

# "Advanced Control Strategies for Grid-Connected Renewable Energy Systems using Power Electronics and Artificial Intelligence"

**DR. R. K. Dhattrak<sup>1</sup>, Prof. Suyog Sangharatna Dhoke<sup>2</sup>, Subodh Sunil Bodhe<sup>3</sup>,**

**Mohammed Shaadurrahim Sheikh<sup>4</sup>, Shivam Rampratap Das<sup>5</sup>, Mayur Anand Pasle<sup>6</sup>, Manish**

**Devidas Karmenge<sup>7</sup>**

Head & Professor, Dept. of Electrical Engg. RCERT, Chandrapur<sup>1</sup>

Assistant Professor, Dept. of Electrical Engg. RCERT, Chandrapur<sup>2</sup>

Dept. of Electrical Engg. RCERT, Chandrapur<sup>3</sup>

Dept. of Electrical Engg. RCERT, Chandrapur<sup>4</sup>

Dept. of Electrical Engg. RCERT, Chandrapur<sup>5</sup>

Dept. of Electrical Engg. RCERT, Chandrapur<sup>6</sup>

Dept. of Electrical Engg. RCERT, Chandrapur<sup>7</sup>

**Abstract:** This paper presents the detailed modelling and simulation of a hybrid renewable energy-based microgrid integrating solar photovoltaic (PV), wind energy generation, battery energy storage, and conventional grid supply. The system is developed using the MATLAB/Simulink environment, enabling accurate representation of dynamic system behavior and real-time performance analysis. Advanced control strategies are implemented using PID controllers combined with logic-based switching mechanisms to ensure efficient coordination among multiple energy sources. A priority-based energy management system (EMS) is designed to maximize the utilization of renewable energy while maintaining system stability and reliability under varying operating conditions.

The proposed system is evaluated under six distinct operational scenarios, including variations in solar irradiance, wind speed, load demand, and battery state of charge. These scenarios help analyze the system's adaptability and robustness in real-world conditions. Simulation results demonstrate that the hybrid microgrid effectively reduces dependency on grid power, enhances energy efficiency, and ensures continuous power supply even during fluctuations in renewable sources. Furthermore, the integration of intelligent control improves overall system reliability, optimizes power flow, and contributes to sustainable energy management.

**Keywords:** Renewable Energy; Energy Efficiency; Solar Power Generation; MATLAB/Simulink; Energy Management System

## 1. INTRODUCTION

The rapid transition toward renewable energy integration has transformed modern power systems, with increasing deployment of solar photovoltaic (PV) systems and wind energy conversion units. These renewable sources are typically interfaced with the grid through power electronic converters such as inverters, which are responsible for converting variable output into stable, grid-compatible AC power. In addition to conversion, these systems play a critical role in maintaining synchronization, regulating voltage and frequency, and ensuring overall power quality.

However, the large-scale integration of renewable energy introduces significant operational challenges due to its intermittent and unpredictable nature. Variations in solar irradiance and wind speed can result in voltage fluctuations, frequency instability, reduced system inertia, and reliability concerns. Conventional control techniques, such as proportional-integral (PI) controllers, are often limited in handling such dynamic and nonlinear conditions, particularly in hybrid and distributed energy systems.

In response to these challenges, hybrid renewable energy-based microgrids have emerged as a viable solution for improving energy reliability and efficiency. By integrating

multiple energy sources such as solar, wind, battery storage, and grid supply, microgrids can ensure continuous power availability while optimizing energy utilization. The effective coordination of these sources requires a robust energy management strategy capable of adapting to varying operating conditions.

This study presents the modelling and simulation of a hybrid renewable energy-based microgrid designed for residential applications. The system integrates solar PV, wind energy, battery storage, and grid supply within a unified framework and is developed using MATLAB/Simulink. A priority-based control strategy is implemented to maximize renewable energy utilization while maintaining system stability and reliability.

The proposed system is evaluated under multiple operating scenarios that consider variations in load demand, renewable energy generation, and environmental conditions. The simulation results demonstrate improved system efficiency, reduced dependence on grid electricity, and enhanced reliability. This work highlights the potential of hybrid microgrid systems in achieving sustainable and cost-effective energy solutions for modern power systems.

