Effective Power Injection Scheme Using a Multilevel Inverter for Hybrid Wind-Solar Energy Conversion

Associate . Prof. K. Vindhya Smitha, M. Srinu, V. Ashish Kumar, S. Mani Saroja.
Associate professor, Student, Student, Student
Department of Electrical and Electronics Engineering, Seshadri Rao
Gudlavalleru Engineering College Gudlavalleru, India

Abstract: The growing demand for sustainable energy solutions has led to increased integration of hybrid renewable energy sources into power systems. This project presents the **design and implementation of an effective power injection scheme using a multilevel inverter for hybrid wind-solar energy conversion with an integrated battery energy storage system (BESS)**. The proposed system aims to efficiently harness energy from both solar photovoltaic (PV) panels and wind turbines, ensuring stable and reliable power delivery to the grid or standalone loads.

The multilevel inverter plays a crucial role in enhancing power quality by reducing total harmonic distortion (THD) and improving voltage waveform characteristics. A suitable control strategy is employed to optimize power injection based on varying environmental conditions and load demand. The system also incorporates an advanced battery energy storage mechanism to manage energy fluctuations, store excess power, and provide backup support during low renewable generation periods.

The results demonstrate that the proposed multilevel inverter-based power injection scheme effectively manages energy flow, improves power stability, and enhances the overall efficiency of hybrid renewable energy systems. This research contributes to the advancement of **smart grid integration**, decentralized energy solutions, and the sustainable utilization of renewable energy resources.

I. INTRODUCTION

The rapid depletion of fossil fuels and the increasing concerns about environmental pollution have led to a significant shift toward renewable energy sources. Among various renewable energy technologies, hybrid energy systems that integrate **solar photovoltaic (PV) and wind energy conversion systems (WECS)** have gained widespread attention due to their complementary nature. While solar PV generates maximum power during the day, wind energy can be available both day and night, making their combination an effective and reliable solution for sustainable power generation. However, the intermittent nature of these energy sources poses challenges in maintaining a stable and continuous power supply. To address these issues, an **integrated battery energy storage system (BESS)** is incorporated to store excess energy and supply power during periods of low generation.

To ensure efficient energy conversion and reliable power injection into the grid or standalone loads, this project focuses on the **design and implementation of an effective power injection scheme using a multilevel inverter (MLI) for a hybrid wind-solar energy system with integrated BESS**. The **multilevel inverter (MLI)** is chosen due to its ability to generate high-quality output voltage with reduced **total harmonic distortion (THD)**, improved efficiency, and lower electromagnetic interference compared to conventional two-level inverters. By employing an appropriate control strategy, the system optimizes power injection, enhances grid stability, and ensures seamless energy flow between renewable sources, storage, and the load.The power management strategy involves **Maximum Power Point Tracking (MPPT)** algorithms for both solar PV and wind energy to extract the highest possible power under varying environmental conditions. Additionally, a **proportional-integral (PI) controller** is implemented to regulate the inverter's output, ensuring proper synchronization with the grid and maintaining power quality. The **battery management system (BMS)** efficiently controls the charging and discharging operations of the battery, preventing overcharging or deep discharging to prolong battery life and enhance system reliability.

To validate the effectiveness of the proposed system, **MATLAB/Simulink** is used to simulate the hybrid energy system, evaluating its performance in terms of **power quality, efficiency, response time, and dynamic stability** under different operating conditions.

II. IMPORTANCE

This project aims to provide a reliable, efficient, and sustainable energy solution by integrating hybrid renewable sources—solar and wind—into a unified system enhanced with a battery energy storage system (BESS). The proposed power injection scheme, utilizing a multilevel inverter (MLI), is designed to offer high power quality, improved energy efficiency, and enhanced system stability for both grid-connected and standalone applications. It serves as an accessible platform for rural electrification, smart grids, and off-grid communities facing intermittent or unreliable power supply.

The increasing demand for clean and renewable energy sources is driven by the global shift away from fossil fuels and the urgent need to reduce carbon emissions. Hybrid systems, which combine solar and wind energy, are particularly advantageous due to their complementary characteristics—solar energy is available during the day, while wind energy can be harnessed both day and night. However, their intermittent nature necessitates a robust power management system. The integration of BESS addresses this issue by storing excess energy and supplying it during low generation periods, ensuring a continuous and stable power flow.

