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PERFORMANCE ANALYSIS OF A MICROGRID FOR THE INTEGRATION OF WIND AND SOLAR ENERGY SOURCES

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Abstract

This study introduces a versatile grid-connected hybrid generation system designed to optimize the utilization of renewable energy sources, specifically wind and solar power. The system is engineered to supply power from these sources individually or simultaneously, depending on their availability. For wind energy, a Permanent Magnet Synchronous Generator coupled with a wind turbine regulates the mechanical output. Meanwhile, solar power generation depends on the operating voltage of the solar cells. The DC outputs from these renewable sources are seamlessly converted into AC power by an inverter, making it usable for the connected load. The system operates under typical room temperatures for solar energy and standard wind speeds in plain areas for wind energy. Its efficiency and robustness are further enhanced by a fuzzy-based Pulse Width Modulation (PWM) system, which effectively reduces harmonic ripples, thereby ensuring the delivery of high-quality AC power to the load. Comprehensive simulation results validate the system's operational principles, demonstrating its feasibility and reliability. This hybrid setup not only maximizes the utilization of renewable energy sources but also ensures a consistent and high-quality power supply, highlighting its potential for sustainable energy integration in modern power grids.

Keywords: Hybrid Generation System, Renewable Energy Integration, Wind and Solar Power, Fuzzy-based PWM, Grid-connected Microgrid.

1. Introduction

The rising worldwide needs for energy, besides the urgent need to combat climate change, has encouraged tremendous improvements in renewable energy sources. Among the different renewable energy sources, wind and solar energy stand out owing to their availability and low environmental effect. However, the inherent intermittency and unpredictability of these sources provide obstacles for their integration into the conventional model power grid, which depends significantly on constant and unforeseeable energy supply from fossil fuels. Microgrids, defined as small grids that may run autonomously or in cooperation with the main energy system, have emerged as a viable answer to these difficulties. Microgrids promote energy security and resilience by permitting local energy production and usage of power. They can integrate multiple renewable energy sources, shepherd energy storage devices, and employ sophisticated management algorithms to maintain a steady and dependable power supply. The growth of microgrids correlates with the worldwide movement towards collaborative energy systems, supporting local producing electricity and consumption. This strategy not only promotes the dependability and efficacy of power supply but also facilitates the gradual shift to a low-carbon economy. This incorporation of wind and solar energy into microgrids offers a big step forward in developing sustainable energy systems, lowering greenhouse gas emissions, and mitigating climate change.

1.1. Importance of Integrating Wind and Solar Energy

Wind and solar energy are rapidly expanding forms of renewable energy on a global scale. Recent findings from the International Energy Agency (IEA) indicate that wind and solar photovoltaic (PV) systems accounted for almost two-thirds of the new capacity integrated into the global power grid in recent times. The surge in these technologies can be ascribed to their decreasing costs, technological advancements, and favorable policy environments. Nevertheless, the variability and intermittency of wind and solar energy pose significant challenges to their integration into the power grid. Wind power generation is influenced by factors such as wind speed and direction, which can vary considerably within short time periods. Similarly, solar energy generation is impacted by elements like cloud cover, time of day, and season, leading to fluctuations in energy production.

Microgrids offer a viable solution to these issues by incorporating energy storage systems and sophisticated control strategies. Energy storage systems, like batteries, can store excess energy generated during periods of high wind or solar activity and release it during periods of low generation. Advanced control techniques are able to manage the energy flow within the microgrid, sustaining a balance between energy supply and demand. The successful incorporation of wind and solar energy into microgrids can yield multiple benefits. It can enhance energy security by decreasing dependence on imported fossil fuels, promote the uptake of clean energy technologies, and fortify the establishment of resilient and flexible energy systems. Furthermore, this integration can aid in reducing greenhouse gas emissions and mitigating the impacts of climate change.

1.2. Objectives and Scope of the Research

This research aims to conduct a comprehensive performance analysis of a microgrid that integrates wind and solar energy sources. The specific objectives of the study are:

- To design and configure a microgrid with wind and solar energy sources.
- To evaluate the performance of the microgrid under various operating conditions.
- To analyse the economic feasibility and potential benefits of integrating wind and solar energy.
- To identify technical challenges and propose solutions for efficient microgrid operation.

The scope of this research includes the development of a simulation model for the microgrid, performance evaluation using key performance indicators, and an economic analysis to assess the cost-effectiveness of the integration.

