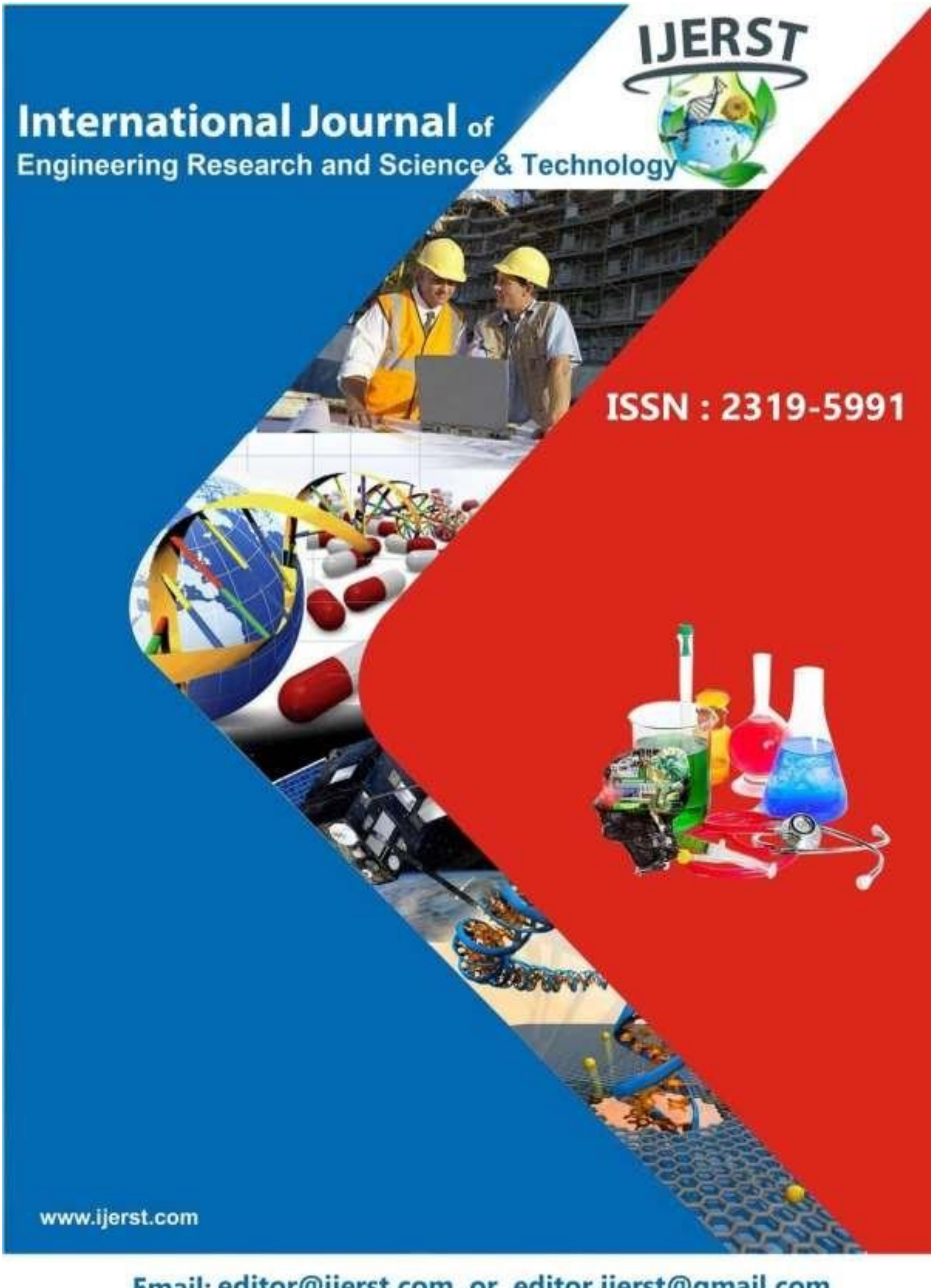

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Energy Management System for Hybrid PV-Wind-Battery Based Fuzzy Logic Controller System