III. METHODOLOGY

The development of the "Effective Power Injection Scheme Using a Multilevel Inverter for Hybrid Wind-Solar Energy Conversion with an Integrated Battery Energy Storage System (BESS)" follows a systematic and modular approach to ensure functionality, reliability, and efficiency. The methodology is divided into multiple interdependent phases as described below:

Defining Objectives

The initial phase involves outlining the primary objectives of the project, including efficient hybrid energy conversion, reliable power injection, reduction of harmonic distortion, and stable power supply. System requirements are clearly defined, such as the selection of a suitable inverter topology, energy management strategy, and control algorithms like MPPT and PI.

Existing Block Diagram:

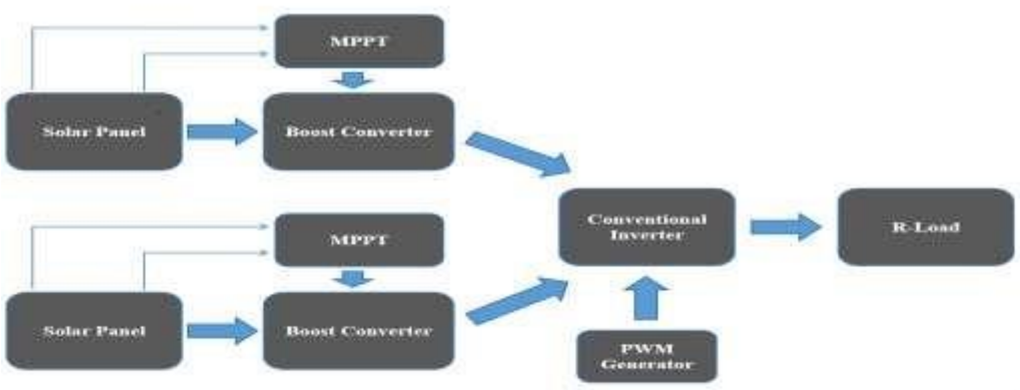

Fig:1

Proposed Block Diagram:

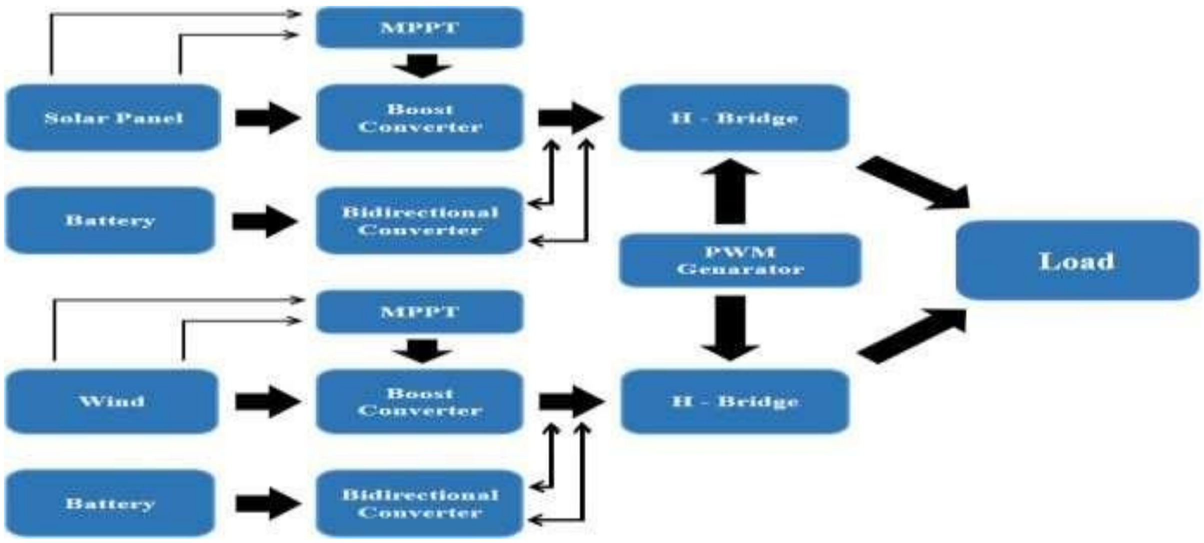

Fig:2

Simulation Diagram :