## **2. LITERATURE REVIEW**

### **Energy Management System for Renewable Energy-Based Microgrid Using MATLAB/Simulink**

The increasing demand for electricity and the depletion of conventional energy resources necessitate the integration of renewable energy sources into power systems. This integration requires robust energy management systems (EMS) to address challenges such as fluctuating power generation, grid stability, and efficient utilization of available resources. The following literature provides insights into the advancements and methodologies in modelling and implementing EMS for hybrid renewable energy-based microgrids using MATLAB/Simulink.

#### **1. Integration of Hybrid Energy Model with Solar PV, Hydro, and Wind Turbine**

This study emphasizes the necessity of hybrid energy systems for ensuring a continuous and reliable electricity supply, particularly under variable solar irradiance and wind speed conditions. The research presents a MATLAB/Simulink-based model integrating solar PV cells, wind turbines, and hydro energy systems. The comparative analysis highlights the advantages of hybrid systems over single-source energy systems, particularly in mitigating intermittency issues and ensuring grid stability. This work underscores the importance of combining multiple renewable energy sources to address fluctuations and improve system resilience, laying a foundation for EMS development.

#### **2. Energy Management System for Hybrid Renewable Energy-Based Microgrid**

This paper introduces a hybrid microgrid comprising solar, wind, and battery storage systems, managed by a fuzzy logic controller (FLC). The proposed EMS ensures efficient power generation and storage by dynamically responding to load variations. Compared to conventional PI controllers, the FLC demonstrates superior performance in managing active power, reactive power, battery state of charge (SoC), and harmonic mitigation. The simulations in MATLAB/Simulink validate the effectiveness of the FLC in enhancing system performance and reliability. This study provides a strong basis for designing intelligent EMS frameworks for hybrid systems.

#### **3. Simulation of Microgrid with Energy Management System**

This work focuses on the implementation of a DC microgrid comprising photovoltaic arrays, wind turbine generators, battery storage, and grid integration. An EMS is developed to schedule generation and load efficiently under variable conditions. The MATLAB/Simulink-based model highlights the role of EMS in ensuring seamless operation under fluctuating generation and load scenarios. By incorporating battery storage, the study addresses energy balance, demonstrating the practical viability of hybrid renewable energy systems in real-world applications. This research supports the development of EMS by providing insights into scheduling and resource allocation.

#### **4. Energy Management System for Microgrid Using ANN Logic Controller**

An Energy Management System (EMS) for a microgrid using an ANN Logic Controller operates as an intelligent, adaptive "brain" that balances fluctuating power generation from renewables like solar and wind with the real-time electricity demand of consumers. Unlike traditional controllers that rely on rigid, pre-defined "if-then" rules, the Artificial Neural Network (ANN) processes complex inputs—such as weather forecasts, current battery State of Charge (SoC), and utility pricing—through layers of interconnected neurons to identify non-linear patterns. This allows the system to make predictive decisions, such as when to store energy in batteries (P<sub>batt</sub>), when to draw from the main grid, or when to trigger peak shaving to minimize operational costs. By continuously learning from historical data and

minimizing an objective cost function (J), the ANN controller ensures high grid reliability and optimal efficiency, effectively navigating the stochastic nature of distributed energy resources without requiring a complex mathematical model of the entire physical system.

### Synthesis and Relevance to the Study Title

The surveyed research collectively provides a comprehensive foundation for designing an EMS for renewable energy-based microgrids using MATLAB/Simulink. Key contributions include:

- 1. Hybrid System Modelling:** All studies underscore the importance of integrating multiple renewable energy sources to address intermittency and ensure system reliability. The models incorporate solar PV, wind turbines, and battery storage, demonstrating the versatility of hybrid systems.
- 2. Controller Design:** The use of advanced controllers, such as PID logic, significantly improves system performance by dynamically adjusting to changing load and generation conditions. The comparative analysis with traditional controllers highlights the benefits of intelligent control strategies in hybrid systems.
- 3. Energy Storage Management:** Effective battery management strategies, particularly those focusing on maintaining optimal SoC, are crucial for enhancing system efficiency and extending battery life. The integration of energy storage systems enables seamless operation under variable conditions.
- 4. Simulation and Validation:** The MATLAB/Simulink platform emerges as a reliable tool for modelling, simulation, and validation of EMS frameworks. Its flexibility and capability to handle complex hybrid energy models make it ideal for testing various control strategies and system configurations.