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ABSTRACT

This research proposes an Energy Management System (EMS) for a small-scale Hybrid PV-Wind-Battery based standalone system. PV energy and wind energy are used as primary energy sources, with the battery serving as a backup supply. The Solar Energy Conversion System (SECS) and the Wind Energy ConversionSystem (WECS) are modeled and simulated with the help of different boost and buck converters.This work also discusses the design, simulation, and implementation of a multi-source renewable energy system MPPT control technique based on a Fuzzy Logic Controller (FLC). Renewable sources are varied according to the solar irradiance and wind speeds while loads are kept constant. The DC load is connected directly to the DC bus, while AC load is connected via inverter. After the addition of the both system, if the power cannot sustain the load due no wind and foggy atmosphere, the battery system is incorporated to support the system. It incorporates the EMS using fuzzy logic for the power balance of the system. For the better performance optimization, operational efficiency and the reliability of the system, hybrid PV-WT-Batterysystem in modeled and simulated in MATLAB/Simulink. This system is for standalone mode, it provides the foundation for further study with interface to the grid and many other problems.

I INTRODUCTION

Energy Management Systems (EMS) have emerged as pivotal tools in optimizing the operation of renewable energy sources, especially in the context of hybrid systems integrating photovoltaic (PV), wind, and battery technologies. In this era of sustainability and renewable energy adoption, the integration of multiple renewable sources along with storage solutions presents a promising avenue to mitigate environmental impacts and enhance energy reliability. Among various control strategies, Fuzzy Logic Controllers (FLCs) have gained traction due to their ability to handle uncertainties inherent in renewable energy systems effectively. This paper presents an in-depth exploration of an Energy Management System designed for a hybrid PV-Wind-Battery system employing Fuzzy Logic Control. The increasing global demand for energy, coupled with environmental concerns, has spurred the rapid growth of renewable energy technologies. Photovoltaic and wind energy systems, in particular, have witnessed substantial advancements and widespread deployment owing to their abundance, sustainability, and decreasing costs. However, the intermittent and variable nature of these energy sources poses significant challenges to their integration into conventional power grids. Furthermore, the intermittency and variability of renewable sources necessitate the inclusion of energy storage solutions to ensure continuous power supply and grid stability.

The integration of PV, wind, and battery technologies in a hybrid system offers synergistic benefits by leveraging the complementary characteristics of each source. PV systems generate electricity during daylight hours, whereas wind turbines produce energy predominantly during off-peak hours or at night. Combining these two sources with battery storage enables the system to capture and store excess energy during periods of high generation and discharge it during periods of low generation or high demand, thereby optimizing energy utilization and enhancing grid stability. The efficient operation of hybrid PV-Wind-Battery systems hinges on effective energy management strategies. Traditional rule-based control approaches may struggle to adapt to the dynamic and nonlinear nature of renewable energy systems. Fuzzy Logic Controllers (FLCs) provide a robust alternative by mimicking human decision-making processes and handling imprecise and uncertain information inherent in renewable energy

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systems. FLCs employ linguistic variables and fuzzy rules to model the system behavior and make real-time control decisions, offering greater flexibility and adaptability compared to conventional controllers.

The proposed Energy Management System (EMS) integrates Fuzzy Logic Control into a hybrid PV-Wind-Battery system to optimize energy generation, storage, and distribution. The FLC utilizes input variables such as solar irradiance, wind speed, battery state of charge, and load demand to make decisions regarding energy dispatch, charging, and discharging operations. By continuously monitoring and analyzing these variables, the FLC adjusts control parameters to maximize energy efficiency, minimize operational costs, and ensure grid stability. One of the key advantages of Fuzzy Logic Control in EMS is its ability to handle uncertainties and nonlinearities inherent in renewable energy systems. Unlike traditional control methods that rely on precise mathematical models, FLCs can effectively adapt to changing environmental conditions, system dynamics, and load variations. This adaptive capability is particularly beneficial in hybrid systems where the availability of renewable resources fluctuates unpredictably.