2. Literature Review

The incorporation of renewable sources of energy that such as wind and solar power into microgrids has attracted considerable interest in recent times. This section provides an overview of the current body of research on microgrid technology, including the use of wind and solar energy, the evaluation of performance, and the economic factors to be taken into account. The assessment of a microgrid's performance, which incorporates wind and solar energy sources, entails the examination of many factors including energy efficiency, stability, the effectiveness, and control mechanisms. Microgrids, consisting of distributed renewable energy sources (RESs) such as photovoltaic (PV) systems and wind turbines, play a crucial role in improving the sustainability and dependability of power networks. For example, the combination of a solar energy system with distributed power generation has demonstrated substantial enhancements in power analysis (88%), energy efficiency (95%), and accuracy (93%) by employing deep learning algorithms for extracting and categorizing features [1]. The stability and control of microgrids (MGs), particularly with higher levels of renewable energy sources (RES) integration, are of utmost importance. Research has shown that the utilization of superconducting magnetic energy storage (SMES) and extreme learning machine (ELM) based PID controllers can successfully regulate the dynamic stability under different operating situations [2] [3]. Furthermore, the utilization of doubly fed induction generators (DFIG) in wind energy systems has demonstrated an enhancement in the stability of voltage under steady-state conditions. Control solutions such as PI controllers have been found to greatly improve the overall performance [4]. Cost optimization is a vital factor that may be achieved by efficiently scheduling electric vehicles (EVs) and adapting needs, resulting in reduced operational costs and emissions. The utilization of a two-stage model employing the convergent barnacles mating optimizer (CBMO) has proven to be successful in reducing generation, reserve, and starting expenses, resulting in significant cost reductions in various situations [5].

Integration of hybrid renewable sources of power, such as solar and wind with battery storage, additionally has been demonstrated to optimize technological, financial, and environmental benefits. For example, a hybrid system in Pakistan obtained a total net current cost of 0.3523/kWh, much cheaper than standard diesel systems [6]. Moreover, multi-objective modeling integrating economic issues and energy management has been presented to tackle the uncertainty in RES output and power pricing. Demand response software and solutions for storage can further cut costs and increase the economic feasibility of MGs [7]. Effective energy management measures, including the employment of the vehicle modified invasive weed optimized operation and sliding mode controllers, enable excellent system reliability, stability, and financially viable operation of freestanding MGs [8]. The design and execution of MGs, comprising part like solar PV panels, wind turbines, energy storage, and inverters, are crucial for ensuring appropriate voltage control and power quality. Proportional resonant (PR) controllers and static transfer switches (STS) play essential roles in providing seamless transitions between grid-connected and islanding modes [9] [10]. In the long run, the integration of wind and solar energy locations into microgrids requires a holistic strategy that incorporates sophisticated control methods, cost optimization, and effective utilization of resources to boost performance, stability, and economic feasibility. The adoption of novel algorithms and hybrid systems can considerably increase the efficiency and longevity of MGs, making them a viable solution for future energy demands.

2.1. Research Gaps and Challenges

- Intermittency and Variability: Need for more accurate and real-time forecasting models and the development of hybrid systems to manage fluctuations in wind and solar energy output.
- Energy Storage: Exploration of alternative energy storage technologies (e.g., supercapacitors, flywheels, hydrogen storage) and optimization of their integration and operation within microgrids.
- Control Strategies: Development and validation of innovative control approaches, such as predictive control and machine learning-based algorithms, to adapt to real-time changes and optimize overall system performance.
- Cost-Effectiveness: Creation of robust economic models that fully capture costs and benefits, including environmental and energy security externalities, and comparative assessments with traditional energy sources.
- Policy Support and Regulatory Frameworks: Identification of effective policy frameworks and regulatory reforms to support microgrid deployment, including incentives and addressing challenges related to energy markets, grid interoperability, and cybersecurity.

3. Methodology

The methodology section covers the methods and procedures used to undertake the performance study of a microgrid incorporating renewable energy from the sun and wind sources. This involves the design of the microgrid, data collecting, modelling, and analytic methodologies.

3.1. Microgrid Design

The microgrid under study consists of wind turbines, solar photovoltaic (PV) panels, energy storage systems (ESS), and a control system. The design considerations include the sizing of renewable energy sources, selection of storage technologies, and configuration of control strategies.

