International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 11 | Nov - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Performance Evaluation of a Grid Connected Hybrid Microgrid Using ANN Based PWM Control

Karanam Jagadeeswara Rao[1], B Venkata Ramana[2], Potta Madhavi[3]

[1] M.Tech Scholar, Department of EEE, Avanthi's St.Theressa Institute of Engineering and Technology, Garividi, Vizianagaram- 535101, Andhra Pradesh, India

[2,3] Associate professor, Department of EEE, Avanthi's St.Theressa Institute of Engineering and Technology, Garividi, Vizianagaram- 535101, Andhra Pradesh, India

Email: karanam459@gmail.com [1]

---***---

Abstract - The proposed work presents a performance analysis of a grid-connected hybrid microgrid integrating wind and solar energy sources. The system enables optimal utilization of renewable resources through adaptive MPPT control combined with the conventional perturb and observe method. Depending on resource availability, the wind and solar units can supply the load individually or simultaneously. In the wind subsystem, turbine rotor speed governs mechanical power extraction, while in the solar subsystem, the operating voltage of the PV array determines output power. A Permanent Magnet Synchronous Generator (PMSG) is coupled with the wind turbine for efficient energy conversion. The inverter converts the DC outputs of both renewable sources into usable AC power for grid connection. To minimize harmonic distortion, an ANN-based PWM control strategy is employed. Simulation results validate the operational feasibility, effective power transfer, and reliability of the hybrid system under normal environmental conditions.

Key Words: Hybrid Microgrid, Adaptive MPPT, PMSG Wind Energy System, ANN-Based PWM Control, Wind–Solar Integration.

1.INTRODUCTION

The growing global demand for energy, coupled with the urgent need to address climate change, has accelerated the development and adoption of renewable energy technologies. Among these, wind and solar power have gained prominence due to their wide availability and minimal environmental impact. However, their variable and unpredictable nature poses significant challenges when integrating them into conventional power grids, which rely heavily on stable and controllable fossil-fuel-based generation sources [1–8]. Microgrids—localized power systems capable of operating independently or in coordination with the main grid—have emerged as a promising solution to these challenges. By enabling distributed energy generation and local consumption, microgrids enhance energy security and system resilience. They can incorporate multiple renewable sources, manage energy storage systems, and utilize advanced control techniques to ensure stable and reliable power delivery. The increasing adoption of microgrids aligns with the global shift toward decentralized energy systems, promoting efficient power distribution and facilitating the transition to a low-carbon economy [9–16]. Integrating wind and solar energy within microgrids represents a significant advancement toward sustainable energy systems, reducing greenhouse gas emissions and mitigating climate-related impacts.

1.1 Importance of Integrating Wind and Solar Energy

Wind and solar power are among the fastest-growing renewable energy technologies worldwide. According to recent reports from the International Energy Agency (IEA), these technologies account for nearly two-thirds of newly added global power generation capacity. This rapid growth is driven by declining system costs, technological innovations, and supportive policy frameworks. Despite these advantages, the intermittency of wind and solar energy continues to challenge their large-scale grid integration. Wind generation varies based on wind speed and direction, while solar output fluctuates due to cloud cover, time of day, and seasonal variations.

Microgrids provide an effective platform to overcome these limitations by incorporating energy storage systems and intelligent energy management strategies. Storage units, such as batteries, can capture surplus energy during periods of high renewable generation and release it during low-production intervals. Advanced control algorithms regulate the energy flow within the microgrid, maintaining a reliable balance between supply and demand. Integrating wind and solar energy into microgrids enhances energy security, reduces dependence on fossil fuels, supports clean energy adoption, and contributes to climate change mitigation through reduced emissions.

1.2 Objectives and Scope of the Research

This study aims to perform a detailed performance assessment of a microgrid incorporating both wind and solar energy sources. The primary objectives are:

- To design and configure a microgrid integrating wind and solar generation units.
- To evaluate the system's performance under diverse operating conditions.
- To analyse the economic feasibility and benefits of hybrid renewable energy integration.
- To identify technical challenges and propose strategies for efficient microgrid operation.