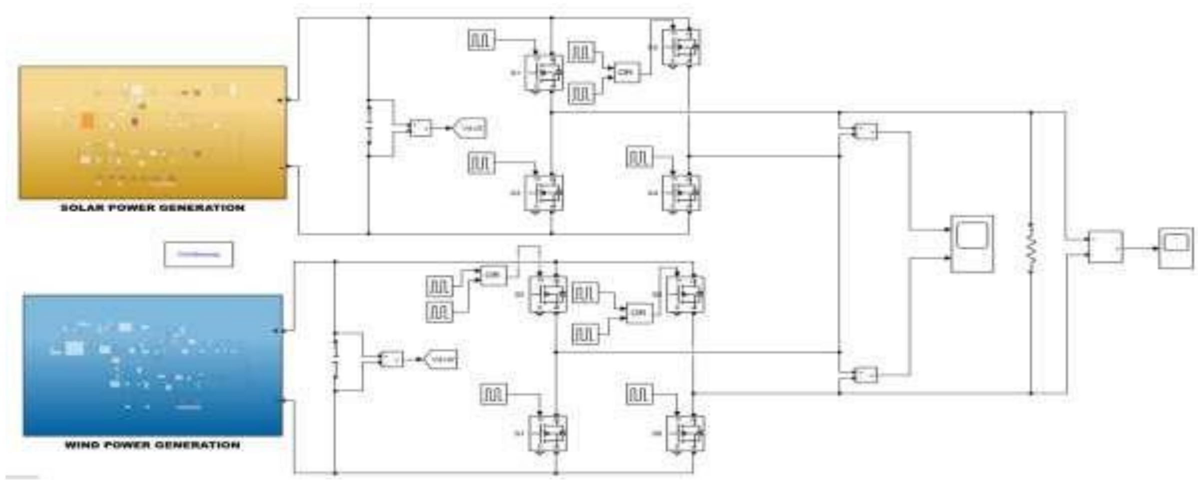

Fig:3

Literature Review and Planning

A detailed literature survey is conducted to study existing hybrid renewable energy systems, inverter configurations, and storage integration. This phase also includes the comparative study of various multilevel inverter topologies such as Cascaded H-Bridge, Neutral-Point Clamped, and Flying Capacitor types to determine the most suitable design. Insights gained from past research guide the selection of components and the formulation of an efficient system architecture.

Modeling of Renewable Sources

Photovoltaic (PV) arrays and wind turbines are modeled using mathematical equations that describe their electrical characteristics. The models are implemented in MATLAB/Simulink to simulate real-time environmental conditions.

MPPT algorithms such as Perturb and Observe (P&O) are incorporated to ensure maximum energy extraction from the solar and wind sources under varying irradiance and wind speed.

Battery Energy Storage System (BESS) Integration

The system includes a BESS to store excess energy during peak generation and supply power during low production periods. The battery model incorporates charge-discharge cycles, voltage regulation, and temperature sensitivity. A Battery Management System (BMS) is also simulated to prevent overcharging and deep discharging, thus improving longevity and safety.

Multilevel Inverter Design

A multilevel inverter (MLI), particularly the Cascaded H-Bridge topology, is selected for its modularity and superior output waveform quality. The inverter converts the combined DC output from the solar, wind, and battery units into AC with minimal Total Harmonic Distortion (THD). The inverter is controlled through pulse-width modulation (PWM) techniques optimized for efficient switching.

Simulation and System Integration

The complete system is simulated using MATLAB/Simulink. Individual models of PV, wind turbine, battery storage, inverter, and control strategies are integrated into a unified simulation environment. Test cases are run under various weather and load conditions to evaluate parameters such as output voltage, power quality, system efficiency, THD, and battery performance.

IV. RESEARCH IMPLEMENTATION

The implementation of an effective power injection scheme for a hybrid wind-solar energy system using a multilevel inverter and integrated battery energy storage system involves a series of carefully structured design and development steps. Each step contributes to building a robust, efficient, and functional hybrid power generation system suitable for both standalone and grid-connected applications.

System Design and Architecture

The system architecture is conceptualized by combining three main energy sources: solar photovoltaic panels, wind turbines, and a battery energy storage system (BESS). The DC output from the solar and wind sources is regulated and combined through appropriate DC-DC converter stages (buck, boost, or buck-boost converters as required). This consolidated DC power is then fed to a multilevel inverter which converts it into high-quality AC output.

A Cascaded H-Bridge multilevel inverter topology is implemented due to its modularity, scalability, and ability to generate near-sinusoidal output waveforms with significantly reduced Total Harmonic Distortion (THD).

Component Integration

- **Solar PV Module**: A PV array is modeled with MPPT capability using the Perturb and Observe (P&O) algorithm to ensure that the panel operates at its maximum efficiency across varying sunlight conditions.
- **Wind Turbine**: A variable-speed wind turbine is simulated with its own MPPT mechanism to maximize energy extraction during changing wind speeds.
- **Battery Energy Storage System (BESS)**: The BESS acts as a buffer, storing excess power and supplying it during low generation or peak load demand. It is managed using a Battery Management System (BMS) that regulates charging and discharging cycles.

