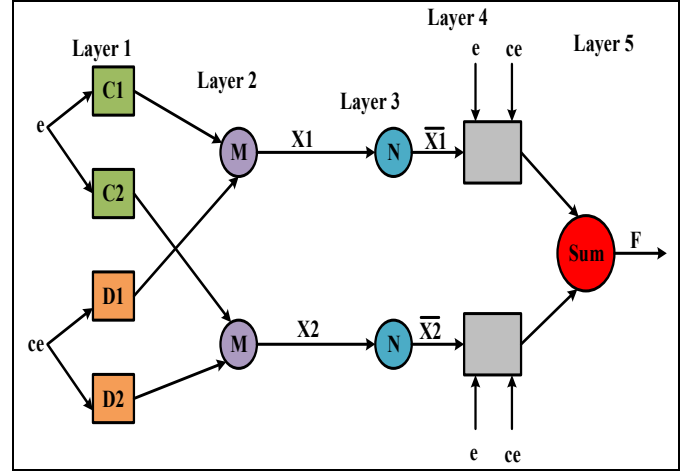


Figure 3: ANFIS controller for wind power generation system.
Source: Authors, (2026).

Figure 3 illustrates the ANFIS structure of the proposed system to enhance the performance. ANFIS works in multiple layers, where each layer has a specific role in handling the inputs and generating the final outputs. The initial layer, commonly called the fuzzification layer, converts exact input values into fuzzy values using membership functions that have been predetermined. In this layer, each node calculates the membership grade corresponding to a particular linguistic term. For instance, if the inputs to node m (where $m = 1, 2, 3, \dots$) are denoted as e and Δe , the node measures the degree to which these inputs belong to the associated fuzzy sets. This process effectively maps the inputs into a fuzzy domain, setting the foundation for subsequent inference operations [27]. All nodes in layer 1 are adaptive, meaning the shape of the membership functions can change during training. The ANFIS mathematical model is expressed as follows:

III. COMPARATIVE ANALYSIS

The output of OOA (Orangutan Optimization Algorithm) and SFOA (Star Fish Optimization Algorithm) techniques has been validated on the basis of (voltage, current, speed, power) using simulations carried out in MATLAB/Simulink. These simulation results are used for comparative analysis with the recommended method and the output diagrams presented in figure 4 and 5. The result of the OOA and SFOA algorithms in a wind power system for the dynamic response over 1 second. All voltage and current waveforms exhibit initial transients but stabilize quickly into sinusoidal patterns. Active and reactive power show early fluctuations, then settle steadily around 10 pu respectively. The rotor speed shows a smooth variation, indicating controlled acceleration. Bus and load current profiles stabilize after initial disturbances, confirming effective system response. The analysis of the convergence of the suggested and competitive algorithm of the wind power system over 100 iterations is given in Figure 6. The Proposed algorithm outperforms others by achieving the lowest fitness value more rapidly and consistently, reaching convergence within approximately 10 iterations. In comparison, Coati Optimization Algorithm (COA) [28], Hiking Optimization Algorithm (HOA) [29], Orangutan Optimization Algorithm (OOA) [30], Star Fish Optimization Algorithm (SFOA) [31] and Puma Optimization Algorithm (POA) [32] exhibit slower convergence and settle at higher fitness values, indicating inferior optimization performance. This demonstrates the superior efficiency and accuracy of the proposed algorithm [33].

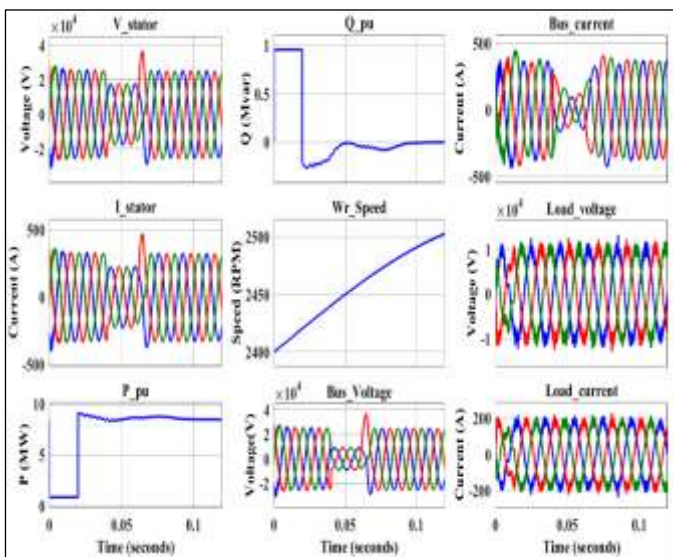


Figure 4: Output waveforms with OOA algorithm.
Source: Authors, (2026).

