

Grid-Connected Hybrid Renewable Energy System with Fuzzy Logic MPPT for Solar Wind-Battery Integration

Shaik Nagulu¹, T A Ramesh Kumar², Jonnala Rohith Balaji³

¹Research scholar, Department of Electrical Engineering, Annamalai University, Chidambaram, India

²Associate Professor, Department of Electrical Engineering, Annamalai University, Chidambaram, India

³Associate Professor, Department of Electrical and Electronics Engineering, Shri Vishnu Engineering College for Women, Bhimavaram India.

Correspondence: ¹shaiknitt218@gmail.com

Abstract

This paper presents the development of a multifunctional grid-connected hybrid energy system (HES) integrating solar photovoltaic (PV) modules, a wind energy conversion system (WECS), and battery energy storage. To address the inherent drawbacks of conventional maximum power point tracking (MPPT) algorithms such as delayed response and suboptimal tracking under fast-varying environmental conditions a Mamdani type fuzzy logic-based MPPT controller is proposed. This controller adaptively modulates the duty cycles of individual DC-DC boost converters, enabling optimal power extraction from both PV and wind sources under dynamic operating conditions. The hybrid energy coordination is implemented without requiring linearized system models, thereby increasing control robustness against parameter variations and environmental uncertainties. Grid interfacing is accomplished using a phase-locked loop (PLL) to ensure synchronization in frequency and phase, while an LCL filter is employed at the point of common coupling (PCC) to attenuate high-frequency switching harmonics, thereby improving power quality in accordance with grid codes. The proposed methodology enhances system dynamic response, stabilizes power output, and facilitates seamless energy sharing among multiple sources. Time-domain simulations conducted in MATLAB/Simulink validate the effectiveness of the proposed control scheme, demonstrating improved system stability, reduced harmonic content, and efficient energy regulation. The novelty of this work lies in the adaptive fuzzy logic-driven coordination of hybrid renewable sources in real time, enabling superior performance, high efficiency, and compliance with grid power quality standards in a hybrid energy system environment.

Keywords: Fuzzy logic, Hybrid energy, Solar, Wind, Battery storage system.

1. Introduction

The increasing dependency on electrical appliances for routine domestic tasks has substantially elevated comfort levels and overall convenience. However, this rapid adoption of electrically powered devices has also caused a considerable rise in household electricity consumption. To accommodate this rising demand, both conventional and renewable energy sources are now being incorporated into modern power systems [1]. Although this hybridization enhances energy availability, it also complicates grid management due to variations in power flow, grid stability, and the dynamic nature of diverse energy generation units. In response to environmental imperatives and sustainability goals, policy makers have promoted a substantial uplift in the penetration of renewable energy in national power grids [2]. Renewable options like photovoltaic (PV) arrays, wind turbines (WT), fuel cells (FC), ultra-capacitors, and geothermal units have gained



International Journal of Technology and Emerging Research (IJTER)

Volume 2 | Issue 7 | 2026 | Article ID: 3374-2854-8583 | <https://doi.org/10.64823/ijter.2607008>

IORO Publications · Texas, USA · www.ioro.org

prominence owing to their eco-friendliness and minimal carbon footprint [3]. Among these technologies, solar and wind-based generation [4], [5] have emerged as the most widespread due to their scalability, cost-effectiveness, and straightforward installation requirements. Unlike fuel-driven generators such as fuel cell stacks and biogas-based systems that require continuous fuel replenishment, solar and wind installations leverage naturally available resources, making them highly practical across diverse geographical locations.