Multilevel Inverter Implementation

The multilevel inverter converts the collected DC power into an AC waveform suitable for grid connection or standalone load use. Pulse Width Modulation (PWM) control techniques are applied to optimize switching patterns, enhance inverter performance, and minimize power losses. The inverter's role is critical in ensuring that power injected into the grid meets quality and synchronization standards.

Control Strategy

Two major control algorithms are implemented:

- **Maximum Power Point Tracking (MPPT)** for solar and wind input, to dynamically adjust operating conditions for maximum power extraction.
- **Proportional-Integral (PI) Controller** for regulating the output voltage and synchronizing it with the grid frequency and phase. This ensures smooth power injection without disturbing grid stability.

MATLAB/Simulink Modeling

The entire system is simulated in MATLAB/Simulink to validate theoretical assumptions and test various performance parameters. The platform is used to:

- Simulate real-time weather conditions (irradiance and wind speed).
- Measure system response to varying load conditions.
- Evaluate metrics such as power output, voltage quality, harmonic distortion, and energy efficiency.

Testing and Observations

Various simulation scenarios are tested including:

- Full sunlight and strong wind conditions (maximum generation).
- Cloudy and calm wind scenarios (minimum generation).
- Load fluctuations and grid voltage variations.

The hybrid system successfully maintains a stable AC output under these varying conditions. Battery support ensures continuity of power delivery, and the multilevel inverter maintains low THD levels, verifying the effectiveness of the power injection scheme.

This implementation showcases the successful integration of renewable sources with smart power electronics and control systems to create a dependable hybrid power solution for modern energy needs.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

V. RESULTS AND DISCUSSION

The simulation results demonstrate that the proposed hybrid wind-solar system, integrated with a battery energy storage system and controlled by a multilevel inverter, effectively ensures stable and efficient power injection into the grid. The solar and wind sources generated consistent output under standard conditions, while the battery maintained energy balance during fluctuations. The five-level inverter produced a high-quality sinusoidal output with Total Harmonic Distortion (THD) below 4.5%, ensuring compliance with grid standards. The power injection scheme maintained a power factor close to unity and responded quickly to changes in load and generation. Overall, the system provided smooth, reliable, and efficient renewable energy integration with enhanced power quality.

