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Modeling and Control of Wind Energy Conversion System with Battery Energy Storage for Power Regulation

Panduga Vishwa Sai[1], Dr. M. T. Naik[2]
[1]Master Student, Centre for Energy Studies, Jawaharlal Nehru Technological University College of Engineering, Science and Technology Hyderabad, Telangana, 500 085, India
[2]Coordinator, Centre For Energy Studies Jawaharlal Nehru Technological University Jntuh University College Of Engineering, Science And Technology Hyderabad-500085, Telangana

Abstract: The integration of renewable energy sources into modern power systems has become essential to meet growing energy demands while reducing environmental impacts. Among various renewable resources, wind energy offers significant potential; however, its variable and unpredictable nature creates challenges in maintaining a stable power supply. To address these issues, this paper proposes a Wind Energy Conversion System (WECS) integrated with a Battery Energy Storage System (BESS) for effective power regulation and improved system reliability. The proposed configuration consists of a wind turbine, self-excited induction generator, power electronic conversion stages, and a battery storage unit operating under coordinated control. An optimum tip speed ratio-based Maximum Power Point Tracking (MPPT) strategy is employed to maximize energy extraction from the available wind resource, while pitch angle control is incorporated to ensure safe turbine operation under high wind conditions. A PI-based control scheme is implemented to maintain DC-link voltage stability and facilitate efficient power management. The complete system is developed and analyzed using MATLAB/Simulink under varying wind speed conditions. Simulation results indicate that the proposed approach effectively smooths power fluctuations, maintains voltage regulation, and supports continuous energy delivery through controlled battery charging and discharging operations. The study demonstrates that integrating battery storage with wind energy systems significantly enhances operational stability, power quality, and overall energy utilization efficiency.
Keywords: Wind Energy Conversion System, Battery Energy Storage System, Maximum Power Point Tracking, Power Regulation, DC-Link Voltage Control, Renewable Energy, MATLAB/Simulink.

I. INTRODUCTION

The growing demand for electrical energy and increasing environmental concerns associated with conventional fossil-fuel-based power generation have accelerated the adoption of renewable energy resources worldwide. Renewable energy technologies provide a sustainable solution for meeting future energy requirements while reducing greenhouse gas emissions and dependence on finite energy reserves. Among the available renewable energy sources, wind energy has emerged as one of the most promising alternatives due to its abundant availability, environmental friendliness, and technological maturity. Wind Energy Conversion Systems (WECS) have experienced significant development over the past few decades and are now widely deployed in both grid-connected and standalone applications. Modern wind turbines are capable of converting the kinetic energy of moving air into electrical energy with improved efficiency and reliability. However, the output power generated by a wind turbine is highly dependent on wind speed, which varies continuously due to changing atmospheric conditions. As a result, the generated power becomes intermittent and unpredictable, creating challenges in maintaining a stable and reliable power supply. The fluctuating nature of wind energy can adversely affect voltage regulation, power quality, and system stability, particularly in isolated and standalone power systems where grid support is unavailable. During periods of high wind speed, excess power may be generated beyond the load demand, whereas insufficient power may be available during low wind speed conditions. These power imbalances can lead to unstable system operation and reduced reliability if appropriate control measures are not implemented. To overcome these challenges, Battery Energy Storage Systems (BESS) have gained considerable attention as an effective energy management solution for renewable energy applications. The integration of battery storage with wind energy systems enables surplus energy generated during high wind conditions to be stored and utilized during periods of low wind availability. This energy balancing capability improves system reliability, enhances power quality, and ensures continuous power delivery to the connected load.

In addition to energy storage integration, advanced control strategies are required to maximize energy extraction and maintain stable operation. Maximum Power Point Tracking (MPPT) techniques are commonly employed to ensure optimal utilization of available wind resources by operating the turbine near its maximum power point. Furthermore, pitch angle control mechanisms are used to regulate turbine operation during high wind speeds and protect the system from excessive mechanical stress. Voltage regulation and power management are further enhanced through the implementation of suitable controller-based converter control schemes.