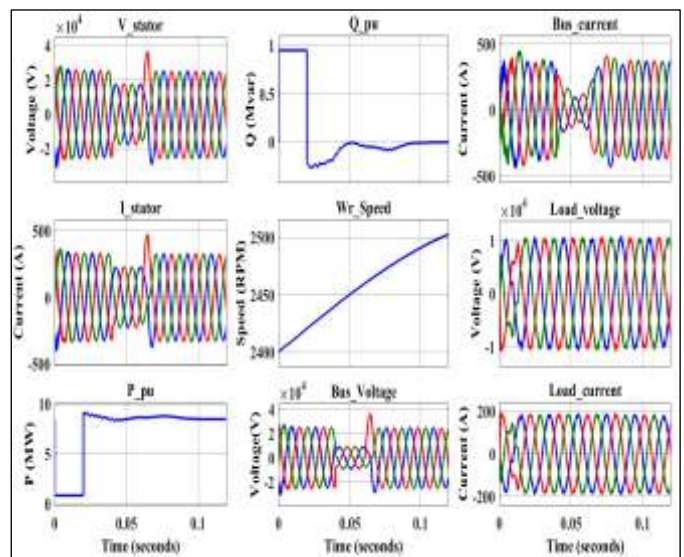


Figure 5: Output waveforms with SFOA algorithm.
Source: Authors, (2026).

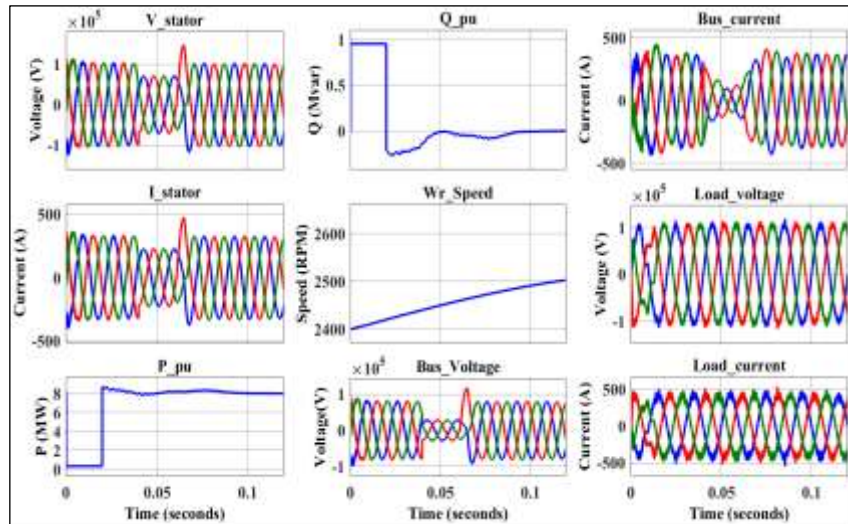


Figure 6: Output waveforms with PSO algorithm.

Source: Authors, (2026).

Comparison of THD values for different control strategies, PID, Fuzzy, PI, ANN, and the suggested model is illustrated in Figure 7. Among them, the suggested controller achieves the lowest THD value (1.39%), indicating superior power quality performance. Table 1 shows the voltage THD values of the wind power system in different cases and Table 4 represents the comparative analysis of the proposed work with the recent related works in the basis on THD values.

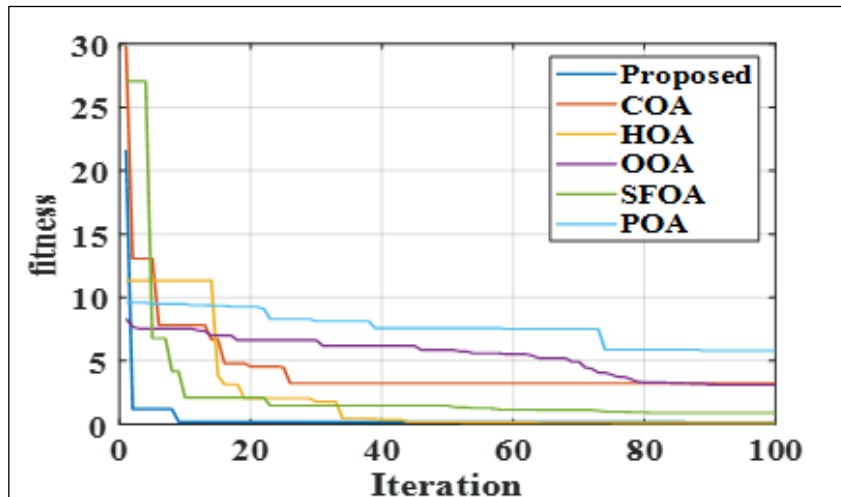


Figure 7: Analysis of convergence.