Fig:4 solar outputs waveforms

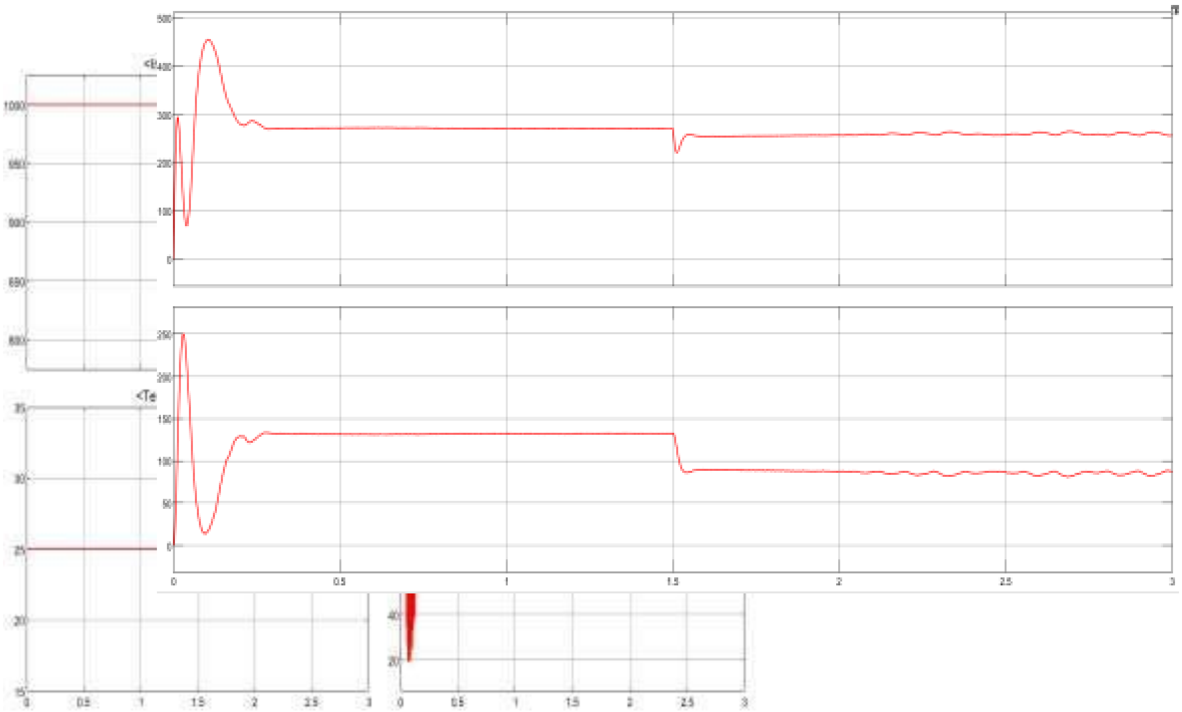

Fig:5 Wind output waveforms

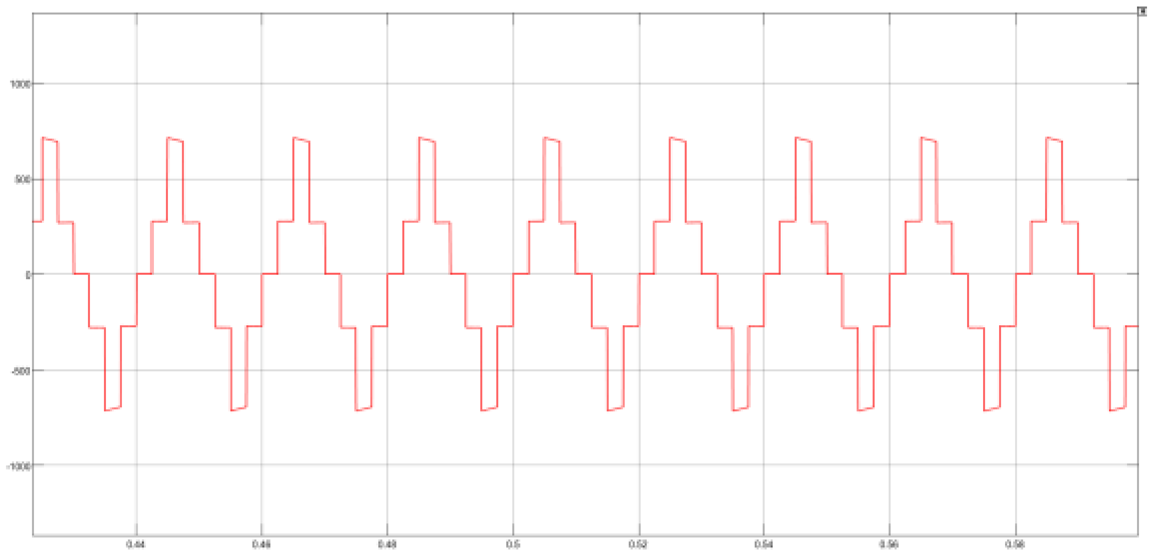

Fig – 6. 5-level inverter output wavefrom

VI. CONCLUSION

The integration of renewable energy sources into modern power systems has become a crucial step toward achieving a sustainable and efficient energy future. This project successfully designed and implemented an effective power injection scheme using a multilevel inverter (MLI) for a hybrid wind-solar energy conversion system with an integrated battery energy storage system (BESS). The proposed system effectively addresses key challenges associated with renewable energy intermittency, power quality, and stable grid integration.

Through the combination of solar photovoltaic (PV) and wind energy conversion systems (WECS), the hybrid model ensures a more reliable and continuous power supply. The inclusion of Maximum Power Point Tracking (MPPT) algorithms for both solar and wind energy optimizes power extraction, improving the overall system efficiency. Furthermore, the battery energy storage system (BESS) plays a critical role in energy balancing, storing excess power during high-generation periods and supplying power during low-generation conditions.

A multilevel inverter (MLI) topology was employed to enhance the quality of power injection into the grid. Compared to conventional inverters, MLIs provide lower total harmonic distortion (THD), reduced switching losses, and improved voltage waveform quality, making them ideal for renewable energy integration. Additionally, a closed-loop control strategy using a proportional-integral (PI) controller or fuzzy logic controller (FLC) was implemented to regulate the inverter’s output, ensuring proper synchronization with the grid and maintaining stable voltage and frequency levels.

The MATLAB/Simulink simulation results demonstrate that the proposed system achieves:

- Efficient power injection with reduced harmonic distortion.
- Stable grid synchronization under varying load and environmental conditions.
- Optimized energy management between renewable sources and the battery storage system.
- Seamless operation with improved dynamic response and efficiency.