Wind turbines, especially those employing Permanent Magnet Synchronous Generators (PMSGs), have proven to be highly effective for large-scale power generation owing to their variable-speed operation and high efficiency. Developments in offshore wind technology have further accelerated their adoption in energy networks. Furthermore, PMSGs enable enhanced energy harvest through MPPT, which modulates the rotor speed according to fluctuations in wind speed [6]. In this context, fuzzy logic-based MPPT control emerges as a superior alternative to traditional MPPT methods such as Perturb & Observe (P&O) [7] and Incremental Conductance (IC), owing to its model-free structure, rapid response, and adaptability under highly variable environmental and load conditions. Implementing a fuzzy inference system [8] in a PV-wind-battery hybrid arrangement not only maximizes power extraction across all sources but also improves the harmonic profile and voltage regulation at the PCC. This underscores the potential of fuzzy logic-driven MPPT control to enhance stability in grid-tied renewable energy systems (RES).

Recent literature reveals a broad range of control schemes that enhance PMSG stability and performance [9]. Liu et al. [10] and Xu et al. [11], for instance, devised control techniques to dampen transient oscillations triggered by variable wind profiles, while Nyan and Song [12] proposed control-based harmonic compensation to improve power exchange and reduce waveform distortion. In contrast to wind turbines, PV modules offer a static, maintenance-free, and low-noise solution that can be readily deployed on both small and large scales. Rapid improvements in PV materials and converter technologies have facilitated multi-gigawatt capacity solar farms to satisfy surging energy consumption requirements [13]. Grid integration of PV power can be achieved with either single- or dual-stage power conversion topologies. While single-stage inverters simplify hardware and reduce cost, they pose control challenges under dynamic operating conditions. Voltage Source Inverter (VSI)-based architectures remain the preferred interface for precise regulation of power flow into the grid. Seasonal variations in solar and wind resource availability solar energy being more abundant in summer and wind energy dominating in winter encourage combined PV-wind systems that offer a complementary power profile for enhanced supply continuity [14]. However, the combination of multiple intermittent energy sources introduces new complexities in power quality, system stabilization, and coordinated control.

Energy Storage Systems (ESS) presents a viable strategy to smooth these fluctuations and bolster grid stability [15]–[16]. By absorbing surplus power during low-demand or high-generation intervals and discharging energy during peak demand or underproduction, ESS enables seamless balancing of power across the network [17]. These storage solutions can be broadly classified into high-power devices such as supercapacitors, superconducting magnetic energy storage (SMES), batteries, and flywheels [18] and energy-centric devices like fuel cells, bulk batteries, solar cells, and redox flow batteries [19]. Energy can also be stored in different forms, including chemical, thermal, and mechanical forms, and released to the grid as required. With the increasing adoption of hybrid RES, HESs have also gained considerable attention for their capacity to combine complementary energy and power characteristics into a unified management framework, further improving operational flexibility and resilience [20]. However, high-frequency cycling can negatively impact battery lifespan, underscoring the need for smart control strategies. To enhance both power quality and energy management, integrating another power source tailored to the system's specific requirements is often advantageous. The proposed hybrid PV-Wind-battery storage system (BSS)

architecture is designed with a possible control loops and power electronic converters, aiming to reduce system complexity while maintaining optimal performance.

The paper is divided the contents as follows:

Section I discuss about the introduction. Section II provides a detailed overview of the proposed hybrid energy system. System design and the associated control strategy are outlined in Section III. Section IV presents the MATLAB setup along with the obtained simulation results. In conclusion, Section V highlights the main outcomes of the study.

2. Configuration of proposed system

The operation of a hybrid energy system is governed by a unified DC bus that interconnects all distributed energy assets. As illustrated in Fig. 1, the configuration integrates wind turbines, photovoltaic (PV) modules, and a battery energy storage unit (BES), each delivering power components designated as P_{Wind} , P_{PV} , and P_{bat} , respectively. Wind turbines capture kinetic energy from airflows and convert it into DC electrical power through an appropriate power-electronic interface, while the PV array directly transforms incident solar irradiation into DC output. The investigated hybrid energy system is configured to support both direct-current and alternating-current load profiles under varying operating conditions. On the DC bus, a continuous load of 1 kW is supplied directly, while two separate AC loads of 1 kW and 1.4 kW are connected on the grid side. To achieve these power requirements, a 3.5 kW-rated wind energy conversion system and a 2 kW-rated photovoltaic (PV) array are integrated into the architecture. Both renewable energy sources employ dedicated power electronic interfaces to regulate their output and ensure seamless power transfer to the common DC link.