Source: Authors, (2026).

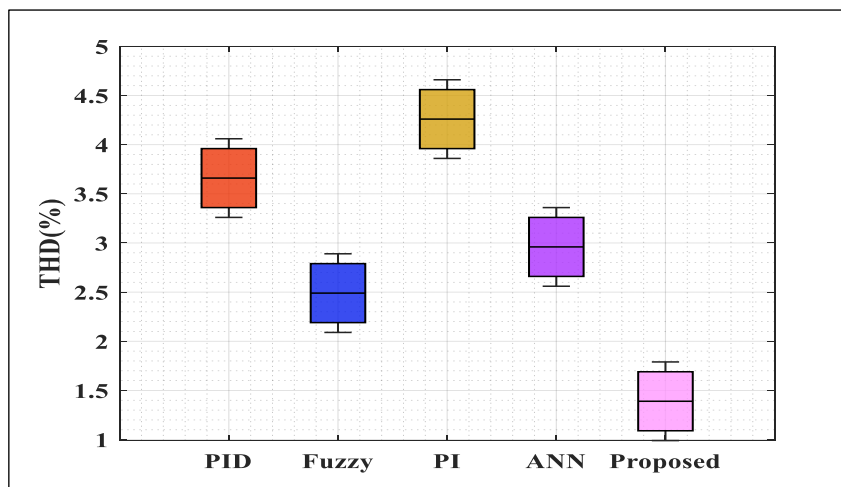


Figure 8: Comparison of THD values with different controllers.

Source: Authors, (2026).

Table 1: THD values of the wind power system under different cases.

Output cases	THD value (%)
Linear load outputs with STATCOM	1.39
Nonlinear load outputs with STATCOM	21.46
STATCOM with an induction motor	7.82
Without STATCOM linear load	19.19
Without STATCOM, non-linear load	27.21

Source: Authors, (2026).

III. MATERIALS AND METHODS

This paper analyzes the capability of a grid-tied wind energy conversion system (WECS) under various load conditions, both with and without a STATCOM, to evaluate improvements in power quality. The results show a substantial reduction in total harmonic distortion (THD) when a STATCOM integrated with an ANFIS controller optimized using the IKOA algorithm is employed. The complete system was modeled in MATLAB, as illustrated in Figure 9.

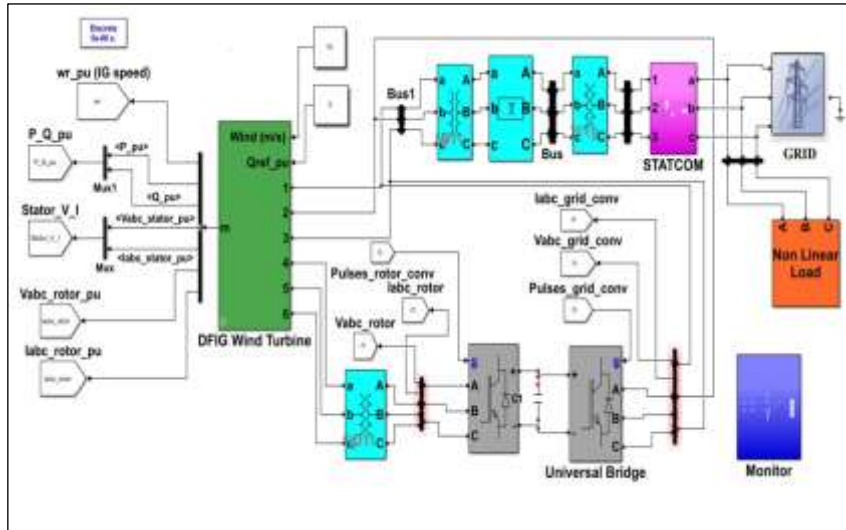


Figure 9: Simulink model without STATCOM with RLC load.