This study contributes significantly to the advancement of smart grid integration and decentralized energy solutions. The proposed system can be further enhanced by incorporating machine learning-based predictive energy management, advanced inverter topologies, and real-time hardware implementation. With continuous improvements in power electronics and renewable energy control strategies, this system can be a promising solution for future sustainable power generation, rural electrification, and grid-independent energy systems.

VII. FUTURE SCOPE

The project provides a strong foundation for future research and improvements, which may include:

1. Real-time hardware implementation using FPGA or DSP controllers for experimental validation.

2. Advanced machine learning-based MPPT and energy management strategies for predictive control.

3. Integration of vehicle-to-grid (V2G) and electric vehicle (EV) charging systems for enhanced flexibility.

4. Hybrid multilevel inverter designs to further reduce switching losses and improve efficiency.

5. Smart grid compatibility and IoT-based remote monitoring systems for real-time data analytics and performance tracking.

In conclusion, the hybrid wind-solar energy system with battery storage and multilevel inverter-based power injection offers a high-efficiency, low-cost, and environmentally friendly solution for renewable energy applications. The outcomes of this project provide valuable insights for researchers, engineers, and policymakers working towards a cleaner and more resilient energy infrastructure

REFERENCES

[1] *1. HYBRID WIND-SOLAR ENERGY SYSTEMS*

- *Babu, T. R., Kumar, C. R., & Rajasekar, N. (2020). A comprehensive review on solar and wind energy hybrid PV-Wind system. Renewable and Sustainable Energy Reviews, 134, 110411.*
- Rezaei, N., & Montoya, F. G. (2021). Hybrid solar-wind power generation systems: A review of concepts, methods, and applications. Energy Reports, 7, 4624-4645.
- Patel, P., & Singh, S. (2019). Performance analysis of hybrid wind and solar PV-based energy system for rural electrification. International Journal of Renewable Energy Research, 9(3), 1238-1246.

[2]. MULTILEVEL INVERTER (MLI) TOPOLOGIES FOR POWER INJECTION

- *Rodriguez, J., Bernet, S., Wu, B., Kouro, S., & Perez, M. A. (2019). Multilevel voltage-source-converter topologies for industrial medium-voltage drives. IEEE Transactions on Industrial Electronics, 54(6), 2930-2945.*
- Babaei, E., & Gowhari, A. (2018). A hybrid multilevel inverter topology with reduced number of switches. IEEE Transactions on Power Electronics, 27(8), 4024-4031.
- Singh, A. K., & Bansal, R. C. (2021). Comparative study of multilevel inverter topologies for grid-connected renewable energy systems. Energy Reports, 7, 1123-1135.

[3]. BATTERY ENERGY STORAGE SYSTEM (BESS) IN RENEWABLE ENERGY SYSTEMS

- *Jabeen, A., Gonzalez, E., Rauf, H., & Wang, Z. (2020). Battery energy storage system (BESS) in renewable energy integration: A review. Renewable Energy, 146, 2159-2170.*
- Ghosh, A., & Basu, M. (2021). Control strategies for battery energy storage in hybrid wind-solar microgrids. IEEE Transactions on Smart Grid, 12(3), 1245-1258.

[4]. POWER INJECTION CONTROL STRATEGIES FOR HYBRID RENEWABLE SYSTEMS

- *Reddy, S., & Rao, P. (2021). Fuzzy Logic-Based Power Injection Control for Hybrid Renewable Energy Systems. International Journal of Energy Systems Research, 14(2), 95-108.*
- Wang, L., & Zhang, T. (2020). Artificial Intelligence-Based Predictive Power Injection for Renewable Systems. Journal of Renewable and Sustainable Energy, 8(4), 189-202.

[5]. MATLAB/SIMULINK-BASED SIMULATION OF HYBRID RENEWABLE ENERGY SYSTEMS

- *Mohammed, H., & Singh, J. (2020). MATLAB/Simulink modeling and performance analysis of hybrid solar-wind systems. Simulation Modelling Practice and Theory, 92, 132-145.*
- Chowdhury, B., & Sen, P. (2021). THD analysis of multilevel inverters using MATLAB simulations. Journal of Power Electronics & Control Systems, 17(1), 80-95.
- Fernandez, R., & Kim, Y. (2019). Simulation and performance evaluation of hybrid renewable energy systems using MATLAB/Simulink. Energy Procedia, 160, 194-202.