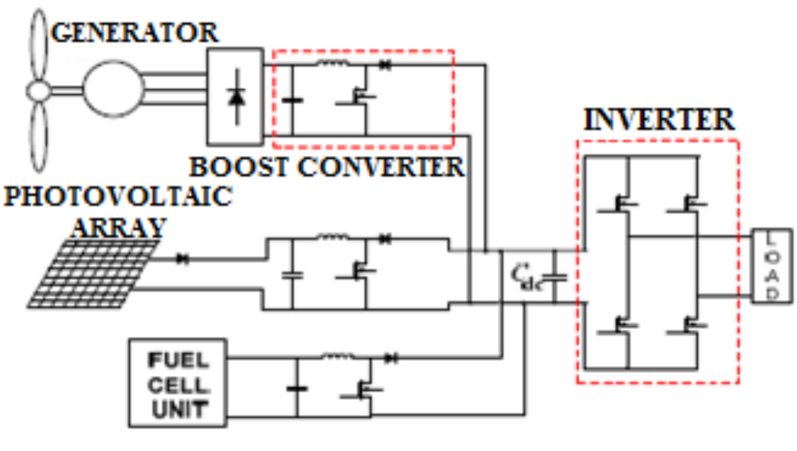

Figure 1. Model of Proposed Hybrid Circuit

3.1.1. Wind Turbines

- **Selection**: Wind turbines were selected based on the local wind resource assessment.
- **Placement**: The optimal placement of wind turbines was determined using geographic information systems (GIS) and wind resource maps.
- **Capacity**: The capacity of the wind turbines was chosen to match the expected wind energy potential and the energy demand of the microgrid.

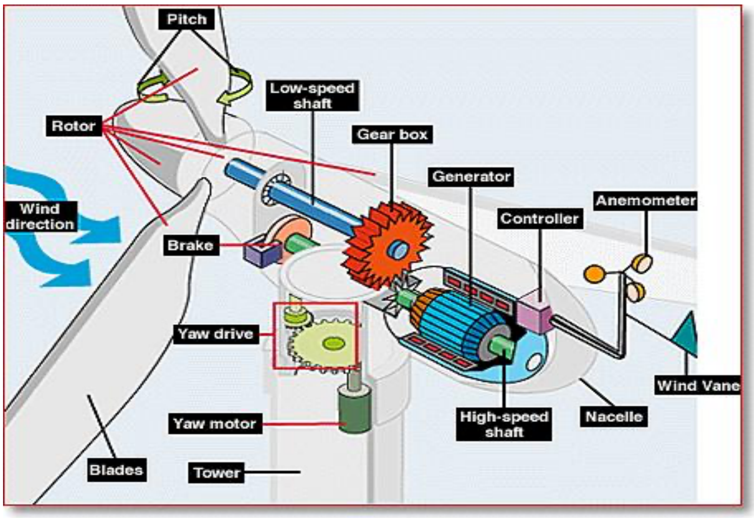

Figure 3. Basic construction of wind turbine

3.1.2. Solar PV Panels

- **Selection**: Solar PV panels were selected based on efficiency, cost, and local solar irradiance levels.
- **Placement**: The optimal placement of solar panels was determined using GIS and solar resource maps.
- **Capacity**: The capacity of the solar PV system was chosen to complement the wind energy generation and meet the energy demand.

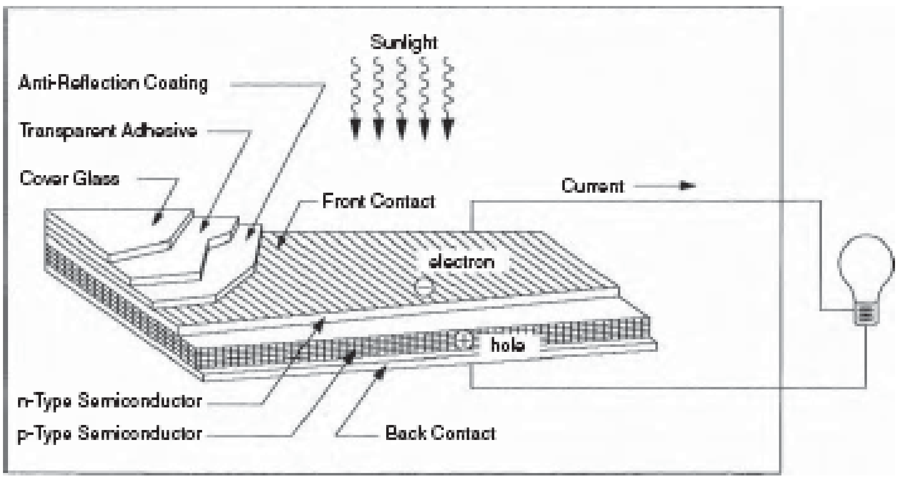

Figure 3. Basic construction of PV cell

3.1.3. Energy Storage Systems

- **Selection**: Energy storage technologies were selected based on capacity, cost, and efficiency. Lithium-ion batteries were chosen for their high energy density and efficiency.
- **Sizing**: The storage capacity was sized to store excess energy generated by the wind and solar systems and provide backup power during periods of low renewable generation.