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

In this section, the time-domain simulation results of the proposed system, generated using MATLAB/Simulink across different operating conditions, are presented in Fig. 8. The simulation parameters of the system are listed below: DFIG Parameters: Stator Phase Resistance = 2.875Ω , Inertia = $0.8e-3\text{Kg-m}^2$, $L_d = L_q = 8.5\text{mH}$, Torque constant 12N m/A peak, Pole pairs = 8, $P_{out}=100\text{kW}$, $V_{rated}=12\text{m/sec}$; Grid Parameters: 480V , 60Hz , X/R ratio=7; DC link capacitor: $5000\mu\text{F}$; DC link voltage= 1100V ; Some cases are examined for the simulation study with different types of loads. Case 1: Simulink model without STATCOM with RLC load Figure 9 shows the output of Simulink model of WECS connected to grid with RLC load without STATCOM. As per IEEE Std. 1547 2003, THD must be below 5%. It can be observed from Fig.12 that the harmonic distortion level is around 20%, which is not within the standards without STATCOM. Owing to an abrupt increase in wind speed, the turbine torque reduces. As a result, the real power output from the wind generation system and inverter output current reduces so STATCOM must be added for the purpose to meet the real and reactive power demand.

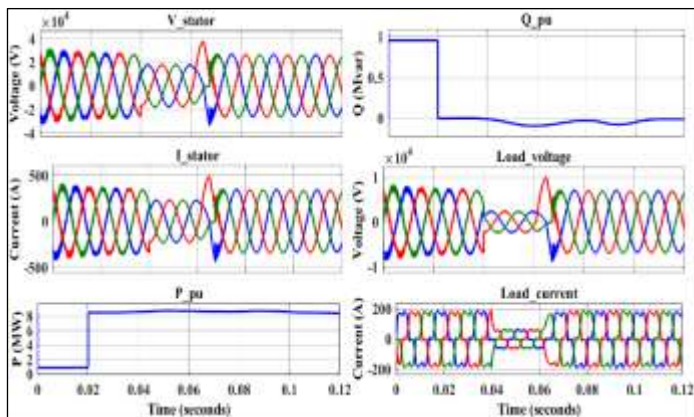


Figure 10: Simulink model without STATCOM with RLC load.

Source: Authors, (2026).

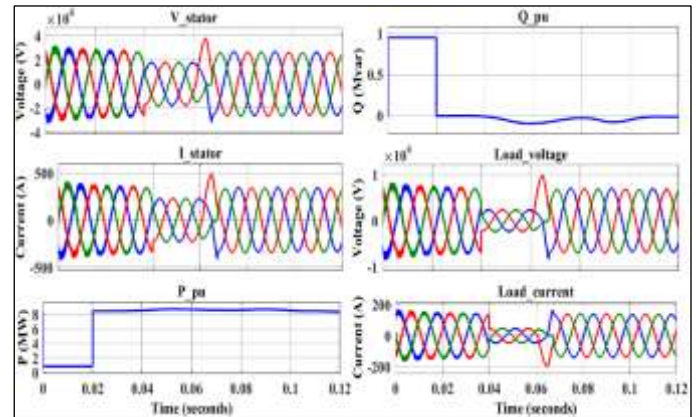


Figure 11: Simulink model without STATCOM with Linear load.

Source: Authors, (2026).

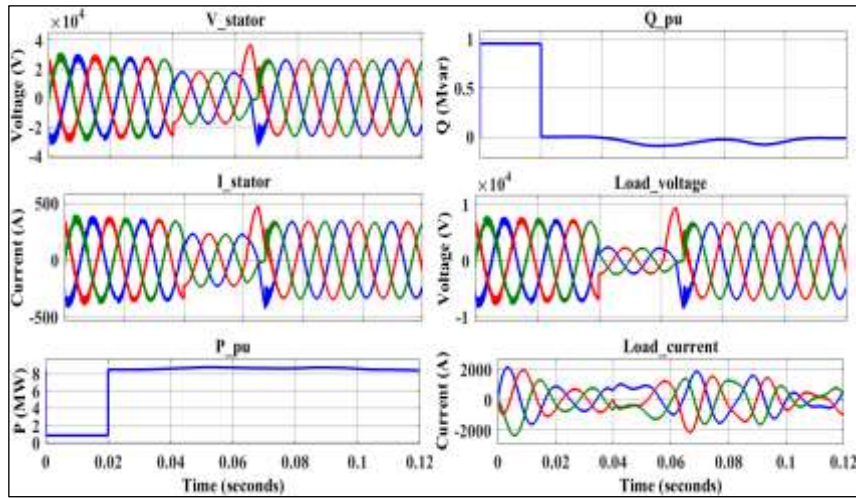


Figure 12: Simulink model without STATCOM with Induction motor load.
Source: Authors, (2026).

