



Rule-Based Energy Management of a Solar–Wind–Battery Hybrid Microgrid Using MATLAB Simulink

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ABSTRACT :

This study proposes an advanced power management strategy for hybrid microgrids integrating renewable energy sources, particularly solar photovoltaic (PV) and wind power, under both islanded and grid-connected operating conditions. Maintaining voltage stability and ensuring efficient power sharing among distributed generators (DGs), energy storage systems (ESS), and the utility grid are key challenges in such systems. Conventional droop control, although widely used for decentralized power sharing, often exhibits limitations in voltage regulation. To overcome these challenges, a voltage-shifting droop control strategy is introduced to dynamically adjust droop characteristics and compensate for voltage deviations, thereby improving power distribution and system stability. During islanded operation, a distributed secondary control mechanism further enhances voltage regulation and current sharing by adaptively tuning droop coefficients. The proposed control framework is evaluated through MATLAB/Simulink simulations to assess its effectiveness under varying operating conditions. Furthermore, the study investigates the impact of changing weather conditions on PV power generation and incorporates a maximum power point tracking (MPPT) algorithm to optimize solar energy extraction and support efficient power management. The simulation results demonstrate significant improvements in voltage regulation, power-sharing accuracy, and overall microgrid stability, highlighting the potential of the proposed approach for reliable and efficient renewable energy integration.

Keywords: MATLAB, MPPT controller, Microgrid, Renewable energy, Energy storage systems.

Introduction

Non-renewable energy sources, such as coal, oil, and natural gas, have traditionally played a major role in electricity generation [1]. However, their environmental impacts and contribution to greenhouse gas emissions have accelerated the transition toward renewable energy technologies. Distributed generation (DG) systems based on renewable energy sources, particularly solar photovoltaic (PV) and wind energy, provide a sustainable alternative for meeting growing electricity demands. Nevertheless, integrating these intermittent energy sources into the alternating current (AC) utility grid presents several technical challenges related to voltage stability, power quality, and power management [2-3]. Hybrid microgrids provide an effective framework for integrating distributed generators, energy storage systems (ESS), and electrical loads while supporting both islanded and grid-connected operating modes. Their hierarchical control architecture typically comprises primary control for decentralized power sharing and secondary control for restoring voltage deviations and improving current-sharing accuracy. Among the available primary control techniques, droop control is widely adopted because of its simplicity, reliability, and ability to facilitate power sharing among parallel-connected sources without requiring extensive communication infrastructure [4].

Despite these advantages, hybrid microgrids encounter several operational challenges, including bus voltage deviations, circulating currents, unequal load distribution, and fluctuations in renewable power generation. Circulating currents may arise from mismatches in the output voltages and impedances of parallel-connected distributed generators, potentially reducing system efficiency and compromising power quality [5]. The virtual resistance method offers an effective approach to mitigating these currents by modifying the apparent output impedance of the converters without introducing the continuous power dissipation associated with physical resistors [6]. However, conventional droop control involves a fundamental trade-off between voltage regulation and accurate power sharing. Smaller droop coefficients generally improve voltage regulation but may reduce the accuracy of proportional load sharing, whereas larger coefficients can enhance power-sharing performance at the expense of voltage stability. Secondary control strategies are therefore essential for compensating for these limitations [7-9]. Depending on the system architecture and communication requirements, secondary control can be implemented using centralized, decentralized, or distributed approaches to improve voltage regulation and power balance. During islanded operation, energy storage systems compensate for the mismatch between renewable generation and load demand, thereby maintaining supply reliability. In grid-connected operation, the utility grid exchanges power with the microgrid to accommodate variations in generation and consumption. Although droop-based control can facilitate coordinated power exchange with the utility grid, challenges such as frequency deviations, communication delays, and variations in operating conditions remain important considerations in achieving stable, reliable, and efficient hybrid microgrid operation.