By synthesizing the methodologies and findings from these studies, this literature review contributes to the development of a robust EMS for renewable energy-based microgrids. It highlights the critical components and strategies required to optimize energy generation, storage, and distribution, ensuring reliability and sustainability in hybrid systems. These insights directly support the research objective of designing and implementing an energy management system tailored for hybrid renewable energy-based microgrids using MATLAB/Simulink.

photons in the light excite electrons in the semiconductor, creating an electric current. This process, known as the photovoltaic effect, generates direct current (DC) electricity. Multiple solar cells are interconnected within a solar panel, and panels are combined into arrays to scale up energy production. To make the electricity usable for homes or the grid, an inverter converts DC into alternating current (AC). Modern systems often include monitoring devices to track performance and optimize efficiency. Another method, concentrated solar power (CSP), uses mirrors or lenses to focus sunlight onto a receiver, heating a fluid (like molten salt) to produce steam that drives turbines, generating electricity. However, PV systems dominate residential and commercial applications due to their modularity and declining costs. Key factors influencing efficiency include panel orientation, tilt angle, geographic location, and exposure to sunlight, with optimal placement maximizing energy capture. Environmental conditions like shading, temperature, and dust accumulation also impact output, necessitating periodic maintenance. Solar energy systems may integrate battery storage to store excess power for use during non-sunny periods or connect to the grid via net metering, allowing surplus energy to be fed back. Advances in materials, such as perovskite solar cells, and bifacial panels that capture light on both sides, continue to enhance efficiency and affordability, making solar energy a cornerstone of sustainable energy solutions.

## 3. PROPOSED SYSTEM

The system presented in this work is a **grid-connected hybrid renewable energy system** that integrates solar and wind energy sources through a centralized DC-link configuration. The architecture is designed to ensure stable operation, efficient energy utilization, and seamless interaction with the utility grid. By combining multiple renewable sources, the system improves reliability and reduces dependency on any single energy source.

The complete system consists of a solar photovoltaic unit, a wind energy conversion unit, a regulated DC bus operating at 700 V, an optional battery storage system, and a three-phase inverter for grid and load connection.

### 3.1 Solar Photovoltaic Subsystem

The solar photovoltaic subsystem converts incident solar radiation into electrical energy using semiconductor-based PV modules. The output generated by the PV array is direct current (DC), and its magnitude is strongly influenced by environmental conditions such as irradiance level and cell temperature.

Due to the nonlinear behavior of PV characteristics, the operating point continuously shifts under changing conditions. To address this, a DC-DC converter is employed between the PV array and the DC bus. This converter regulates the output voltage and enables operation near the maximum power point, ensuring efficient energy extraction.

In addition to voltage control, the converter enhances system stability by smoothing fluctuations before delivering power to the DC link.

### 3.2 Wind Energy Conversion Subsystem

The wind energy subsystem captures kinetic energy from moving air using a wind turbine and converts it into electrical energy via a generator. The electrical output of the generator is typically variable in amplitude and frequency due to fluctuating wind speeds.

To make this power compatible with the DC-link structure, the generated AC output is first converted into DC using a rectification stage. Subsequently, a DC-DC converter is used to regulate the voltage level and align it with the DC bus requirements.

This subsystem complements solar generation, particularly during periods of low sunlight, thereby enhancing the overall consistency of power generation.

### 3.3 Common DC Bus (700 V DC Link)

A constant **700 V DC bus** is utilized as the central coupling interface of the system. It acts as a shared platform for integrating multiple energy sources and facilitating controlled power transfer.

The DC bus performs several essential functions:

- **Integration of Sources:** It combines the outputs of solar and wind subsystems into a single energy channel.
- **Voltage Regulation:** It maintains a stable DC voltage despite fluctuations in generation and load demand.
- **Power Coordination:** It manages the distribution of energy among sources, storage, and loads.
- **Bidirectional Energy Flow:** It supports energy exchange between storage systems and the grid when required.