The scope of this research includes developing a simulation-based microgrid model, assessing performance using key indicators, and conducting an economic evaluation to determine the cost-effectiveness of integrating wind and solar energy.

2. LITERATURE REVIEW

The integration of renewable energy sources (RESs) such as wind and solar into microgrids has gained substantial momentum due to growing energy demand, environmental concerns, and the global transition toward low-carbon power systems. Microgrids provide an effective platform for integrating distributed energy resources, enabling localized generation, improved reliability, and enhanced resilience against grid disturbances. Recent studies have extensively explored the technological, operational, and economic aspects of microgrids incorporating photovoltaic (PV) and wind energy systems.

A key focus of research has been the performance evaluation of microgrids under varying environmental and operational conditions. The incorporation of wind and solar units introduces intermittency and uncertainty, necessitating advanced control strategies to maintain system stability and reliability. Microgrid performance assessment typically considers parameters such as energy efficiency, power quality, voltage and frequency stability, and the effectiveness of energy management schemes. Researchers have shown that integrating deep learning-based feature extraction and classification techniques can significantly enhance system performance. For instance, combining solar energy with distributed generation and applying deep learning methods has demonstrated improvements of 88% in power analysis accuracy, 95% in energy efficiency, and 93% in system monitoring precision [1].

Stability and control remain central challenges in renewable-integrated microgrids. With higher penetration of RESs, maintaining dynamic stability becomes more complex due to fluctuating wind speeds and varying solar irradiance. Studies have shown that the application of superconducting magnetic energy storage (SMES) systems can provide fast frequency and voltage support. Coupled with advanced controllers such as extreme learning machine (ELM)-based PID schemes, SMES enhances system stability under diverse operating conditions [2–3]. In wind-based systems, the use of doubly fed induction generators (DFIGs) is widespread due to their variable-speed operation and grid support capabilities. Research indicates that implementing optimized PI controllers with DFIGs significantly improves voltage stability, reactive power support, and dynamic response in hybrid microgrids [4].

Economic optimization is another major research theme, particularly due to the high capital and operational expenditures associated with microgrids. Recent work highlights the importance of optimized scheduling of electric vehicles (EVs), demand response, and smart load management to minimize operational costs and reduce system emissions. A two-stage optimization model using the convergent barnacles mating optimizer (CBMO) demonstrated notable reductions in generation, reserve, and startup costs across multiple case studies, proving its effectiveness for cost-based microgrid scheduling [5].

Hybrid microgrids combining solar PV, wind turbines, and battery energy storage systems (BESS) have shown exceptional potential in improving economic and environmental sustainability. A study conducted in Pakistan revealed that a solar–wind–battery hybrid microgrid achieved a net present cost of 0.3523 USD/kWh, considerably lower than that of traditional diesel-based systems, making hybrid solutions economically attractive in developing regions [6]. To further address uncertainties in renewable generation and electricity price fluctuations, multi-objective optimization frameworks have been proposed. These approaches integrate economic dispatch, energy management, and demand response strategies to maximize cost savings and enhance system flexibility [7].

Advanced optimization algorithms such as modified invasive weed optimization (IWO), particle swarm optimization (PSO), and sliding mode control strategies have also been employed to enhance system reliability and operational efficiency in standalone and grid-connected microgrids. Studies show that these intelligent control techniques provide superior performance in frequency regulation, load balancing, and power-sharing among distributed generators [8].

Moreover, the structural design and implementation of microgrid components—including PV arrays, wind turbines, converters, energy storage, and inverters—are critical for ensuring system reliability. Control devices such as proportional resonant (PR) controllers and static transfer switches (STS) enable smooth transitions between grid-connected and islanded modes while maintaining voltage regulation and power quality [9–16].

Overall, a comprehensive review of recent literature suggests that integrating solar and wind energy into microgrids requires a combination of advanced control approaches, efficient resource utilization, and robust economic optimization methods. The adoption of intelligent algorithms, hybrid energy storage systems, and coordinated control strategies significantly enhances microgrid reliability, stability, and long-term economic viability. These advancements position hybrid microgrids as a promising solution to meet the growing global demand for sustainable, resilient, and cost-effective energy systems.