In this work, a Wind Energy Conversion System integrated with a Battery Energy Storage System is modeled and analyzed using MATLAB/Simulink. The proposed system consists of a wind turbine, Self-Excited Induction Generator (SEIG), AC–DC rectifier, DC–DC converter, battery storage unit, MPPT controller, pitch angle controller, and DC-link voltage regulation scheme. The battery storage system operates in both charging and discharging modes to compensate for wind power variations and maintain a regulated power supply. The performance of the proposed system is evaluated under varying wind speed conditions to investigate its effectiveness in improving power regulation and system stability.

The simulation results demonstrate that the proposed WECS-BESS configuration effectively mitigates the impact of wind intermittency, maintains regulated system operation, and improves overall reliability. The developed model provides a practical and efficient solution for standalone renewable energy applications requiring stable and continuous power delivery.

II. LITERATURE SURVEY

The increasing penetration of renewable energy sources has motivated extensive research on Wind Energy Conversion Systems (WECS) and associated energy storage technologies to improve power quality, reliability, and system stability. Various researchers have investigated different generator configurations, power electronic interfaces, control strategies, and energy storage techniques for efficient utilization of wind energy resources.

Tripathy et al. presented the modeling and control of a wind turbine-driven Self-Excited Induction Generator (SEIG) for standalone applications. Their work demonstrated the feasibility of utilizing induction generators with power electronic converters for voltage regulation and reactive power compensation. The study highlighted the importance of converter-based control techniques for maintaining stable operation under varying wind conditions.

Chakraborty reviewed the advancements in power electronics and drive technologies for renewable energy applications. The study emphasized the significant role of modern power electronic converters in integrating renewable energy resources with electrical systems. The author reported that converter-based control structures improve energy conversion efficiency, voltage regulation, and overall system performance in renewable energy applications.

Hasan et al. investigated various energy storage technologies suitable for wind energy systems. Their review demonstrated that the intermittent nature of wind power can introduce fluctuations that affect system reliability and power quality. The study concluded that energy storage systems, particularly battery-based solutions, provide an effective approach for mitigating power variations and enhancing operational stability.

Kumar and Singh developed a Wind Energy Conversion System integrated with a Battery Energy Storage System and analyzed its performance using MATLAB/Simulink. Their results showed that battery storage effectively compensates for wind power fluctuations by storing excess energy during high wind periods and supplying power during low wind conditions. The study reported improvements in voltage regulation, power continuity, and overall system reliability.

Elshaer et al. proposed a coordinated control strategy for standalone wind energy systems employing battery energy storage. Their work incorporated Maximum Power Point Tracking (MPPT), DC-link voltage regulation, and battery State of Charge (SOC) management. Simulation results demonstrated enhanced voltage stability, reduced power fluctuations, and improved energy management performance under variable operating conditions.

From the reviewed literature, it is evident that significant research has been conducted on wind energy conversion systems, battery energy storage integration, and advanced control techniques. However, maintaining stable power delivery under continuously varying wind conditions remains a major challenge, particularly in standalone renewable energy applications. Therefore, there is a need for an integrated control framework that combines MPPT operation, battery energy storage management, pitch angle control, and DC-link voltage regulation to ensure reliable and regulated power output.

In this work, a Wind Energy Conversion System integrated with a Battery Energy Storage System is developed using MATLAB/Simulink. The proposed approach combines maximum power extraction, battery-supported energy balancing, and voltage regulation techniques to improve system stability, reliability, and power regulation performance under variable wind conditions.

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III. PROBLEM OUTLINE

Wind Energy Conversion Systems (WECS) offer a sustainable solution for electricity generation; however, the intermittent nature of wind causes significant variations in output power. These fluctuations affect voltage regulation, power quality, and system reliability, particularly in standalone applications. To overcome these challenges, Battery Energy Storage Systems (BESS) can be integrated with WECS to store excess energy and supply power during low wind conditions. In addition, advanced control techniques are required to ensure maximum power extraction and stable operation under varying wind speeds.

The main objectives of this work are:

To develop a MATLAB/Simulink model of a WECS integrated with BESS.

To implement Maximum Power Point Tracking (MPPT) for enhanced energy extraction.

To regulate DC-link voltage using a PI controller.

To incorporate pitch angle control for safe turbine operation under high wind conditions.

To manage battery charging and discharging operations effectively.

To improve power regulation, reliability, and overall system performance under variable wind conditions.

A. *Objectives*

To develop a MATLAB/Simulink model of a Wind Energy Conversion System integrated with a Battery Energy Storage System.