Maintaining a stable DC-link voltage is crucial, as it directly influences inverter performance and overall system efficiency.

### 3.4 Battery Energy Storage System

A battery energy storage system can be incorporated to improve system flexibility and reliability. It serves as an intermediate energy buffer that compensates for the variability of renewable sources.

Its primary roles include:

- Storing surplus energy generated during high production periods
- Supplying power during low generation or peak demand conditions
- Assisting in maintaining DC bus voltage stability
- Reducing dependence on the grid

The battery operates dynamically in charging or discharging mode based on system requirements and is governed by an energy management strategy.

### 3.5 Three-Phase Voltage Source Inverter

The three-phase voltage source inverter acts as the interface between the DC system and the AC grid. It converts the DC power available at the DC bus into a three-phase AC output suitable for grid connection and local consumption.

The inverter is responsible for:

- Converting DC voltage into sinusoidal AC voltage
- Synchronizing with grid parameters such as frequency, phase, and voltage
- Controlling the flow of active and reactive power
- Minimizing harmonic distortion using modulation techniques

The inverter ensures that the generated power is delivered efficiently and in compliance with grid standards.

## 4. BLOCK DIAGRAM

The **block diagram of the "Renewable Energy-Based Microgrid Performance Analysis" system** visually represents the integration of key components designed to optimize renewable energy sources for a residential load. This diagram provides a clear understanding of the system's architecture and the interactions between its various elements, ensuring efficient energy utilization and reliability.

- **Solar Panels:** The solar panels capture sunlight and convert it into electrical energy. The energy generated is directed to the energy management system for further distribution.
- **Wind Turbines:** Wind turbines harness wind energy to generate electricity. Similar to solar panels, the energy produced by wind turbines is fed into the energy management system.
- **Conventional Grid Electricity:** This component represents the traditional electrical grid, providing a stable and reliable source of electricity to the residential load.

**Battery system:** The system also includes a Battery System, which governs the storage and release of energy in the battery storage units. The battery system ensures that excess energy from renewable sources is efficiently stored and made available during periods of low energy production, enhancing the system's reliability and sustainability.