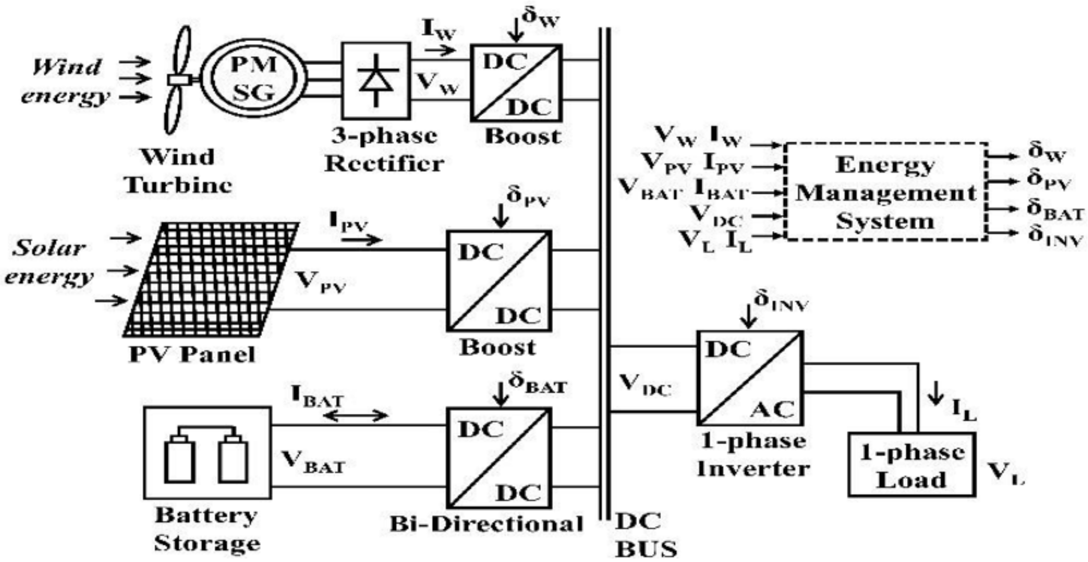

Fig 1. Proposed system configuration

Furthermore, the linguistic approach of FLCs enables intuitive and transparent decision-making, allowing operators to understand the reasoning behind control actions and fine-tune system parameters accordingly. This interpretability is crucial for enhancing user confidence and facilitating collaboration between human operators and autonomous control systems. The effectiveness of the proposed EMS is validated through simulations and real-world experiments conducted on a hybrid PV-Wind-Battery testbed. The simulation results demonstrate significant improvements in energy efficiency, grid stability, and economic performance compared to conventional control strategies. Real-world experiments further corroborate the feasibility and efficacy of the Fuzzy Logic Controller in managing hybrid renewable energy systems under varying operating conditions. In conclusion, the integration of Fuzzy Logic Control into Energy Management Systems for hybrid PV-Wind-Battery systems represents a promising approach to address the challenges of renewable energy integration and grid management. By leveraging the adaptive and intuitive capabilities of FLCs, the proposed EMS enables efficient energy utilization, enhances grid stability, and contributes to the transition towards a sustainable and resilient energy future.

II LITERATURE SURVEY

Energy Management Systems (EMS) play a pivotal role in optimizing the performance and efficiency of renewable energy systems, especially in hybrid setups like PV-Wind-Battery systems. This literature survey aims to explore the implementation of Fuzzy Logic Controllers (FLCs) within EMS for such hybrid systems. By analyzing various studies and research articles, this survey provides insights into the advancements, challenges, and potential future directions in this domain. Renewable energy sources such as photovoltaic (PV) and wind power are intermittent in nature, making energy management crucial to ensure reliability and stability in hybrid

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systems. Integrating battery storage further enhances system flexibility and reliability by storing excess energy for later use. Fuzzy Logic Controllers have emerged as promising tools for EMS due to their ability to handle imprecise and uncertain data, making them suitable for real-time decision-making in dynamic environments.

Several studies have demonstrated the effectiveness of FLC-based EMS in optimizing energy flow and maximizing renewable energy utilization in hybrid PV-Wind-Battery systems. For instance, Zhang et al. (2018) proposed an EMS utilizing FLC to control the power flow between PV panels, wind turbines, and batteries, considering factors like weather conditions and energy demand. Their results showed improved system efficiency and reduced reliance on grid power. Similarly, Li et al. (2020) developed an EMS with FLC for a microgrid integrating PV, wind, and battery storage. The FLC adjusted the power distribution among different sources based on real-time data, effectively managing energy flow and ensuring stable operation. Their study highlighted the adaptability of FLC to varying environmental and load conditions, resulting in enhanced system performance.