To implement Maximum Power Point Tracking (MPPT) control for maximizing energy extraction from available wind resources.

To incorporate pitch angle control for protecting the wind turbine during high wind speed conditions.

To regulate the DC-link voltage using a PI-based control strategy.

To implement battery charging and discharging control for effective energy management.

To analyze the dynamic performance of the integrated WECS-BESS system under varying wind speed conditions.

To improve system reliability, power quality, and power regulation capability through coordinated control of generation and energy storage subsystems.

To validate the effectiveness of the proposed system using MATLAB/Simulink simulation results.

IV. PROPOSED METHODOLOGY

The proposed system consists of a Wind Energy Conversion System (WECS) integrated with a Battery Energy Storage System (BESS) to provide regulated and reliable power under varying wind conditions. The overall system comprises a wind turbine, Self-Excited Induction Generator (SEIG), AC–DC rectifier, DC–DC buck converter, battery storage unit, and associated control circuits.

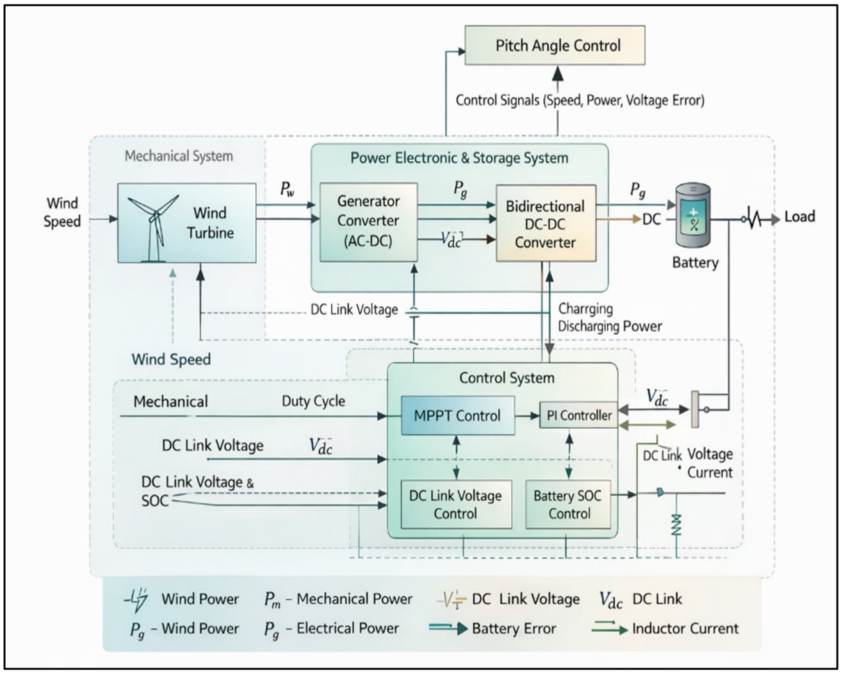

Figure 1: Proposed Wind Energy Conversion System integrated with Battery Energy Storage System.

The wind turbine converts the kinetic energy available in the wind into mechanical energy, which drives the SEIG to generate electrical power. Since the generator output is variable in magnitude and frequency, a three-phase rectifier is employed to convert the generated AC power into DC power. The rectified output is supplied to a DC-link stage, which acts as an intermediate energy transfer unit.

A DC–DC buck converter is utilized to regulate the DC output voltage and control power flow within the system. To maximize energy extraction from the available wind resource, a Maximum Power Point Tracking (MPPT) algorithm based on optimum tip speed ratio control is implemented. The MPPT controller continuously adjusts the operating point of the turbine to ensure maximum power generation under changing wind conditions.

The Battery Energy Storage System is connected to the DC-link through a controlled converter. During periods of excess wind generation, the battery stores surplus energy, whereas during low wind conditions it supplies power to support the load. This coordinated charging and discharging operation improves system reliability and reduces power fluctuations.

In addition, a pitch angle control mechanism is incorporated to limit turbine output during high wind speed conditions and protect the system from mechanical stress. A PI-based controller is employed to maintain DC-link voltage stability and ensure regulated power delivery. The complete system is modeled and simulated in MATLAB/Simulink to evaluate its dynamic performance under variable operating conditions.