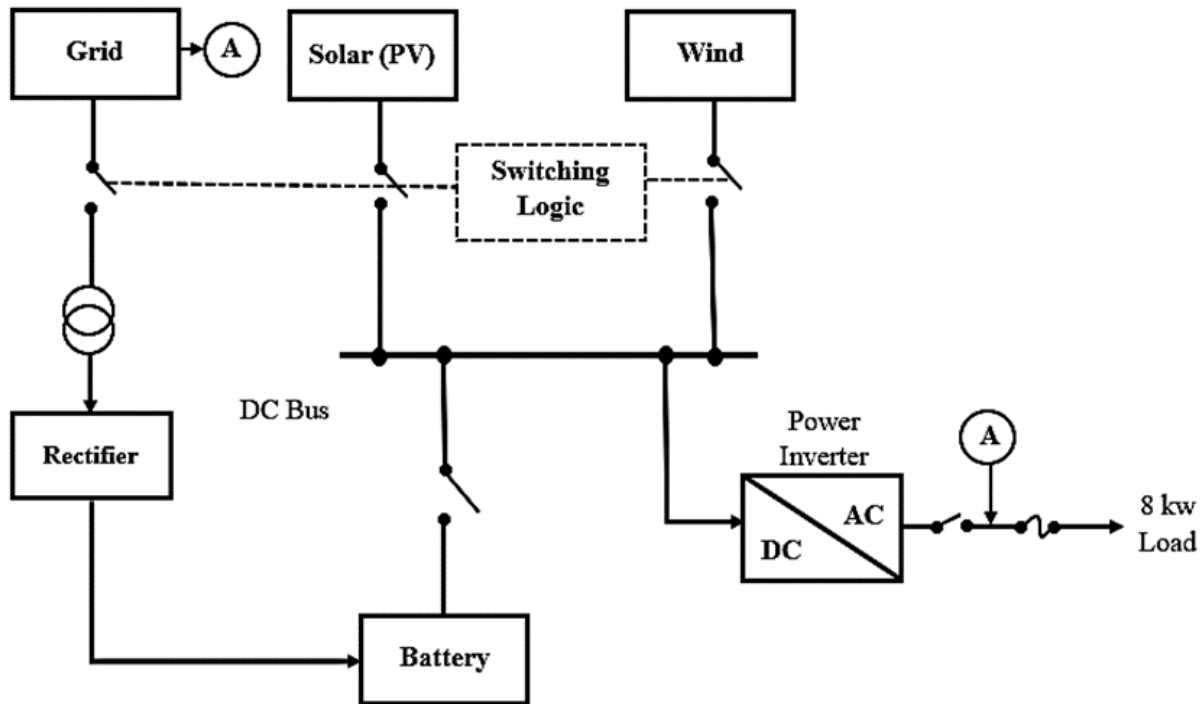


Fig: block diagram of the "Renewable Energy-Based Microgrid Performance Analysis

### 5. MATHEMATICAL MODELLING

To understand the behavior of the proposed hybrid renewable system, it is necessary to develop mathematical models for each of its major components. These models help in analyzing system dynamics and designing appropriate control strategies.

#### 5.1 Solar Photovoltaic Model

The output characteristics of a solar photovoltaic module are nonlinear and depend on environmental conditions such as irradiance and temperature. The current generated by the PV cell can be expressed as:

$$I = I_{ph} - I_o \left( e^{\frac{V}{nV_T}} - 1 \right)$$

In this equation,  $I_{ph}$  represents the current generated due to sunlight, while  $I_o$  corresponds to the diode saturation current. The term  $V_T$  denotes the thermal voltage, and  $nn$  is the diode ideality factor.

This relationship shows that the output current varies exponentially with voltage, making it necessary to operate the PV system at its optimal point to achieve maximum efficiency.

#### 5.2 Wind Energy Conversion Model

The power available from wind depends primarily on wind speed and turbine characteristics. It can be described using the following expression:

$$P = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta)$$

Here,  $\rho$  is the air density,  $A$  is the area swept by the turbine blades, and  $v$  is the wind velocity. The coefficient  $C_p$  represents the efficiency of the turbine and is a function of the tip-speed ratio  $\lambda$  and pitch angle  $\beta$ .

Since the power varies with the cube of wind speed, even small changes in wind conditions can significantly impact the generated power.

### 5.3 DC-Link Dynamics

The DC bus acts as a common link between different subsystems, and its voltage must be maintained within a stable range. The dynamic behavior of the DC-link voltage is given by:

$$C \frac{dV_{dc}}{dt} = I_{in} - I_{out}$$

where  $C$  is the capacitance of the DC-link, and  $I_{in}$  and  $I_{out}$  represent the input and output currents, respectively. This equation indicates that any imbalance between incoming and outgoing currents leads to voltage variation, highlighting the importance of proper control.

## 6. POWER ELECTRONICS INTERFACE

In hybrid renewable energy systems, power electronic converters play a crucial role in enabling efficient energy conversion and controlled power flow between different components. These converters ensure compatibility between variable renewable sources and the fixed requirements of the DC-link and grid.

### 6.1 DC–DC Converter Stage

Each energy source in the system is connected to the DC-link through an individual DC–DC converter. Since the output of both solar and wind subsystems varies with environmental conditions, direct connection to the DC bus is not feasible.

The DC–DC converters are responsible for maintaining a stable and regulated output voltage. In addition, they facilitate maximum power extraction by continuously adjusting the operating point of the sources.

The main functions of these converters include:

- Matching source output with DC-link voltage requirements
- Enabling maximum power point operation
- Providing controlled and smooth power transfer

The converter operation is governed by duty cycle control, which is continuously updated based on system conditions to ensure efficient performance.

### 6.2 Inverter Control Mechanism

A three-phase voltage source inverter is used to interface the DC system with the AC grid. The inverter converts the regulated DC voltage into a three-phase AC supply suitable for grid connection and local loads.

The operation of the inverter is based on switching techniques and feedback control mechanisms. Sinusoidal Pulse Width Modulation (SPWM) is commonly used to generate gating signals for the switching devices.