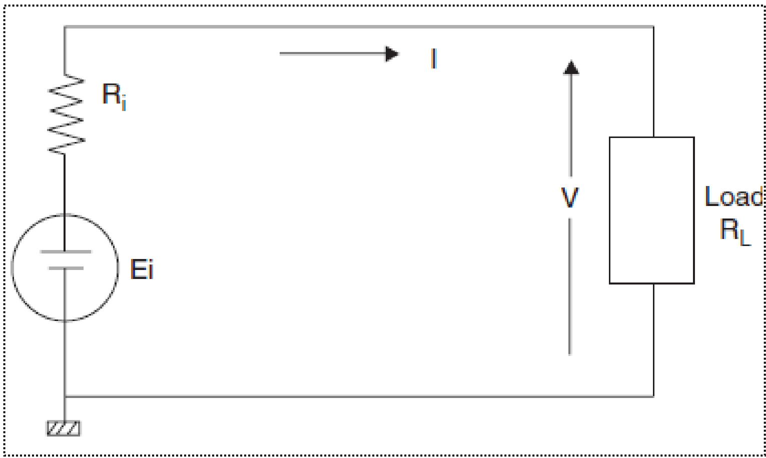

Figure 4. Equivalent electrical circuit of battery showing internal voltage and resistance

3.1.4. Control System

- **Configuration**: The control system was configured to manage the generation, storage, and distribution of energy within the microgrid.
- **Algorithms**: Advanced control algorithms were implemented to optimize energy usage, maintain system stability, and ensure a reliable power supply.

3.2. Fuzzy Logic Controller

The essential usage of Fuzzy control framework based on statistical principles is progressively effective. Fuzzy frameworks are successfully altered by adding new standards or additional features to boost execution. Fuzzy control may be utilized to strengthen current conventional frameworks for oversight by adding a layer of understanding to the on-hand control strategy. The Fuzzy logic controller includes of Fuzzy Inference System Editor. The reconstruction of sensitive exchanging circuit is developed in this FIS editorial manager. VCr and ICr are the contributing factors of the fuzzy controller. The yield of the controller is new worth. This Graphical User Interface contains of FIS Editor, Membership work Editor, Rule Editor, Rule Viewer and Surface Viewer.

3.2.1. Fuzzy Inference Diagram

The fuzzy logic controller the construction sketch unifies every part of the fuzzy inference process we have covered so far. It presents a thorough understanding of how fuzzy inference occurs, displaying the flow to data through the many steps of the process.

Fuzzy inference is the approach used to translate an input parameter to an output adopting fuzzy logic principles. This mapping gives the basis for making decisions or spotting trends. The method of fuzzy inference covers numerous significant considerations:

- **Membership Functions**: Define how input variables are categorized into fuzzy sets.
- **Fuzzy Logic Operators**: Apply logical operations (AND, OR, NOT) to combine fuzzy sets.
- **Fuzzy Rules**: IF-THEN statements that describe the relationships between inputs and outputs based on expert knowledge.

In summary, the fuzzy logic controller outline shows the complete fuzzy inference process, including how data is processed through membership functions, how fuzzy rules are applied, and how the resulting outputs are determined. This process helps in designing effective control strategies for various applications by translating imprecise or uncertain input information into actionable control decisions.

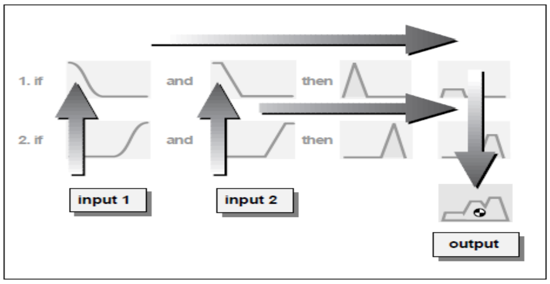

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Figure 5. Fuzzy Inference Diagram

Fuzzy logic inference devices have found efficient applications across diverse fields, including automated control, data classification, decision analysis, systems with experts, and vision for computers. Due to its multidisciplinary aspect, the topic of fuzzy inference systems is recognized by multiple separate names, demonstrating its enormous scope and diverse uses.

4. Simulation Results

The simulation results section provides a comprehensive overview of the performance analysis of the microgrid designed for integrating wind and solar energy sources. This section details the outcomes from various simulation scenarios, evaluates the effectiveness of the microgrid design, and discusses the implications of these results in the context of energy management and optimization.