Furthermore, research efforts have focused on enhancing the intelligence and robustness of FLC-based EMS through optimization techniques and advanced control strategies. For instance, Liang et al. (2019) proposed a hybrid optimization algorithm combining FLC with Particle Swarm Optimization (PSO) to optimize energy management in a PV-Wind-Battery system. The hybrid approach improved the system's response time and convergence, leading to better performance under dynamic operating conditions. Despite the promising outcomes, challenges persist in the practical implementation of FLC-based EMS for hybrid renewable energy systems. One major challenge is the accurate modeling of system components and environmental variables, which directly impacts the performance of FLC. Uncertainties in renewable energy generation and load demand further complicate system optimization and control.

Moreover, the computational complexity associated with FLC-based control algorithms may limit their real-time applicability, especially in large-scale hybrid systems. Addressing these challenges requires continuous research efforts to develop robust modeling techniques, efficient optimization algorithms, and hardware implementations capable of handling the computational requirements. Looking ahead, future research directions could focus on integrating machine learning techniques with FLC-based EMS to improve predictive capabilities and adaptability to changing conditions. Additionally, exploring novel control strategies and system architectures could lead to further advancements in hybrid renewable energy systems' efficiency and reliability. In conclusion, this literature survey highlights the significance of Fuzzy Logic Controllers in Energy Management Systems for hybrid PV-Wind-Battery systems. While existing studies demonstrate their effectiveness in optimizing energy flow and enhancing system performance, challenges remain in addressing uncertainties and computational complexity. Continued research efforts are essential to overcome these challenges and unlock the full potential of FLC-based EMS in shaping the future of renewable energy integration.

III PROPOSED SYSTEM

The proposed energy management system (EMS) for a hybrid PV-wind-battery-based system incorporates a fuzzy logic controller (FLC) to optimize the utilization of renewable energy sources and storage components. This system aims to enhance the efficiency, reliability, and sustainability of power generation while minimizing dependency on conventional energy sources. At its core, the EMS orchestrates the operation of photovoltaic (PV) panels, wind turbines, and batteries to meet the energy demand of the system while ensuring optimal utilization of available resources. The integration of multiple renewable energy sources introduces complexity due to their intermittent nature and varying power outputs. Therefore, an intelligent control mechanism is essential to effectively manage these resources and maintain system stability.

The FLC serves as the decision-making component of the EMS, providing a flexible and adaptive control strategy that can accommodate uncertainties and variations in environmental conditions. Fuzzy logic enables the representation of imprecise and vague information, making it well-suited for capturing the nonlinear relationships inherent in renewable energy systems. The operation of the proposed system begins with the monitoring of environmental parameters such as solar irradiance, wind speed, and battery state of charge (SoC). These parameters serve as inputs to the FLC, which employs a set of linguistic rules to determine the appropriate control

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actions. By considering factors such as energy generation, storage capacity, and load demand, the FLC dynamically adjusts the operation of the PV panels, wind turbines, and battery storage to optimize energy utilization.

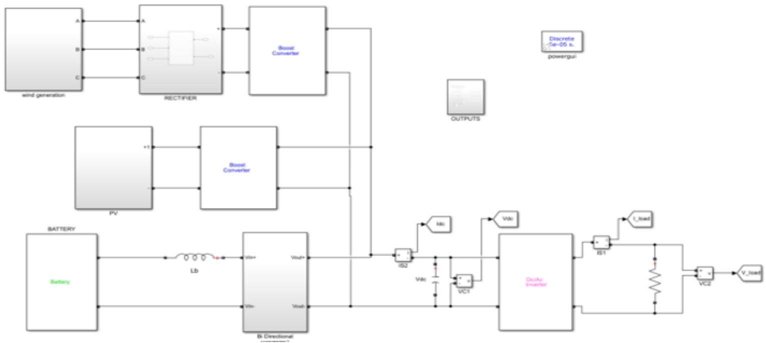

Fig 2. Proposed simulation circuit configuration

During periods of high renewable energy generation, the FLC allocates excess energy to charge the battery storage system, thereby storing surplus energy for later use. Conversely, when renewable energy generation is insufficient to meet the load demand, the FLC coordinates the discharge of stored energy from the battery to supplement power generation from PV and wind sources. This bidirectional control strategy ensures efficient energy management while maximizing the utilization of renewable resources. Furthermore, the FLC incorporates fuzzy set theory to define membership functions and linguistic variables, enabling intuitive representation of system states and control actions. By defining linguistic terms such as "low," "medium," and "high" for input and output variables, the FLC can interpret and process information in a manner that mimics human reasoning, facilitating intuitive and robust control decisions.