2. Problem Statement

This section highlights the major challenges associated with developing an effective power management strategy for hybrid microgrids, particularly in maintaining the balance between power generation and load demand while ensuring stable bus voltage. One of the primary challenges is achieving accurate and proportional current sharing among multiple distributed generators and energy storage systems connected to a common bus. Although conventional droop control is widely employed because of its simplicity and decentralized operation, it presents inherent limitations in voltage regulation and power-sharing accuracy. The selection of appropriate droop coefficients significantly influences microgrid performance, as higher coefficients can improve current-sharing accuracy but may lead to considerable voltage deviations, whereas lower coefficients generally support better voltage regulation but may compromise proportional power sharing. These limitations become more pronounced under dynamic operating conditions, including sudden load variations and fluctuations in renewable energy generation. Therefore, an improved control strategy incorporating coordinated primary and secondary control mechanisms is required to enhance voltage stability, minimize current-sharing errors, and ensure reliable power distribution among distributed generation units, energy storage systems, and the utility grid. The proposed approach aims to overcome the limitations of conventional droop control by improving voltage regulation and current-sharing performance under both steady-state and transient operating conditions.

3. Objective of Proposed Research Work

The primary objective of this research work is to develop and analyze a hybrid microgrid model integrating solar photovoltaic (PV), wind energy, and battery energy storage systems to ensure reliable, efficient, and stable power management. Maximum Power Point Tracking (MPPT) algorithms will be implemented to maximize renewable energy extraction under varying environmental conditions. An effective energy management strategy will be designed to balance power generation and load demand while maintaining DC-link voltage and ensuring AC-side voltage and frequency stability. The performance of the proposed system will be evaluated under varying solar irradiance, wind speed, and load conditions to assess its dynamic response, power-sharing capability, and operational reliability. Furthermore, a voltage-shifting droop control strategy will be developed to minimize voltage deviations, improve proportional current sharing among distributed generation units, and enhance overall microgrid stability under varying load conditions in both islanded and grid-connected operating modes.

4. Research Methodology

Hybrid Microgrid Configuration: The proposed microgrid integrates photovoltaic (PV) and wind turbine systems, with DC and AC power converters for energy conversion. PV is connected to the DC bus through a DC-DC boost converter, and wind power is rectified to DC using an uncontrolled rectifier. Both systems incorporate MPPT and droop control for efficient power management.

Energy Storage and Power Flow: The battery storage unit is connected to the DC bus through a bidirectional DC-DC converter, enhancing system stability. The grid is connected via a bidirectional DC-AC converter, allowing bidirectional power flow between the microgrid and the main AC grid, managed by droop control for voltage regulation and power-sharing.

System Stability and Control: The PV and wind turbine units can operate together, with the wind turbine supplying power when the PV system is inactive (e.g., at night). The setup ensures stable power distribution through droop control for managing power flow and maintaining voltage regulation.