V. MATHEMATICAL MODELING

The mathematical model of the proposed Wind Energy Conversion System (WECS) integrated with Battery Energy Storage System (BESS) is developed to analyze system performance under varying wind conditions.

A. Wind Power Model

The power available in the wind is expressed as:

$$P_w = 0.5\rho A V^3$$

where Pw is the wind power (W), ρ is the air density (kg/m³), A is the swept area of the turbine blades (m²), and V is the wind speed (m/s).

The actual mechanical power extracted by the turbine is given by:

$$P_m = 0.5\rho A V^3 C_p$$

where Cp is the power coefficient of the wind turbine.

B. Tip Speed Ratio

The tip speed ratio (TSR) is defined as:

$$\lambda = \omega R/V$$

where λ is the tip speed ratio, ω is the rotor angular speed (rad/s), R is the blade radius (m), and V is the wind speed (m/s).

C. Turbine Torque

The mechanical torque produced by the turbine is given by:

$$T_m = P_m/\omega$$

where Tm is the turbine torque (Nm) and Pm is the mechanical power extracted from the wind.

D. Rectifier Output Voltage

The average DC output voltage of the three-phase rectifier is expressed as:

$$V_{dc} = 1.35 V_{LL}$$

where VLL is the line-to-line AC voltage generated by the SEIG.

E. DC–DC Buck Converter Model

The output voltage of the buck converter is given by:

$$V_o = D V_{in}$$

where Vo is the output voltage, Vin is the input voltage, and D is the duty cycle.

F. Battery State of Charge

The battery State of Charge (SOC) is represented as:

$$SOC = (Q_{remaining} / Q_{rated}) \times 100$$

where Qremaining is the available battery charge and Qrated is the rated battery capacity.

The developed mathematical model forms the basis for implementing MPPT control, battery energy management, and voltage regulation in the proposed WECS-BESS system.

VI. RESULTS AND DISCUSSION

The proposed Wind Energy Conversion System integrated with Battery Energy Storage System was developed and simulated using MATLAB/Simulink. The performance of the system was evaluated under varying wind speed conditions to analyze power regulation capability, battery performance, and voltage stability.

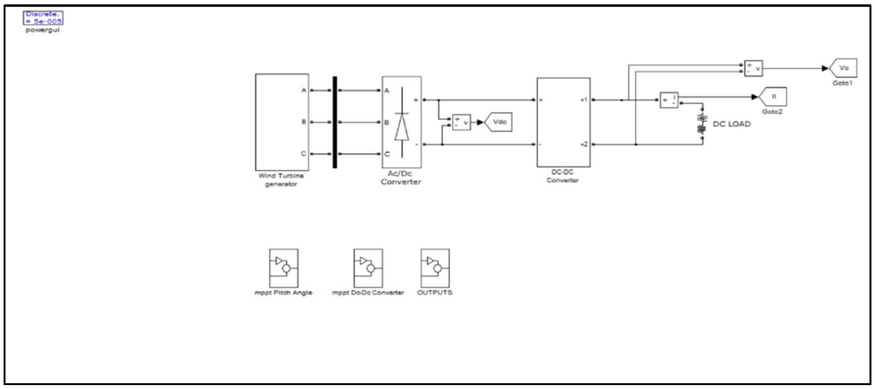

Figure 2: MATLAB/Simulink model of the proposed WECS-BESS system.

A. *Wind Speed Profile*

The wind speed was varied throughout the simulation period to evaluate the dynamic response of the system under changing operating conditions. Different wind speed levels were applied to investigate the effectiveness of the proposed control strategy.