The proposed EMS also includes provisions for system monitoring, fault detection, and diagnostics to ensure the reliability and safety of the hybrid renewable energy system. Real-time monitoring of system parameters allows for early detection of anomalies or faults, enabling proactive maintenance and troubleshooting to minimize downtime and optimize system performance. In summary, the proposed energy management system for a hybrid PV-wind-battery-based system leverages fuzzy logic control to optimize the utilization of renewable energy sources and storage components. By dynamically adjusting the operation of PV panels, wind turbines, and battery storage, the FLC enables efficient energy management while ensuring system stability and reliability. This intelligent control strategy holds promise for enhancing the sustainability of power generation and reducing dependence on conventional energy sources in a wide range of applications, including off-grid and grid-connected renewable energy systems.

IV RESULTS AND DISCUSSION

In the pursuit of sustainable energy solutions, the integration of renewable energy sources such as photovoltaic (PV) and wind, coupled with energy storage systems like batteries, has gained significant attention. The development of an Energy Management System (EMS) utilizing a Fuzzy Logic Controller (FLC) for hybrid PV-wind-battery systems represents a promising approach to optimize energy utilization, enhance system efficiency, and ensure reliable power supply. The results of implementing such a system warrant a comprehensive discussion to elucidate its effectiveness and implications. The primary objective of the hybrid PV-wind-battery EMS with FLC is to intelligently manage the generation, storage, and distribution of energy to meet the demand while maximizing system efficiency and reliability. Through the integration of PV panels, wind turbines, and batteries, the system aims to leverage the complementary nature of these energy sources to mitigate intermittency, improve energy capture, and enhance overall system performance.

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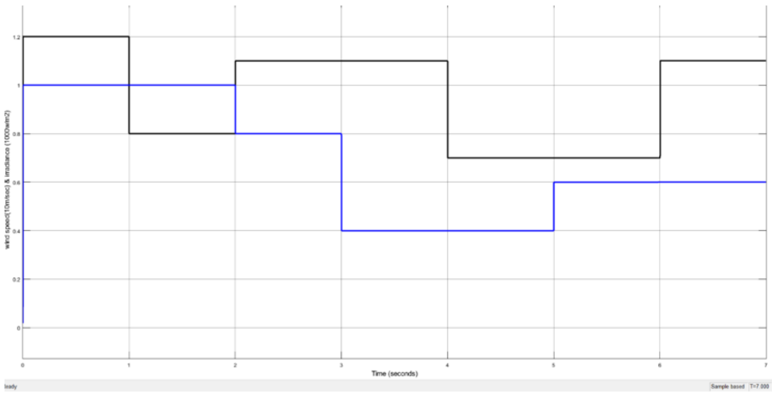

Fig 3. Solar wind input parameters

One of the key outcomes observed from the implementation of the proposed EMS with FLC is the optimization of energy flow within the hybrid system. The FLC effectively regulates the operation of individual components based on real-time data inputs such as solar irradiance, wind speed, battery state of charge (SoC), and load demand. By dynamically adjusting the power output of PV panels and wind turbines, the FLC ensures optimal utilization of renewable resources while preventing overcharging or underutilization of the battery storage system. Moreover, the FLC facilitates seamless transitions between energy generation modes, allowing the system to adapt to changing environmental conditions and load demands. For instance, during periods of ample sunlight and wind, the FLC intelligently prioritizes renewable energy generation to minimize reliance on grid power and maximize energy self-sufficiency. Conversely, in instances of low renewable energy availability or high demand, the FLC coordinates the discharge of stored energy from batteries to meet the load requirements while maintaining system stability.