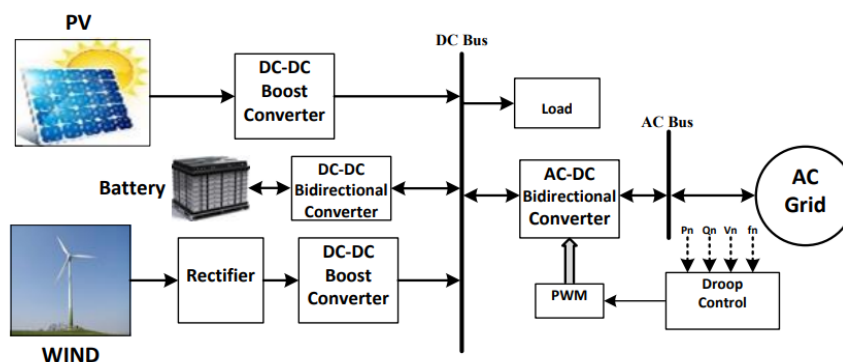


Fig. 1 Block Diagram of Hybrid Microgrid

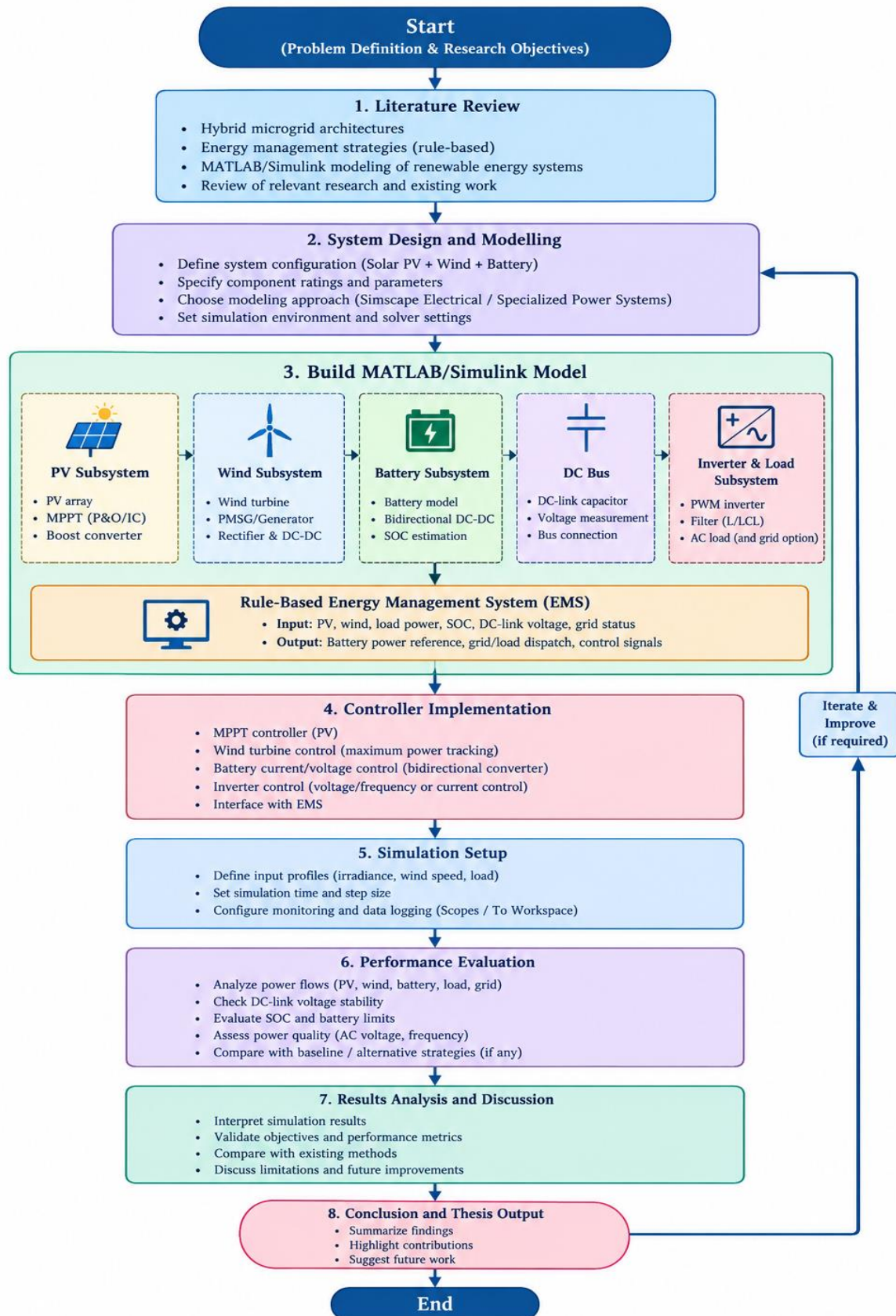


Fig. 2 Flow chart of proposed research work

Parameters of the proposed hybrid microgrid

Photovoltaic array (PV) system (DG 1) Power output 10.0 KW

Wind generation system (DG 2) Power output 8.50 KW
 Energy Storage (ES) system power output 5.0 KW
 power of AC Grid Maximum output 10.0 KW
 Load 20.0 KW
 Voltage of Rated DC bus 400.0 V

5. Operation Mode of Power Management

A hybrid microgrid operates in three distinct modes, as outlined in Tables 1 and 2. The mode switching occurs based on variations in the bus voltage range. In Mode I, the grid helps maintain the stability of the hybrid microgrid. During this mode, the distributed generation (DG) unit operates in maximum power point tracking (MPPT) mode, while the grid operates in droop mode. The DG unit typically functions in MPPT mode to capture the maximum energy possible from solar and wind sources. When sufficient energy is generated from both, the DG output increases, causing an increase in the bus voltage. To maintain a stable bus voltage, the DG unit switches to Mode II. In Mode III, the energy storage battery stabilizes the system by operating in droop mode during discharging conditions.