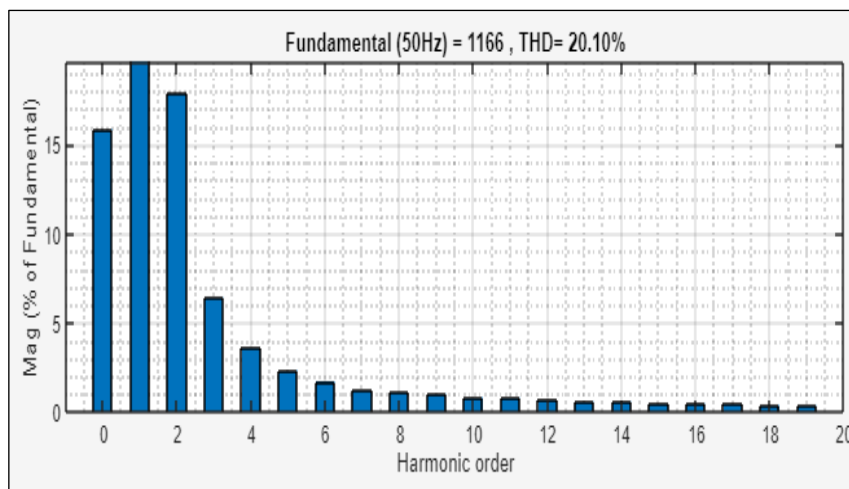


Figure 13: THD analysis of current without STATCOM.
Source: Authors, (2026).

Case 2: Simulink model with STATCOM with RLC load Figure 8 shows the Simulink model of WECS with STATCOM connected to grid with RLC load. Figure 13 presents the time-domain simulation results, including stator voltage, inverter output voltage, active and reactive power, wind speed, bus voltage, and the percentage THD variation of the output current. It is noticeable from Fig.9 that the proposed model has the harmonic distortion level is around 2 %, which is well within the standards.

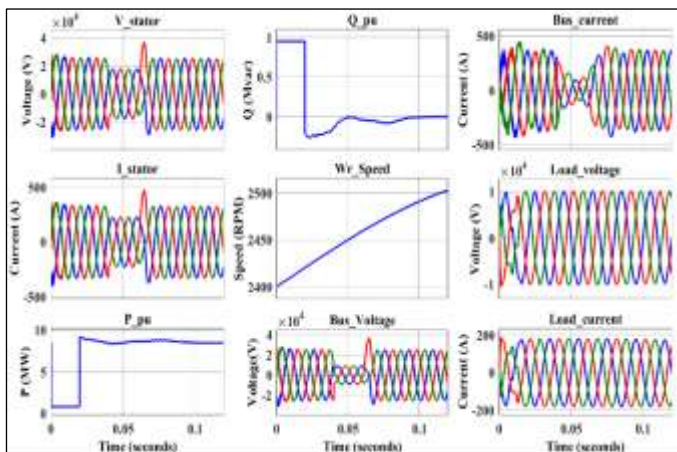


Figure 14: Simulink model without STATCOM with RLC load.
Source: Authors, (2026).

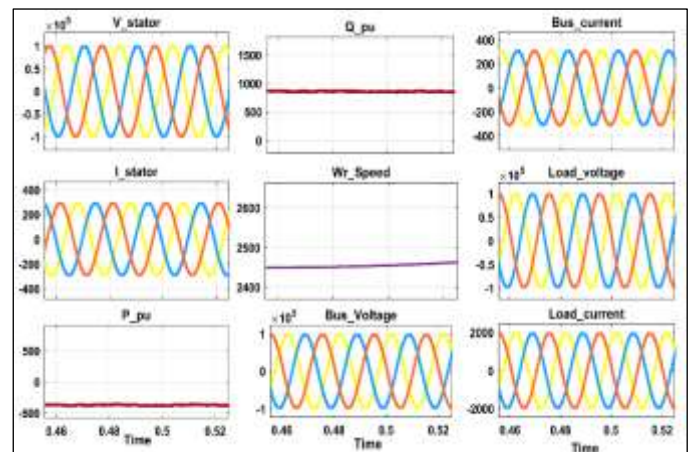


Figure 15: Linear load outputs with STATCOM.
Source: Authors, (2026).