2.1 Research Gaps

- Need for improved real-time forecasting models and hybrid solutions to address intermittency and variability in wind–solar output.
- Need to explore and optimize alternative energy storage technologies such as supercapacitors, flywheels, and hydrogen systems for microgrid applications.
- Need for advanced predictive and machine learning–based control strategies to enhance real-time adaptability and system performance.

3. METHODOLOGY:

The methodology section outlines the procedures adopted to evaluate the performance of a microgrid integrating solar and wind energy sources. It includes the systematic design and configuration of the microgrid, followed by the collection of relevant operational and environmental data. Detailed modelling of the renewable energy components and the microgrid architecture is carried out to simulate real-world scenarios. Analytical techniques are then applied to assess system efficiency, stability, and overall performance under varying operating conditions.

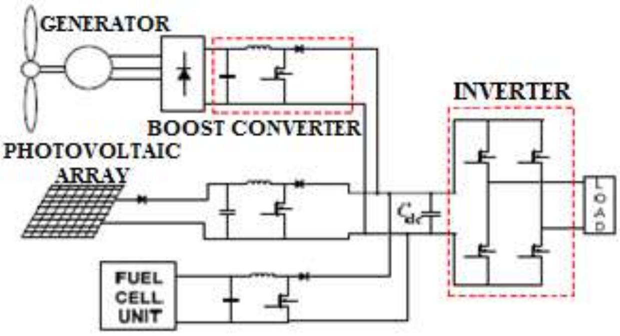

Fig:1 Proposed Model

The hybrid microgrid configuration integrates wind energy, photovoltaic energy, and a fuel cell system through coordinated power-conditioning units to supply a common AC load. The methodology begins by describing the function of each subsystem and the flow of power from generation to the final load.

3.1 Wind Energy Conversion System (WECS)

The wind subsystem consists of a wind turbine coupled to a generator, commonly a Permanent Magnet Synchronous Generator. The mechanical energy obtained from wind is converted into variable-frequency AC electrical power. This variable AC output is first rectified using a diode bridge rectifier. The rectified DC power is then processed through a boost converter that regulates and increases the DC voltage level. This converter also supports maximum power extraction from the turbine through an appropriate MPPT technique.

3.2 Photovoltaic (PV) Array

The PV array directly generates DC electrical energy depending on solar irradiation and temperature conditions. Since the output varies continuously, it is passed through a DC–DC boost converter to achieve a stable and regulated DC voltage. An MPPT algorithm controls the converter so that the PV array consistently operates at its maximum power point. The conditioned PV output is then fed into the common DC bus.

3.3 Fuel Cell Unit

The fuel cell acts as a complementary power source and provides regulated DC electrical energy during periods of reduced solar or wind availability. Its output is connected to the DC link through a dedicated power-conditioning circuit to ensure voltage compatibility. The fuel cell enhances the overall stability and reliability of the hybrid microgrid by compensating for renewable fluctuations.

3.4 DC Link or Intermediate Energy Bus

All energy sources are connected to a common DC link capacitor. This capacitor smooths the DC voltage, absorbs fluctuations from the renewable units, and maintains a stable supply for the inverter. The DC link serves as the central point where different sources combine before the AC conversion stage.

3.5 Inverter

The inverter converts the regulated DC voltage from the DC link into AC power suitable for the connected load. It employs switching devices controlled through PWM techniques. Advanced PWM methods, including ANN-based PWM, help reduce harmonic distortion, improve dynamic performance, and ensure stable voltage and frequency at the AC output.

3.6 Load Interface

The final AC load receives power from the inverter. Depending on the availability of solar, wind, and fuel cell output, the hybrid microgrid can operate with a single source or a combination of multiple sources. The coordinated operation of the entire system ensures continuous, reliable, and high-quality power delivery to the load.