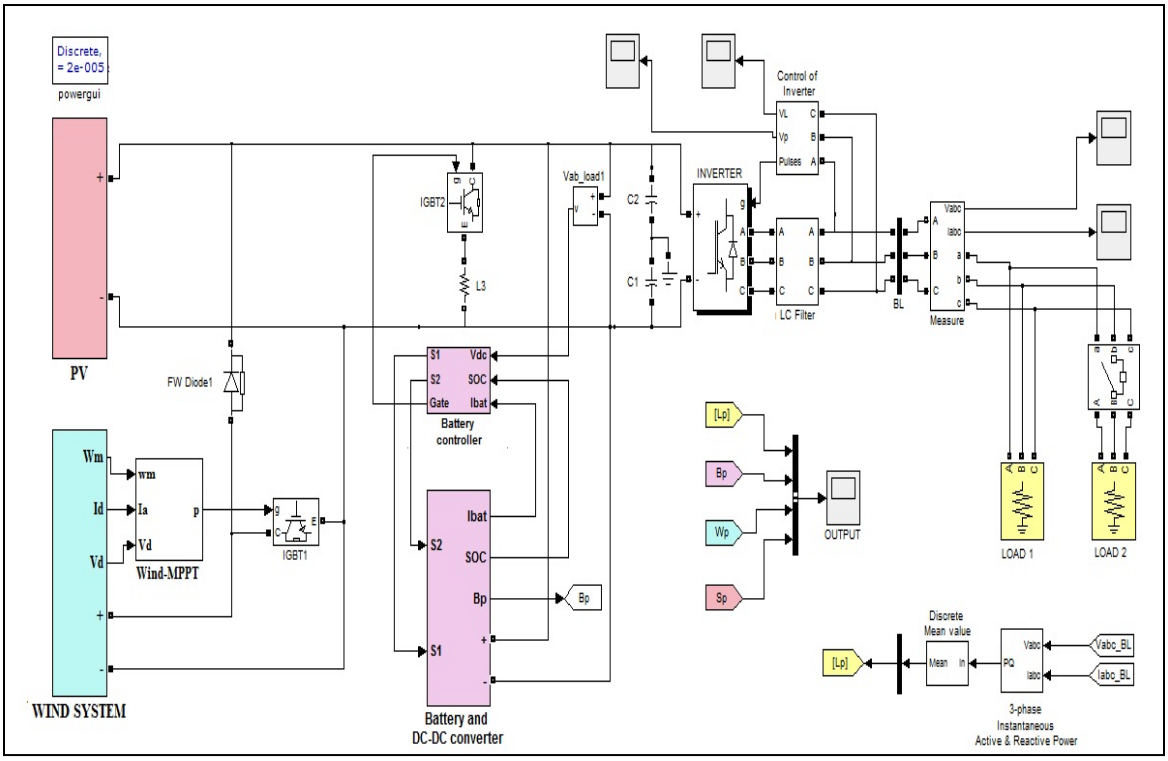

Figure 6. Composite Simulation Model of Proposed Hybrid System

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

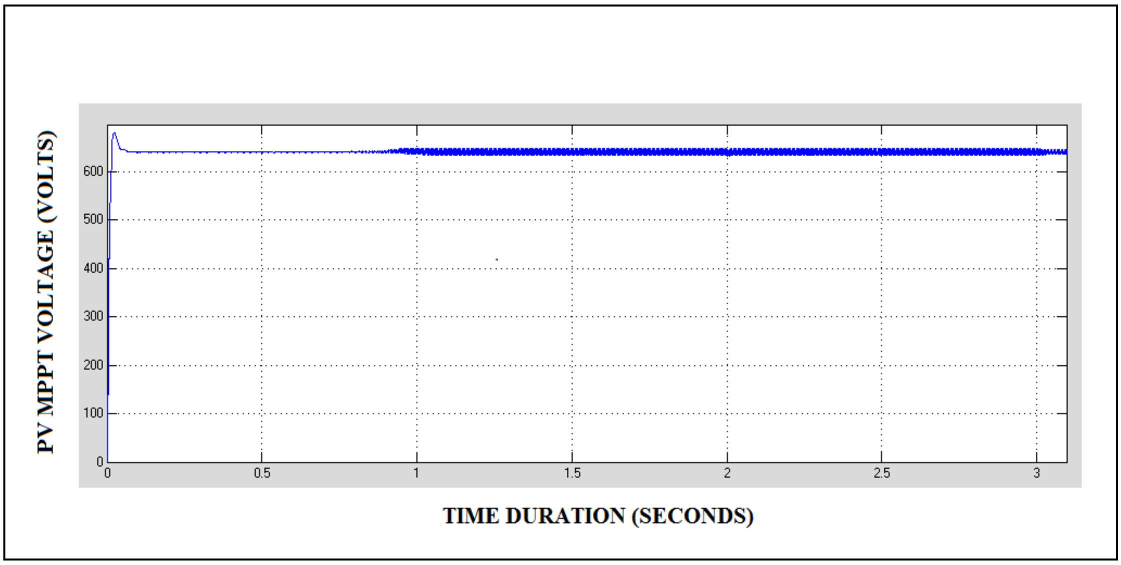

Figure 7. Phase Voltage observed at the PV array