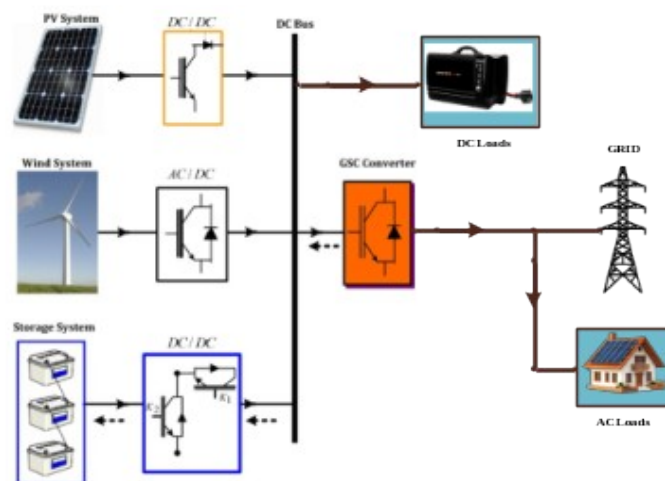


Fig.1 Proposed grid interfaced hybrid energy system

Additionally, a 5 kW-capacity battery energy storage system (BESS) is incorporated to enhance supply flexibility and resilience. The BESS operates in bidirectional mode, absorbing surplus energy during periods of high renewable generation and delivering stored power during deficits or emergencies. This coordinated arrangement of wind, PV, and battery storage not only meets the steady-state demand on both DC and AC sides but also provides effective energy buffering and supply continuity during transient fluctuations and grid disturbances.

3. Control methodology

3.1. Modelling of Solar PV cell:

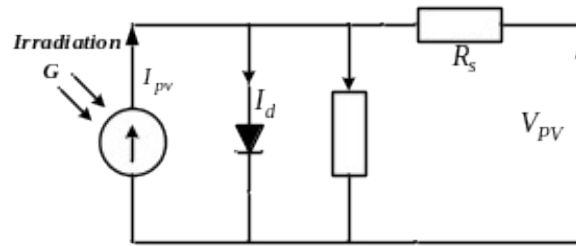


Fig. 2 circuit of a PV cell

Figure 2 shows the schematic representation of a one diode method of a solar cell. The basic equation that explains the I-V characteristics of an ideal solar cell include:

$$I = I_{pv} - I_d \quad (1)$$

Where solar cell current is denoted with I_{pv} and I_d is the diode current. The schottky diode equation can be written as

$$I_d = I_o \left[\exp\left(\frac{qV}{akT}\right) - 1 \right] \quad (2)$$

The revised I-V characteristics of a solar cell can be described by substituting Eq. (2) for Eq. (1).

$$I = I_{pv} - I_o \left[\exp\left(\frac{qV}{akT}\right) - 1 \right] \quad (3)$$

Where I_o is the diode's leakage current, q is the electron charge ($1.6021 \cdot 10^{-19}$ C), K is the Boltzmann constant ($1.3805 \cdot 10^{-23}$ J/K), T is the temperature of the junction between p and n (Kelvin). The V-I features of a realistic PV array are denoted as:

$$I = I_{pv} - I_o \left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (4)$$

I_{pv} is the solar current, while I_o denotes threshold current. R_p is parallel equivalent resistance, R_s denotes resistance in series, and V_t denotes the thermal potential of a solar cell. The solar cell current is affected by sun irradiation and temperature. The junction diode current may be expressed as:

$$I_o = I_{o,n} \left(\frac{T}{T_n}\right)^3 \exp \left[\frac{qE_g}{aK} \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (5)$$

Where, semiconductor band gap is represented with E_g .