6. Result and Discussion

6.1. Experimental Analysis

Comparison of Series and Parallel Connected PV Modules under Varying Radiation and Temperature Conditions. Solar PV Panel Integrated with a DC-DC Converter and MPPT Technique. The Observe (P&O) algorithm and Perturb is implemented within the “PIC microcontroller” for tracking the maximum power point efficiently.

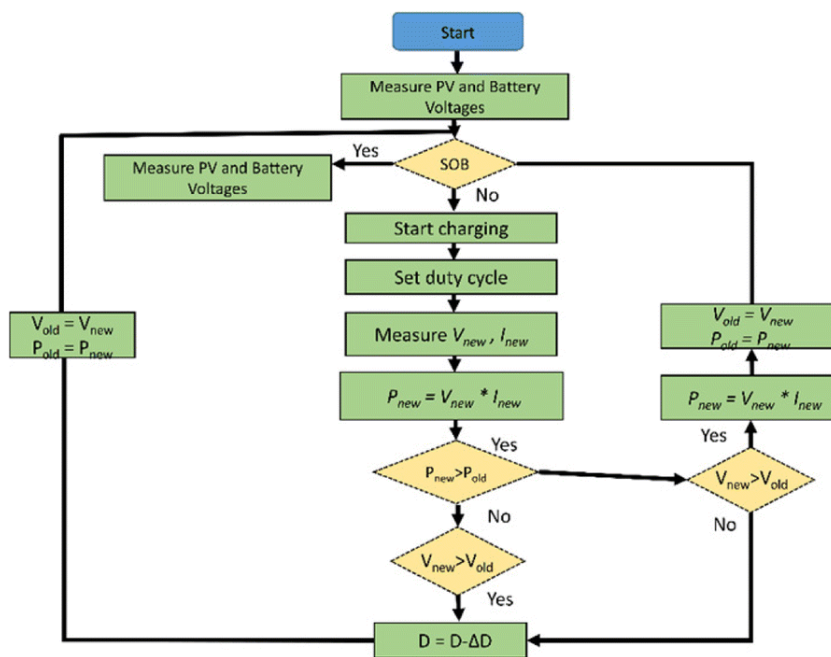


Fig. 3 Design of a P-&O algorithm based MPPT charge controller

6.2. I-V Characteristic Curve

Short-Circuit Current (I_{sc}): The maximum current at zero voltage, referred to as the short-circuit current (I_{sc}), is determined by connecting the terminals of the PV module directly in a short circuit. Open-Circuit Voltage (V_{oc}): The maximum voltage at zero current is termed the open-circuit voltage (V_{oc}). The I-V curve represents the relationship between the current and voltage output of the PV module under different conditions as depicted in Figures 5(a) and 5(b).