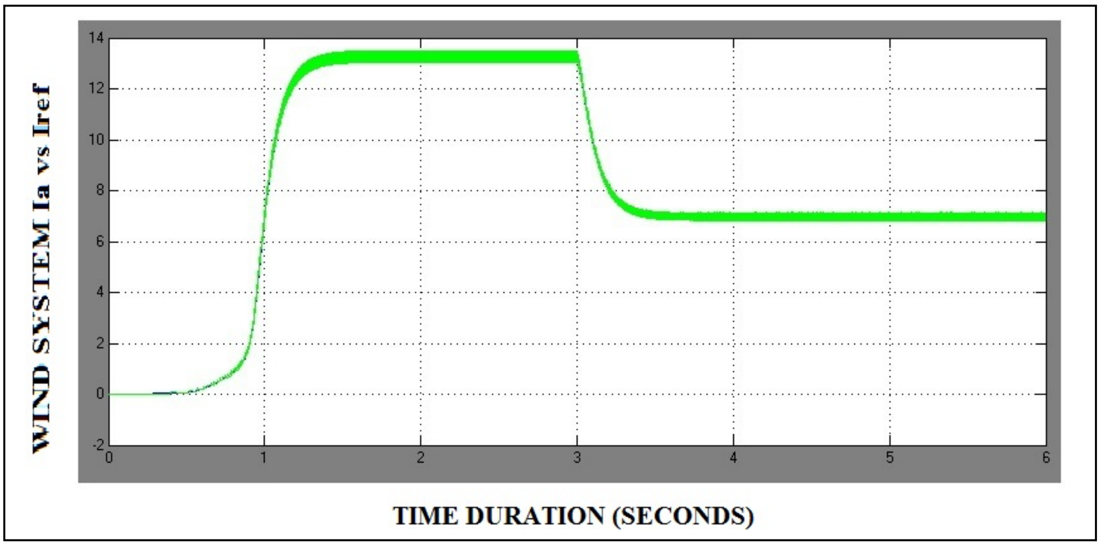

Figure 8. The relative variation curve of Actual Current (Ia) and Reference Current (Iref)

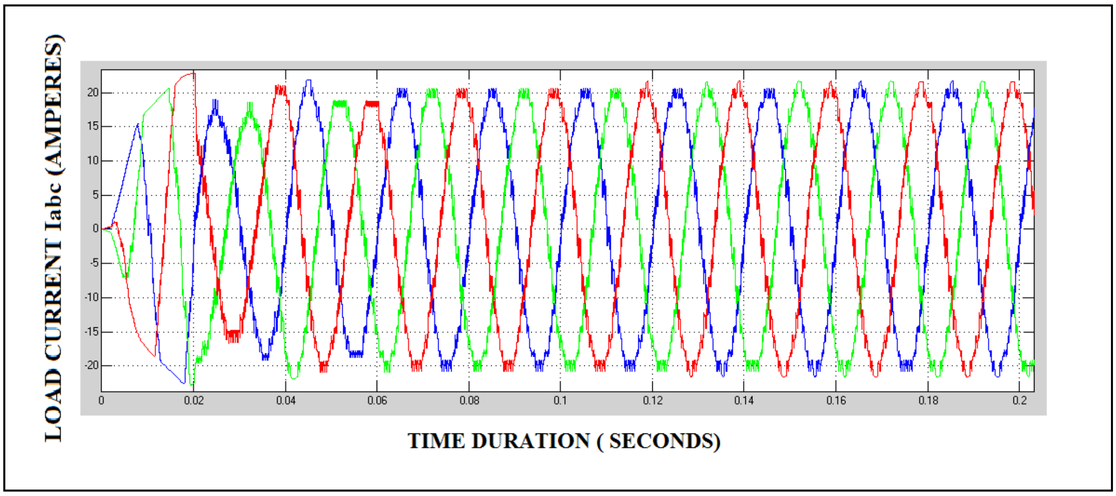

Figure 9. The load current supplied to the load s sinusoidal n nature as depicted n the simulation