3.2. Modelling of wind energy conversion system:

The large-scale deployment of wind turbines has faced certain challenges, primarily due to the variable nature of wind speeds and the significant initial investment required. To predict and analyse the power output from wind turbines, several modelling approaches are available, including linear and quadratic methods, as well as statistical models like the Weibull distribution. The mechanical power produced by wind turbine is presented in Eq. (6).

$$P_w = \frac{1}{2} \rho A C_p(\lambda, \beta) V_{wind}^3 \quad (6)$$

Where ρ is the air density, C_p is the power coefficient depends on the λ known as tip speed ratio and β known as the pitch angle. A and V_w represents swept area and wind speed. The ration of blade tip speed to wind speed is given in Eq. (7).

$$\lambda = \frac{\omega_t R}{V_{wind}} \quad (7)$$

Where ω_t and R denotes the rotor speed of the wind and turbine radius. The dynamic equation for the rotational momentum of the turbine is given as below Eq. (8) & (9).

$$J \frac{d\omega_t}{dt} = T_{aero} - T_{em} - B\omega_t \quad (8)$$

$$T_{aero} = \frac{P_{wind}}{\omega_t} \quad (9)$$

Where T_{aero} is the aerodynamic torque, T_{em} is the electromagnetic torque in the generator and B is the viscous coefficient. The electromagnetic torque evolved by the generator is given as

$$T_{em} = \frac{3}{2} p \lambda_m i_q \quad (10)$$

Where p is the number of poles, λ_m is the flux linkage, i_q is the q-axis stator current.

3.3. Fuzzy logic control:

The given block diagram illustrates the architecture of a fuzzy logic controller (FLC) employed in hybrid renewable energy systems integrating wind, solar, and battery storage units. The controller begins with fuzzification, where real-time input variables such as power deviations, voltage fluctuations, or state-of-charge are converted into fuzzy linguistic variables using predefined input membership functions. These fuzzy inputs are processed by the fuzzy inference engine, which operates based on a knowledge base comprising a data base (membership function definitions) and a set of fuzzy rules designed to handle non-linearity's and uncertainties in the system. The fuzzy inference mechanism generates corresponding fuzzy outputs, which are then translated back into precise control signals through defuzzification, using output membership functions. This process enables adaptive and intelligent control of power flow, improving stability and system responsiveness in the HES.