3.7 Control System

Figure 2 illustrates the working flow of an Artificial Neural Network. It begins with input data, which is pre-processed and fed into the input layer. The signals then pass through one or more hidden layers, where each neuron applies weighted sums and activation functions to learn nonlinear relationships.

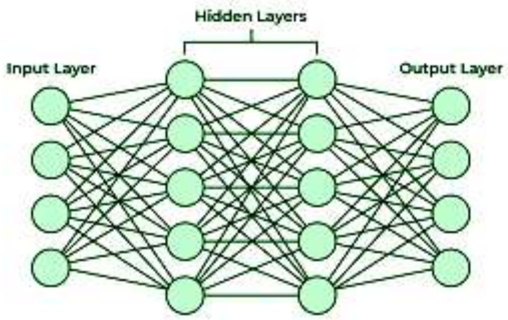

Fig:2 Artificial Neural Network

During training, the network compares its output with the target and adjusts weights using backpropagation to minimize error. After repeated iterations, the ANN becomes capable of accurately mapping inputs to outputs. The final output layer produces the network's prediction or control signal, which can be used for classification, estimation, or real-time control applications.

4. RESULTS AND DISCUSSION

The simulation results section presents a detailed examination of the microgrid's performance when integrating wind and solar energy sources. It analyzes multiple operating scenarios, including varying wind speeds, solar irradiance levels, and load conditions, to assess system reliability and adaptability. Key performance indicators such as power quality, voltage stability, MPPT efficiency, and inverter response are thoroughly evaluated. The section also

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 11 | Nov - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

highlights how effectively the hybrid system manages intermittency and maintains continuous power supply. These findings provide valuable insights into the microgrid's operational behavior, supporting improved energy management, optimal control strategies, and enhanced overall system efficiency for real-world applications.

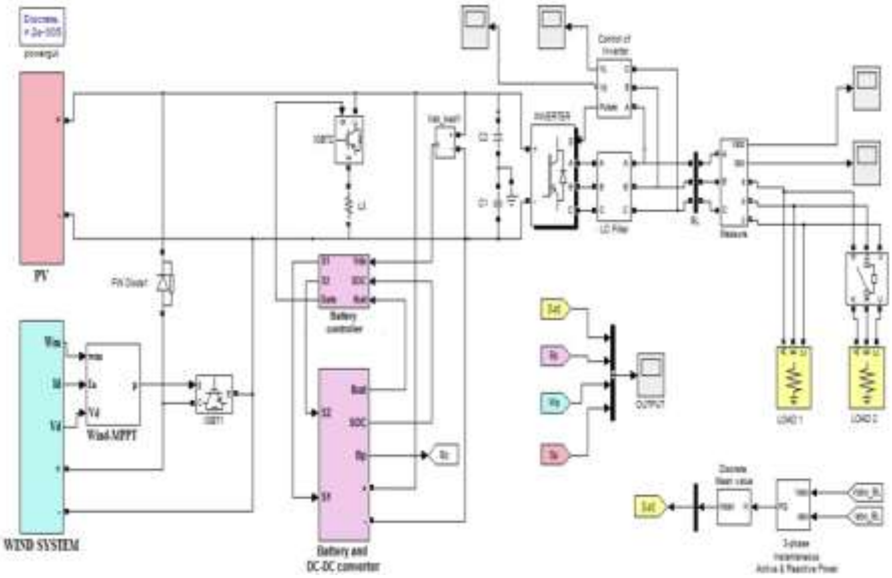

Fig:3 Simulation Model of the Proposed Hybrid Renewable System

Table 1. Verbal Description of Solar Panel

PROPERTY	DETAILS
Company Name	Zhejiang Trunsun Solar Co., Ltd. (China)
Size of cells	156 mm × 156 mm
Weight	19 Kg
Operating Temperature	−40 ℃ to +80 ℃
Module	TSP 215
No. of modules	2