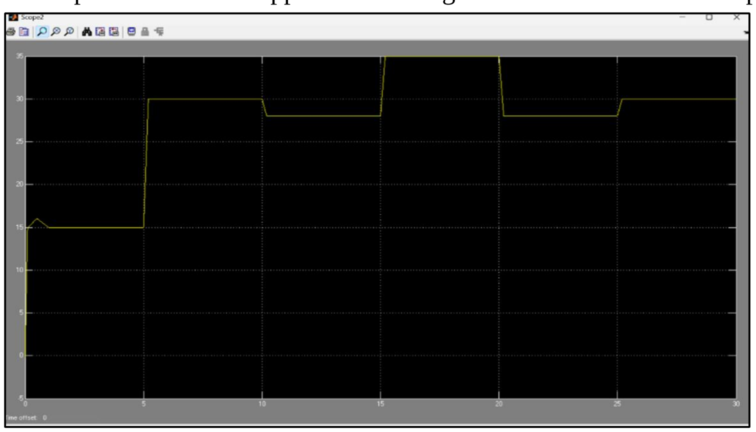

Figure 3: Variable wind speed profile applied to the WECS

B. *Rotor Speed Response*

The rotor speed follows the variation in wind speed and responds effectively to changing operating conditions. The obtained results indicate stable turbine operation without excessive oscillations, demonstrating satisfactory dynamic performance.

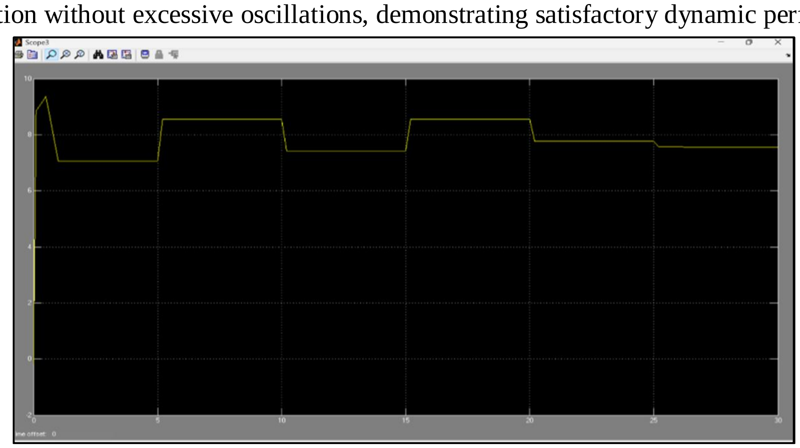

Figure 4: Rotor speed response under varying wind conditions

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C. Electromagnetic Torque Characteristics

The electromagnetic torque varies according to the available wind energy and turbine operating conditions. Torque fluctuations observed during wind speed transitions quickly settle, indicating effective control of the generator system.

D. Output Power Performance

The generated power changes with variations in wind speed and follows the maximum power extraction strategy implemented through MPPT control. The results show that the system successfully utilizes available wind energy and maintains improved power generation performance.

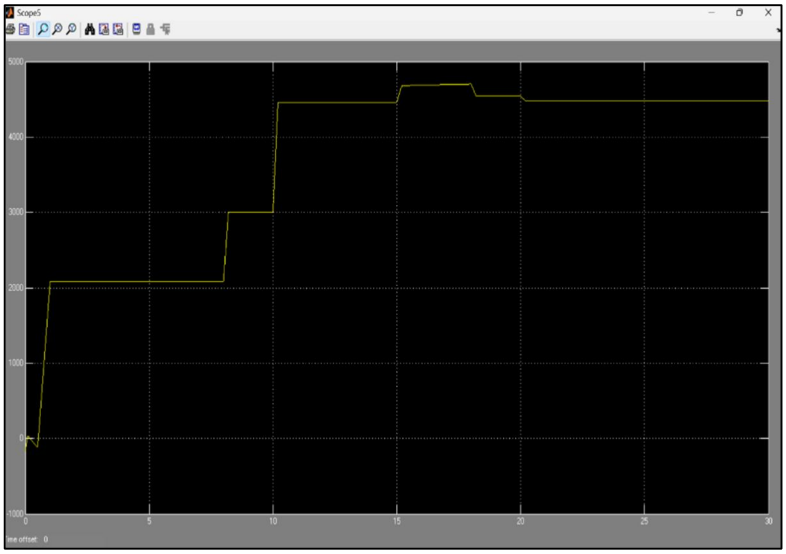

Figure 5: Output power variation of the proposed WECS

E. DC-Link Voltage Regulation

The DC-link voltage remains within the desired operating range throughout the simulation period. The PI controller effectively regulates the DC-link voltage despite fluctuations in wind speed, ensuring stable power transfer between system components.