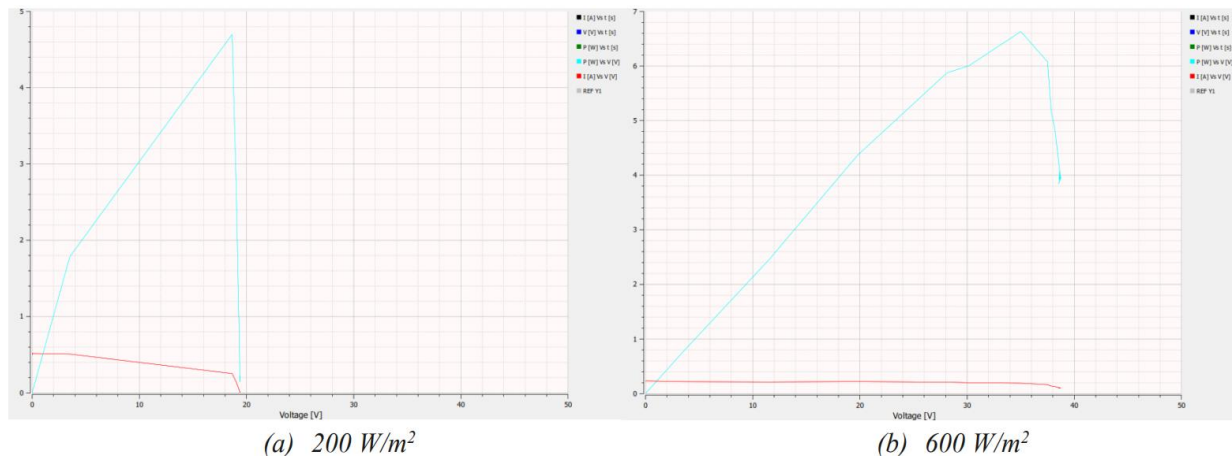


Fig.5 P-V& I-V curve for Two series connected PV module

Table 1. Comparison of Real-Time Parameters at Varying Irradiance Levels for Series Modules

Parameter	200 W/m ²	400 W/m ²	600 W/m ²	800 W/m ²	1000 W/m ²
V _{oc} [V]	36.77	36.96	38.72	38.62	38.48
I _{sc} [A]	0.18	0.18	0.23	0.32	0.23
V _m [V]	36.72	36.91	37.91	38.09	32.82
I _m [A]	0.10	0.10	0.19	0.20	0.21
P _m [W]	3.66	3.68	6.63	6.54	5.81
Fill Factor [%]	0.55	0.56	0.74	0.73	0.66
Efficiency [%]	4.14	6.60	8.53	12.09	16.90

Table 2: Results at Different Irradiance Levels and a Fixed Temperature of 35°C for Series and Parallel PV Modules

Temp. (°C)	Series Module Voltage (V)	Series Module Current (A)	Series Module Power (W)	Parallel Module Voltage (V)	Parallel Module Current (A)	Parallel Module Power (W)
32	39.60	0.11	4.33	19.78	0.01	0.23
34	39.40	0.10	4.23	19.48	0.01	0.19
36	39.40	0.11	4.23	19.48	0.01	0.15
37	38.92	0.10	3.91	19.42	0.01	0.17
38	38.92	0.11	3.91	19.42	0.01	0.17

The control strategies were tested using MATLAB simulations and experimental analysis. The simulation model included a hybrid microgrid with PV, wind, energy storage, and an AC grid. The results showed that the proposed voltage-shifting-based droop control strategy effectively improved voltage regulation while maintaining current sharing accuracy. The secondary control technique further enhanced performance under dynamic load conditions. The experimental analysis included testing PV modules in series and parallel configurations under varying temperatures and radiation levels. The results demonstrated how the system managed power between the PV, battery, and load under different irradiance conditions. In grid-connected systems, surplus power was fed back to the grid when the irradiation was sufficient, while the load drew power from the grid and PV when irradiation was insufficient.

7. Conclusion

The hybrid microgrid system demonstrated effective operation in both islanded and grid-connected modes by integrating solar (PV), wind, battery storage, and the AC grid. The system adapts to various operational modes to maintain power balance, using droop control for proportional load distribution among parallel converters. To address voltage drop with increasing load current, a voltage-shifting-based droop control strategy is employed for better voltage regulation. Secondary control is introduced, including compensating controllers and an average voltage controller to correct primary control voltage output. Additionally, the combination of current controllers and droop coefficient controllers ensures accurate current sharing between converters. Simulation results confirm the effectiveness of these strategies, improving system stability under varying load conditions. Experimental analysis of power management under different load conditions demonstrates that in islanded mode, the PV system powers the battery and

load, while in grid-connected mode, excess power is fed into the grid. Future work focuses on advancing power management for hybrid microgrids primarily powered by renewable energy, aiming to maintain power balance and stable bus voltage across different operational modes. A new algorithm is introduced where bus voltage is the primary control parameter to manage power among Distributed Generation, Energy Storage, and the utility grid. A voltage-shifting-based primary droop control technique is developed to overcome voltage regulation challenges, ensuring both power-sharing and voltage stability. The secondary control system enables accurate current sharing and voltage restoration during transient load changes. By integrating average current controllers with droop coefficient controllers, this approach improves current sharing accuracy and voltage regulation under dynamic load conditions. Experimental analysis of PV modules under varying conditions shows significant power and current increases in series-connected modules with higher irradiance. In standalone systems, when PV power is insufficient, the battery supplies the required power, and grid-connected systems allow excess power to be fed into the grid.

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