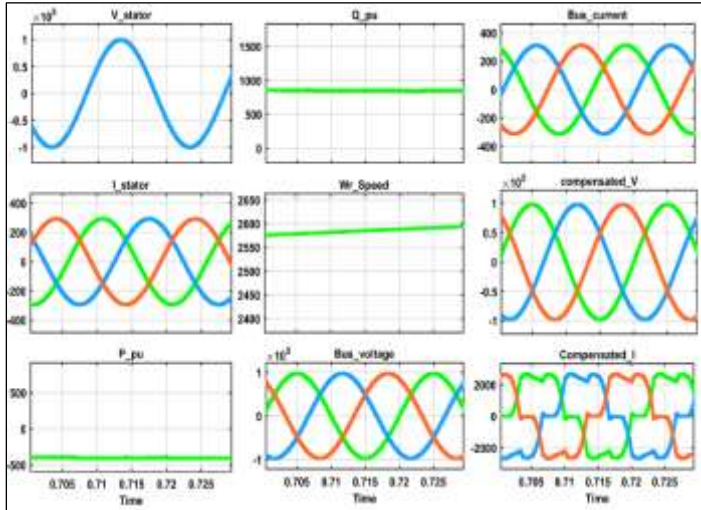


Figure 16: Nonlinear load with STATCOM.
Source: Authors, (2026).

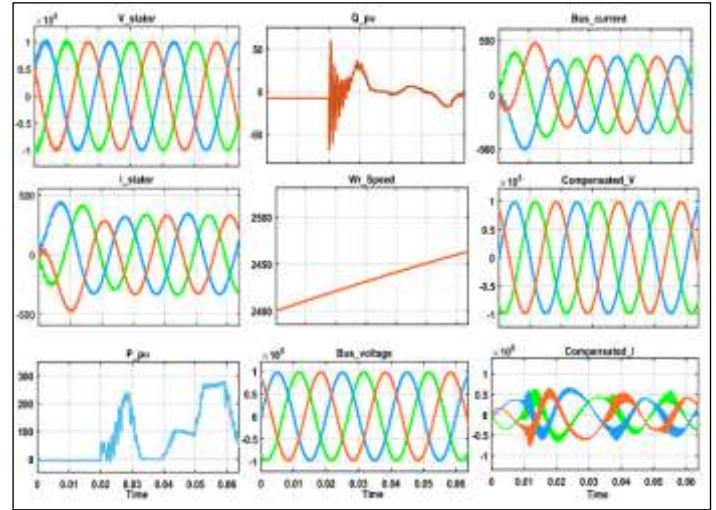


Figure 17: STATCOM with induction motor.
Source: Authors, (2026).

V. CONCLUSIONS

This paper introduces an efficient and novel control strategy to increase stability in a wind energy system. A DFIG-based wind energy conversion system is employed as the primary input source. To regulate voltage and smooth power fluctuations, BESS is integrated in parallel with the DC-link capacitor of a STATCOM. To further enhance power quality and system stability under various fault conditions, such as voltage sags, swells, unbalanced voltages, and currents, an ANFIS controller optimized using the IKOA is implemented within the STATCOM control framework. This control approach enhances the dynamic response and performance of wind turbines within the wind farm, ensuring effective compensation and system resilience. The proposed methodology is modelled as well as validated utilizing MATLAB/Simulink. The proposed algorithm demonstrates superior optimization performance by achieving the lowest fitness value more rapidly and consistently. Compared to other techniques, it is significantly better than HOA, POA, SFOA, COA, and OOA, which show slower convergence rates and stabilize at higher fitness values. Furthermore, with respect to power quality, the proposed controller achieves a 1.39% THD value is very low relative with other techniques THD values, so it indicating its effectiveness in enhancing output waveform quality. In contrast, the PI controller yields the highest THD, followed sequentially by the PID, ANN, and Fuzzy controllers. These results collectively highlight the superior efficiency, accuracy, and power quality enhancement capabilities of the proposed algorithm. In the future, researchers can focus on using moderate hybrid methods to increase the stability of wind power systems. This approach can also help achieve higher accuracy and support real-time application development

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Archana K, Pushparajesh V.
Methodology: Archana K.
Investigation: Archana K.
Discussion of results: Archana K and Pushparajesh V.
Writing – Original Draft: Archana K.
Writing – Review and Editing: Archana K and Pushparajesh V.
Resources: Pushparajesh V.
Supervision: Pushparajesh V.
Approval of the final text: Archana K and Pushparajesh V.

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