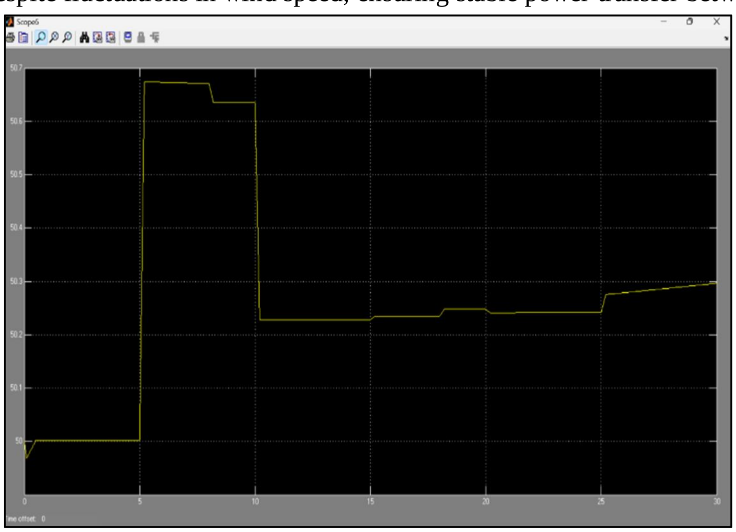

Figure 6: DC-link voltage response showing effective voltage regulation

F. Inductor Current Response

The current through the DC–DC converter inductor remains continuous and stable during operation. Minor transient variations occur during changes in wind speed; however, the converter quickly reaches steady-state operation.

G. Battery State of Charge Analysis

The battery State of Charge (SOC) exhibits controlled charging and discharging behavior according to system requirements. During periods of excess generation, the battery stores energy, whereas during reduced wind conditions it supports the load by supplying stored energy. The SOC remains within safe operating limits throughout the simulation.

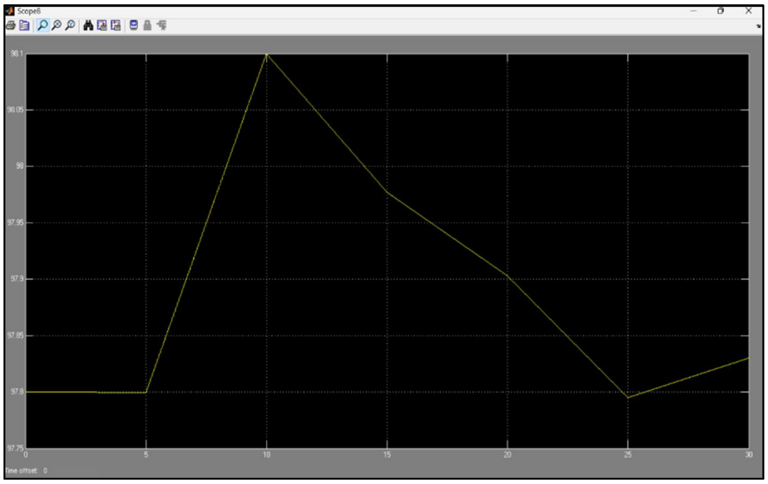

Figure 7: Battery state of charge variation during simulation

H. Battery Voltage Characteristics

The battery voltage remains stable during both charging and discharging modes. The obtained results confirm proper battery management and effective integration of the storage system with the wind energy conversion system.

The simulation results demonstrate that the proposed WECS-BESS configuration effectively mitigates the impact of wind power fluctuations and provides regulated power delivery. The coordinated operation of MPPT control, pitch angle regulation, battery energy storage, and DC-link voltage control enhances system stability, improves power quality, and ensures reliable operation under varying wind conditions.

VII. CONCLUSION

This paper presented the modeling and control of a Wind Energy Conversion System (WECS) integrated with a Battery Energy Storage System (BESS) for regulated power delivery under varying wind conditions. The proposed system incorporated a Self-Excited Induction Generator (SEIG), AC–DC rectifier, DC–DC buck converter, MPPT control, pitch angle control, and battery energy storage for effective energy management. The complete system was developed and analyzed using MATLAB/Simulink. Simulation results demonstrated that the MPPT controller successfully maximized wind energy extraction, while the battery storage system effectively compensated for power fluctuations through controlled charging and discharging operations. The PI-based controller maintained DC-link voltage stability, ensuring reliable power transfer and improved system performance. The obtained results confirm that the proposed WECS-BESS configuration enhances power regulation, system stability, and reliability, making it suitable for standalone renewable energy applications.