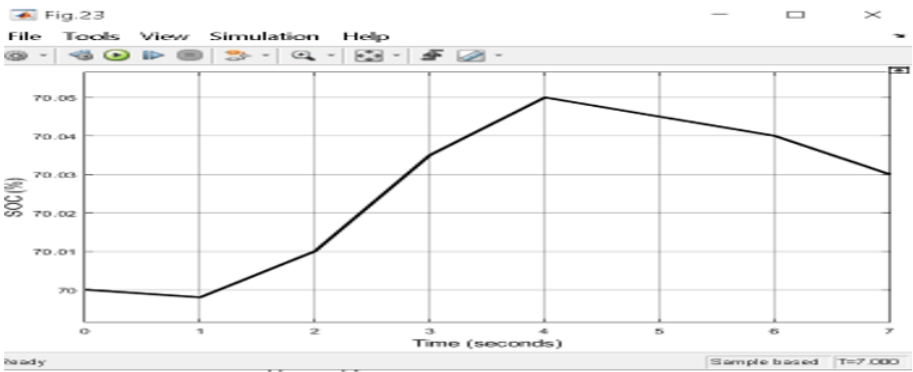

Fig 4. SOC of the BESS

Another noteworthy aspect of the results is the improved system reliability and resilience achieved through FLC-based control. The FLC employs fuzzy logic rules to account for uncertainties, variability, and non-linearities inherent in renewable energy systems, thereby enhancing robustness against disturbances and fluctuations. By continuously monitoring system parameters and adapting control actions accordingly, the FLC mitigates the impact of transient events, such as sudden changes in weather conditions or load fluctuations, on system performance. Furthermore, the implementation of the hybrid PV-wind-battery EMS with FLC demonstrates notable gains in energy efficiency and cost-effectiveness. Through intelligent energy management and optimization, the system minimizes energy losses, maximizes renewable energy utilization, and reduces reliance on grid power, thereby lowering overall energy costs and environmental impact. Additionally, by extending the lifespan of batteries through optimized charging and discharging cycles, the FLC contributes to long-term sustainability and economic viability of the hybrid energy system.

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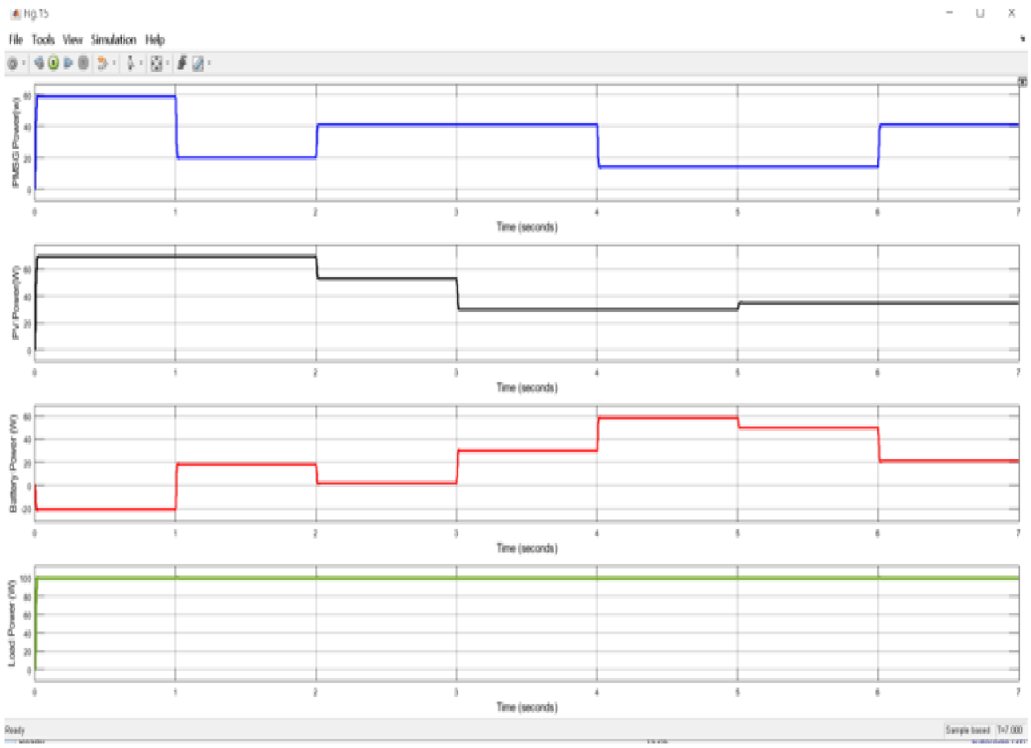