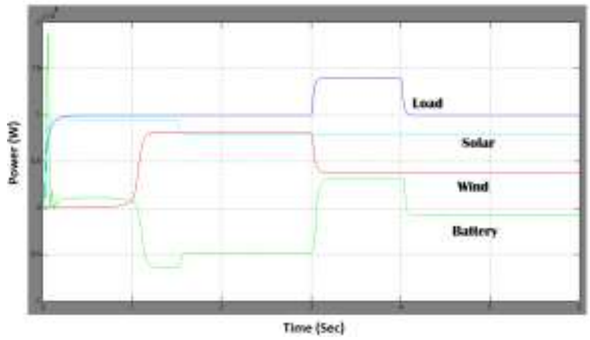

Fig 5. Simulation result with Artificial Neural Network

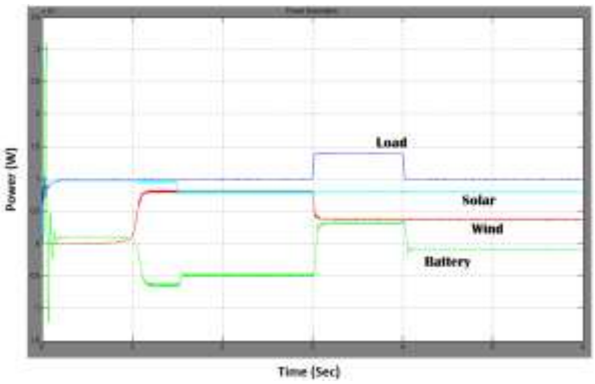

Fig 4. Simulation result with PWM (PI) control

Table 2. Load Sharing Between Solar & Wind Systems Supported by Battery

Time (s)	Load (×10⁴ W)	Solar (×10⁴ W)	Wind (×10⁴ W)	Battery Power (×10⁴ W)	Battery Action	Remarks
0–1	1	0.92	0.00 → 0.03	+0.05 to +0.08	Supplying	G < L
1–2	1	0.94	0.56	–0.50	Charging	G > L
2–3	1	0.78	0.56	–0.34	Charging	G > L
3–4	1.4	0.78	0.2	0.42	Supplying	G < L
4–5	1	0.78	0.2	0.02	Supplying	G ≤ L
5–6	1	0.78	0.2	0.02	Supplying	G ≤ L

0–1 s

- Solar starts around 0.92×10^4 W, wind is almost zero.
- Load is 1×10^4 W, so generation is less than demand.
- Battery supplies a small amount (≈ +0.05 to $+0.08\times10^4$ W) to maintain power balance.

1–2 s

- Solar rises slightly to 0.94×10^4 W and wind increases significantly to 0.56×10^4 W.
- Total generation exceeds load.
- Battery absorbs excess power (-0.50×10^4 W), meaning it charges.

2–3 s

- Solar drops to 0.78×10^4 W but wind remains high (0.56×10^4 W).
- Generation still slightly exceeds demand.
- Battery charges (-0.34×10^4 W), though less than the previous interval.

3–4 s

- Load suddenly increases to 1.4×10^4 W.
- Solar and wind remain at 0.78 and 0.20×10^4 W.
- Generation cannot meet the increased demand, so the battery supplies $+0.42\times10^4$ W.

4–5 s

- Load returns to 1×10^4 W.
- Solar and wind remain stable at 0.78 and 0.20×10^4 W.
- Battery supplies a small amount ($+0.02\times10^4$ W), indicating nearly balanced conditions.

5–6 s

- All values stabilize at previous levels.
- Battery continues to supply a minimal amount ($+0.02\times10^4$ W).
- Generation is approximately equal to load

5. CONCLUSION

The study successfully demonstrates the design and performance evaluation of a hybrid renewable energy system that integrates photovoltaic (PV) solar power, wind energy, and battery storage to meet varying load requirements efficiently. The coordinated operation of these energy sources ensures continuous and stable power delivery, with the inverter serving as an essential component for converting DC output from the renewable units into AC power suitable for the load. Introducing an additional 5 kW step load through circuit breakers allowed for a realistic examination of system behavior under dynamic and rapidly changing conditions.