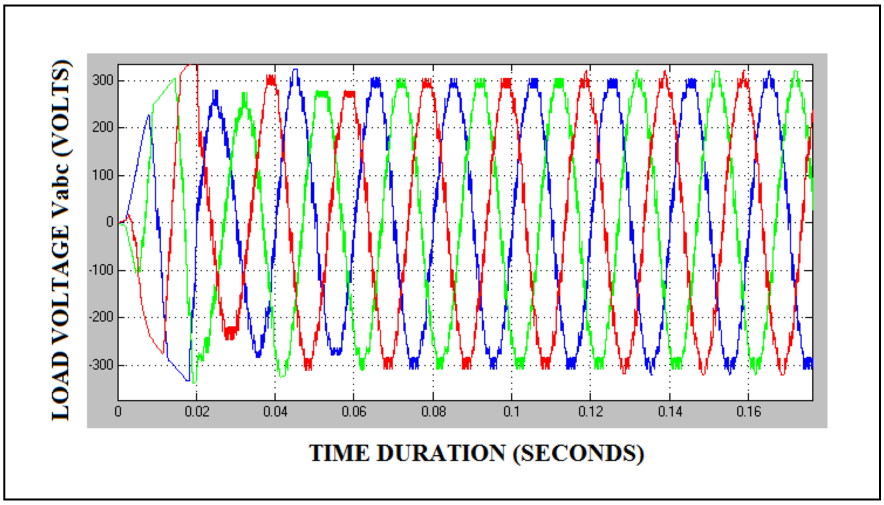

Figure 10. Three Phase Voltage Supplied To The Load By The nverter

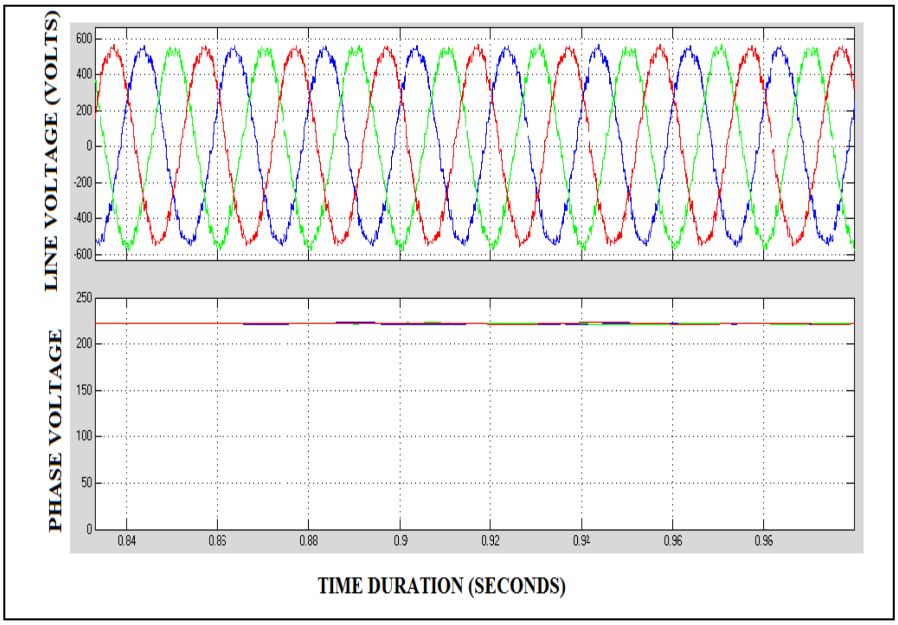

Figure 11. AC Line Voltage and Phase Voltage Given By The nverter

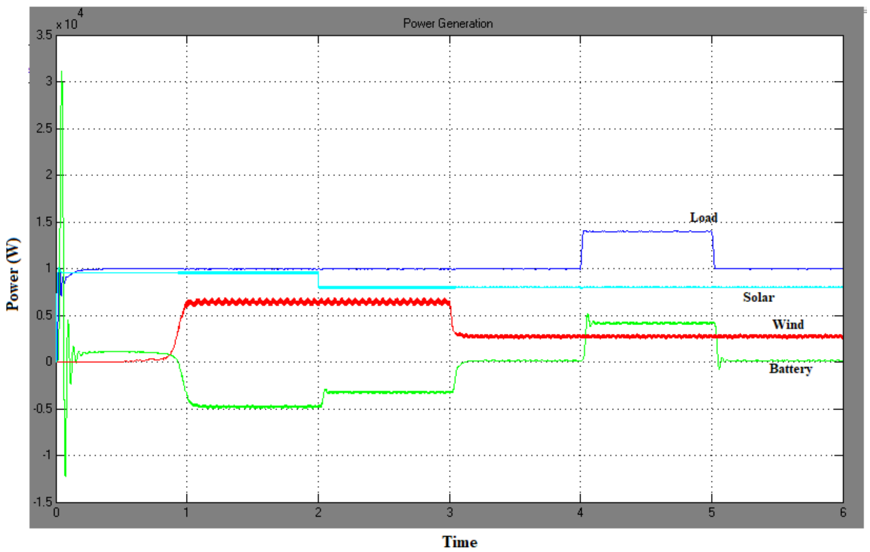

Figure 12. Simulation result with PWM (PI) control

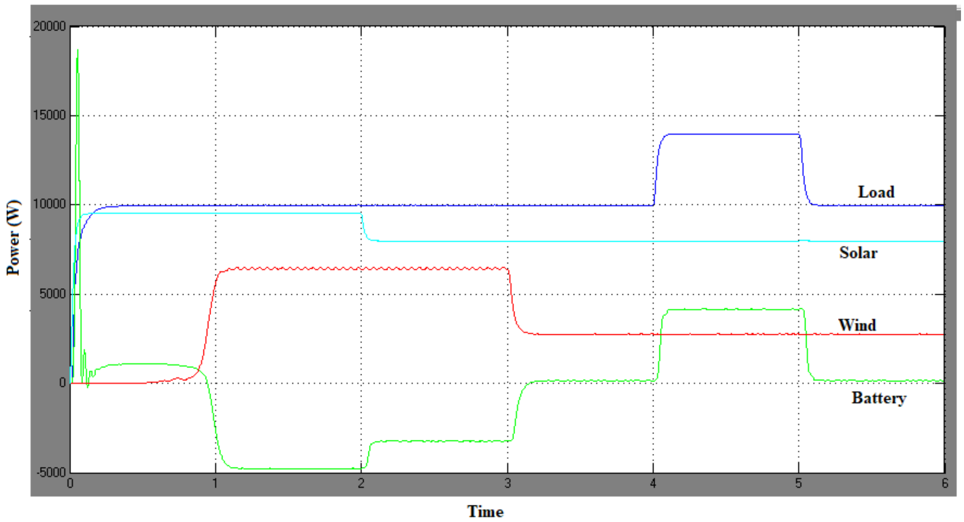

Figure 13. Simulation result with fuzzy logic controller

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

TIME (sec)	LOAD $(\times 10^4)$ W	SOLAR $(\times 10^4)$ W	WIND $(\times 10^4)$ W	BATTERY POWER $(\times 10^4)$ W	BATTERY ACTION	REMARKS
$0-1$	1	0.92	0 (0-0.8 s)	+0.08	Supplying	G < L
		0.92	0.03 (0.8 s)	+0.05		
$1-2$	1	0.94	0.56	−0.5	Charging	G > L
$2-3$	1	0.78	0.56	−3.4	Charging	G > L
$3-4$	1	0.78	0.2	+0.02	Supplying	G ≤ L
$4-5$	1.4	0.78	0.2	+4.2	Supplying	G < L
$5-6$	1	0.78	0.2	+0.02	Supplying	G ≤ L

5. Conclusion

In this study, a comprehensive performance analysis of a hybrid microgrid system integrating photovoltaic (PV) arrays, wind turbines, and battery storage was conducted. The primary objective was to evaluate the effectiveness of this system in meeting load demands under varying conditions and to compare the performance of a Fuzzy Logic Controller (FLC) against a traditional Pulse Width Modulation (PWM) controller. The simulation results demonstrated that the hybrid microgrid effectively managed energy generation and consumption, achieving a high level of efficiency and reliability. The integration of PV and wind resources, supported by a battery storage system, enabled the microgrid to meet the 5kW additional load consistently, even under challenging conditions such as high demand and low resource availability.

The comparison between the FLC and PWM controllers highlighted that the FLC significantly outperformed the PWM controller in terms of efficiency, stability, and disturbance reduction. The FLC's ability to adapt to dynamic conditions and optimize the control of the inverter led to improved power output and system reliability. Overall, the study concludes that the hybrid microgrid system, managed with an FLC, provides a robust and efficient solution for integrating renewable energy sources. Future work should explore advanced forecasting models and new storage technologies to further enhance the performance and cost-effectiveness of microgrid systems.

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