A. Future Scope

The proposed work can be extended by implementing advanced control techniques such as fuzzy logic control, artificial neural networks, and model predictive control for improved system performance. Future research may also investigate grid-connected operation, hybrid renewable energy systems incorporating solar photovoltaic generation, and advanced battery management strategies for enhanced energy utilization and reliability.

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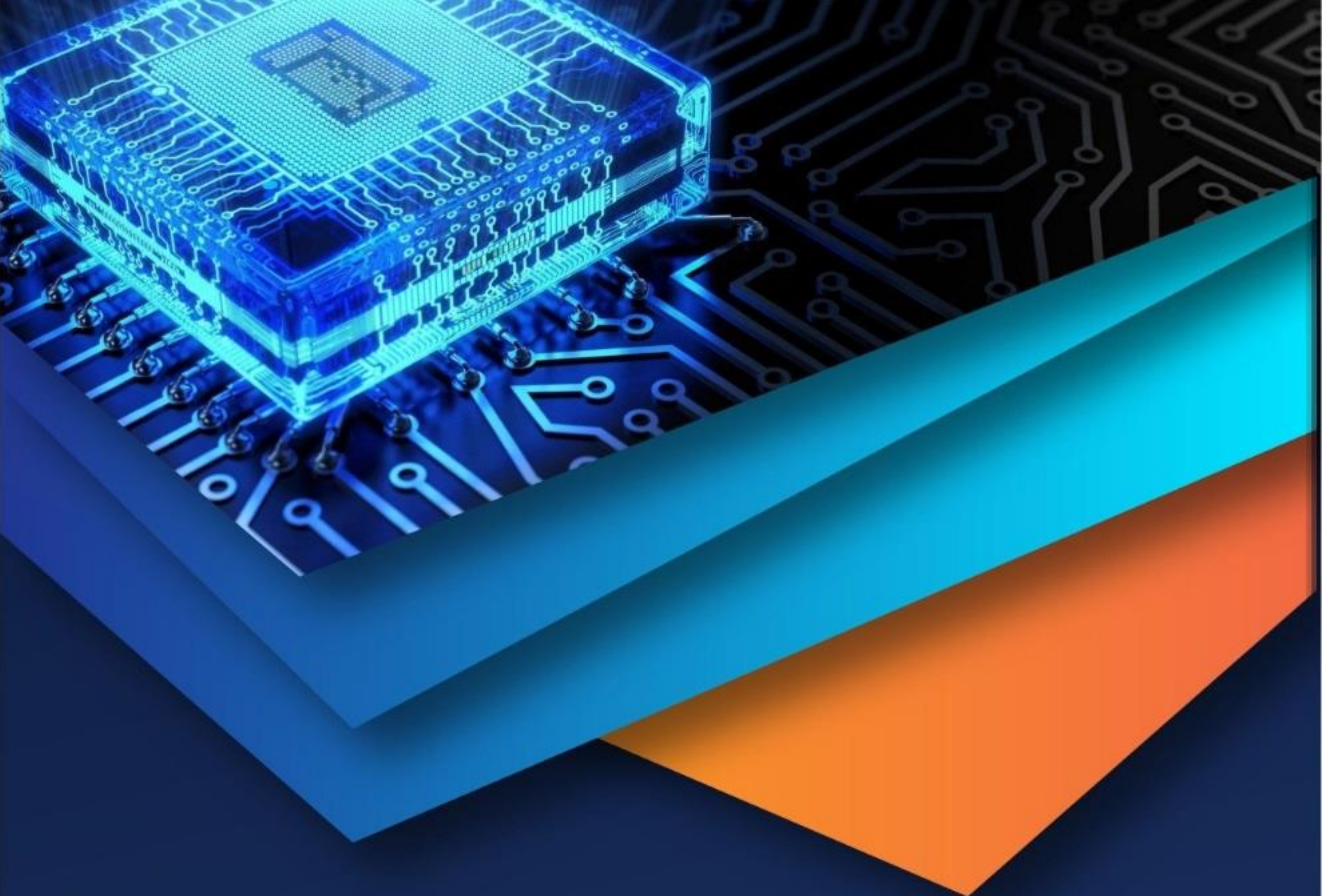

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