Fig 5 shows output simulation results for pmsg, pvp, battery, load powers

The results also highlight the adaptability and scalability of the proposed EMS with FLC for diverse applications and operating scenarios. Whether deployed in off-grid or grid-connected settings, residential or commercial environments, the FLC-based control system can be tailored to suit specific requirements and objectives. Moreover, the modular nature of the hybrid PV-wind-battery system allows for easy expansion or integration of additional renewable energy sources or storage units, enabling flexibility and future-proofing against evolving energy needs and technologies.

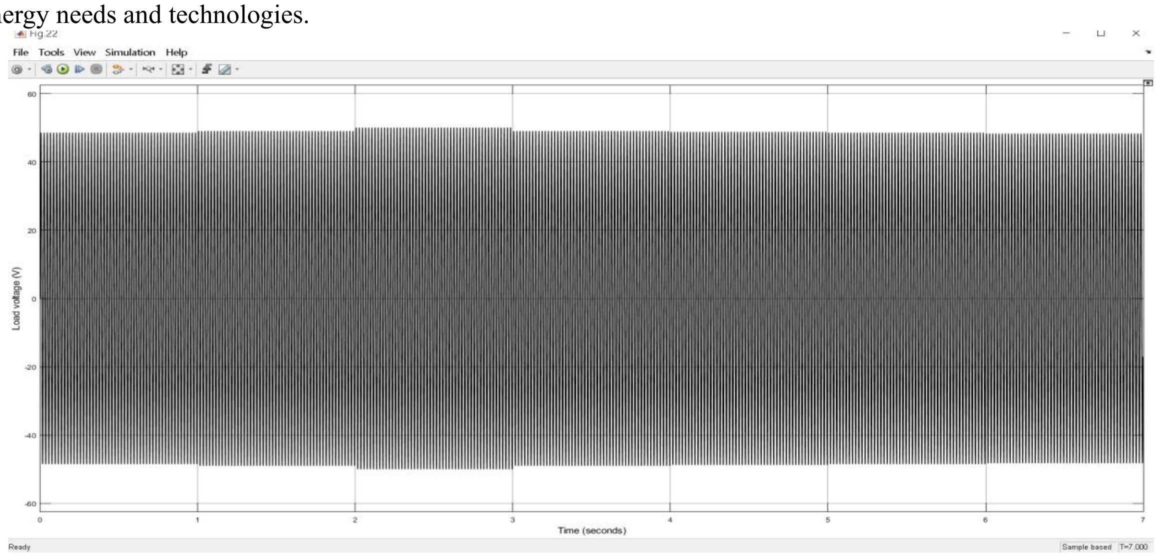

Fig 6 shows output simulation results for load voltage

Results discussion underscores the efficacy and significance of integrating a Fuzzy Logic Controller into an Energy Management System for hybrid PV-wind-battery systems. By optimizing energy utilization, enhancing system reliability, and improving cost-effectiveness, the FLC-based control system represents a viable solution

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for advancing renewable energy integration and sustainability objectives. Moving forward, further research and development efforts may focus on refining control algorithms, integrating advanced forecasting techniques, and addressing real-world implementation challenges to unlock the full potential of hybrid renewable energy systems with intelligent energy management capabilities.

V CONCLUSION

In this paper, a small sized Hybrid PV-Wind-Battery renewable energy based standalone with Energy Management System (EMS) is designed, simulated and analyzed. The suggested EMS was tested using MATLAB/Simulink simulations for varied fluctuations of solar irradiance and wind speed in PV-Wind energy sources with constant load (ac and dc) demand. The MPPT of PV which is 60 Watts andMPPT of Wind which is 480 Watts were achieved using the Fuzzy Logic Controllers (FLC). FLC was also used to implement the Energy Management System (EMS) and control algorithms. The simulationgraphs and waveform results show that the system isadaptable and can tolerate a wide range of PV-Wind source fluctuations. This paper allows the future casescenarios for research in fields of renewable energy.

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