The control system of the inverter consists of:

- A voltage regulation loop to maintain output voltage stability
- A current control loop to regulate the injected current
- A modulation scheme to produce near-sinusoidal waveforms

These control actions ensure proper synchronization with the grid, regulate power exchange, and maintain stable operation even under varying load conditions.

## 7. CONTROL STRATEGY

The performance of the overall system largely depends on how effectively the control mechanisms are implemented. Proper coordination between different control loops is necessary to maintain stability and ensure efficient energy utilization.

### 7.1 DC-Link Voltage Regulation

The DC-link voltage must remain constant for proper inverter functioning. Any fluctuation in this voltage can affect the quality of power supplied to the grid.

To maintain stability, the actual DC voltage is continuously monitored and compared with a predefined reference value. The difference between these values is processed through a PI controller, which generates a corrective signal.

Based on this signal, the duty cycle of the DC–DC converters is adjusted to restore the DC-link voltage to its desired level. This closed-loop system enables quick response to disturbances.

### 7.2 Grid Synchronization Technique

For safe and efficient grid connection, the inverter output must be synchronized with the grid voltage. This includes matching frequency, phase angle, and magnitude.

A Phase-Locked Loop (PLL) is employed to achieve this synchronization. The PLL continuously tracks the grid voltage and extracts phase and frequency information.

By aligning the inverter output with these parameters, the system ensures smooth power transfer and avoids disturbances such as circulating currents or instability.

## 8. ARTIFICIAL INTELLIGENCE-BASED CONTROL

Traditional control methods often struggle with nonlinear behavior and unpredictable variations in renewable energy systems. To address these limitations, intelligent control techniques are introduced.

### ANN-Based Energy Management System

An Artificial Neural Network (ANN) is utilized as a supervisory controller for managing energy flow within the hybrid system. The ANN processes multiple inputs and determines optimal control actions in real time.

Typical inputs to the ANN include:

- Solar irradiance level
- Wind speed variations
- DC-link voltage
- Load demand

Based on these inputs, the ANN generates outputs such as:

- Distribution of power between different sources
- Control signals for switching devices
- Charging and discharging commands for the battery

This approach enables adaptive decision-making without requiring explicit mathematical models.

## 9. ENERGY MANAGEMENT STRATEGY

The system follows a structured priority-based energy management approach:

1. Solar energy is utilized as the primary source
2. Wind energy supports generation when solar output is insufficient
3. Excess energy is stored in the battery
4. Grid supply is used only when renewable sources are inadequate

This strategy ensures efficient utilization of renewable energy while minimizing dependence on the grid.

## 10. ADVANTAGES OF THE PROPOSED SYSTEM

The proposed hybrid system offers several benefits:

- Improved reliability through multi-source integration
- Simplified architecture using a common DC bus
- Enhanced adaptability with AI-based control
- Reduction in harmonic distortion
- Scalability for future expansion

## 11. CONCLUSION

In this work, a comprehensive theoretical framework for a grid-connected hybrid renewable energy system has been presented. The system combines solar and wind energy sources through a common DC-link configuration, enabling coordinated and efficient operation. By incorporating advanced control techniques along with artificial intelligence-based methods, the overall performance of the system is significantly improved.

The proposed approach effectively maintains DC-link stability, manages power flow between different sources, and ensures reliable power delivery to the grid. In addition, the integration of intelligent control enhances the system's ability to adapt to changing environmental and load conditions. These features make the proposed system a promising solution for modern power systems where renewable energy penetration is continuously increasing.

## 12. FUTURE WORK

Although the proposed system demonstrates strong theoretical performance, several extensions can be considered to further enhance its practical applicability.

Future developments may include implementing the system on real-time hardware platforms to validate its performance under actual operating conditions. The integration of advanced monitoring techniques, such as IoT-based systems, can provide better supervision and control of system parameters.

Further research can also explore the use of deep learning algorithms for predictive control and improved decision-making. In addition, incorporating electric vehicle charging infrastructure within the system can expand its functionality in smart grid environments. Finally, the development of advanced communication frameworks will support better coordination and control in distributed energy systems.

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