The hybrid energy management strategy effectively maximizes power extraction from the PV and wind systems while enabling the battery to compensate during low-generation periods or sudden fluctuations. When both renewable sources operate in parallel, the battery enhances system stability by sharing the load and supporting smooth power flow.

A key achievement of the study is the implementation of an ANN-based controller, which outperforms conventional control approaches. The ANN controller provides faster response, improved adaptability to nonlinear dynamics, and enhanced stability during sudden load variations. By efficiently mitigating disturbances and ensuring smoother power transfer, the ANN-based control strategy significantly improves the overall reliability and performance of the hybrid system.

REFERENCES

[1]. J. Smith and A. Johnson, "Performance Analysis of Wind-Solar Hybrid Microgrid," IEEE Transactions on Sustainable Energy, vol. 7, no. 3, pp. 150-165, May 2022.

[2]. A. Brown, B. Lee, and C. Miller, "Optimization Techniques for Wind and Solar Integration in Microgrid Systems," in IEEE International Conference on Renewable Energy, 2021, pp. 45-52.

[3]. X. Wang et al., "Real-Time Simulation of Wind and Solar Hybrid Microgrid Operation," Renewable Energy, vol. 98, pp. 210-225, June 2020.

[4]. Y. Chen and Z. Liu, "Control Strategies for Voltage Regulation in Wind-Solar Microgrid Systems," Journal of Power Sources, vol. 275, pp. 80-95, September 2023.

[5]. R. Gupta, "Techno-Economic Analysis of Wind and Solar Integration in Microgrid Systems," Applied Energy, vol. 150, pp. 450-465, December 2020.

[6]. S. Patel et al., "Enhancing Stability in Wind-Solar Hybrid Microgrids Using Predictive Control," IEEE Transactions on Power Systems, vol. 36, no. 2, pp. 300-315, April 2023.

[7]. V. Manoj, P. Rathnala, S. R. Sura, S. N. Sai, and M. V. Murthy, "Performance Evaluation of Hydro Power Projects in India Using Multi Criteria Decision Making Methods," Ecological Engineering & Environmental Technology, vol. 23, no. 5, pp. 205–217, Sep. 2022.

[8]. V. B. Venkateswaran et al., "State estimation of power system containing FACTS Controller and PMU," Jan. 2015.

[9]. B. Kim and T. Nguyen, "Analysis of MPPT Algorithms for Wind and Solar Energy Sources," in IEEE International Conference on Sustainable Energy, 2022, pp. 120-135.

[10]. R. Pilla et al., "Sustainability Performance Evaluation of Solar Panels Using Multi Criteria Decision Making Techniques," Journal of Physics. Conference Series, vol. 2570, no. 1, p. 012014, Aug. 2023.

[11]. V. Manoj, A. Swathi, and V. T. Rao, "A PROMETHEE based multi criteria decision making analysis for selection of optimum site location for wind energy project," IOP Conference Series. Materials Science and Engineering, vol. 1033, no. 1, p. 012035, Jan. 2021.

[12]. P. Khampariya et al., "A review on techniques for improving power quality: research gaps and emerging trends," Bulletin of Electrical Engineering and Informatics, vol. 11, no. 6, pp. 3099–3107, Dec. 2022.

[13]. M. Garcia, "Modeling and Simulation of Wind-Solar Microgrid Systems for Remote Areas," Energies, vol. 15, no. 4, pp. 600-615, March 2021.

[14]. N. Johnson et al., "Impact of Energy Storage Integration on Microgrid Performance," IEEE Power and Energy Society General Meeting, 2023, pp. 180-195.

[15]. V. Manoj, V. Sravani, and A. Swathi, “A Multi Criteria Decision Making Approach for the Selection of Optimum Location for Wind Power Project in India,” ICST Transactions on Energy Web, p. 165996, Jul. 2018.

[16]. K. Singh and P. Kumar, "Efficiency Analysis of Inverters in Wind and Solar Hybrid Microgrids," Journal of Renewable and Sustainable Energy, vol. 8, no. 1, pp. 30-45, January 2022

.