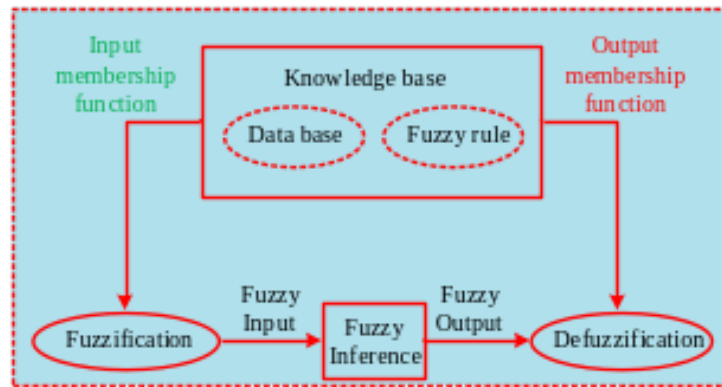


Fig.3 Block diagram of Fuzzy logic controller

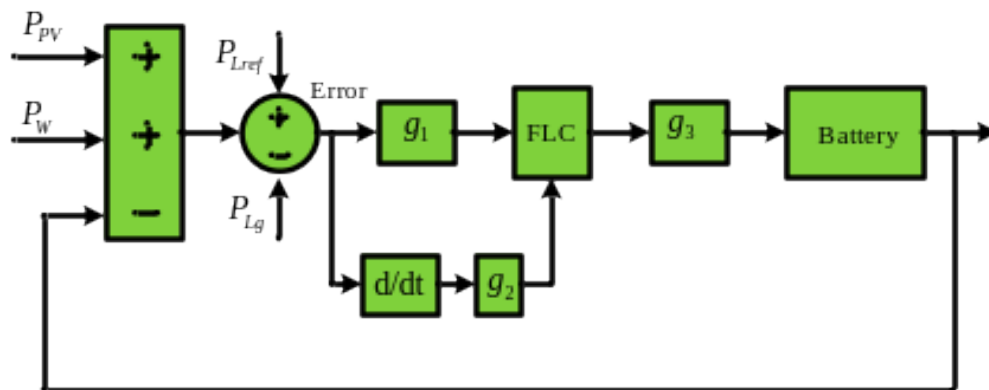


Fig. 4 Control block diagram of hybrid energy system

The provided control block diagram represents a fuzzy logic controller designed for managing power flow in a hybrid energy system integrating wind, solar, and battery storage. The total power demand is determined by summing the photovoltaic power (P_{PV}) and wind power (P_W) to form the available generation, which is compared against the load power demand (P_L) to generate an error signal (E). This error, along with its rate of change (dE/dt), forms the input to the FLC. The error and its derivative are scaled appropriately using input gains g_1 and g_2 to normalize the input range for effective fuzzy inference. The FLC processes these signals based on a predefined rule base and outputs a control signal, which is then scaled by gain g_3 and sent to the battery energy storage system. This control strategy allows the battery to compensate for the power mismatch, thereby maintaining system stability, regulating power flow, and enhancing the reliability of the hybrid renewable energy system.

4. Results and discussions

A hybrid renewable energy configuration integrating a wind turbine generator, a solar PV array, and a battery storage system has been developed and interfaced with the utility grid. The entire architecture was accurately modelled and simulated within the MATLAB/Simulink platform to systematically analyse its transient response, power-sharing capability, and steady-state behaviour under fluctuating renewable power availability and variable load profiles. Moreover, the simulation studies investigated control strategies for seamless power exchange between the grid and the hybrid system. The results highlight the system's potential to enhance energy reliability and optimize resource utilization in dynamic operating environments.

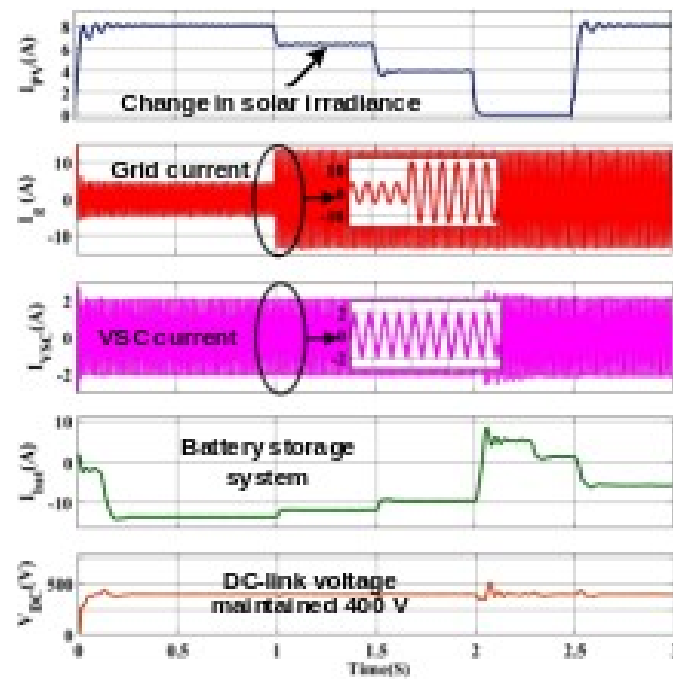


Fig.5 System parameters during change in solar irradiance

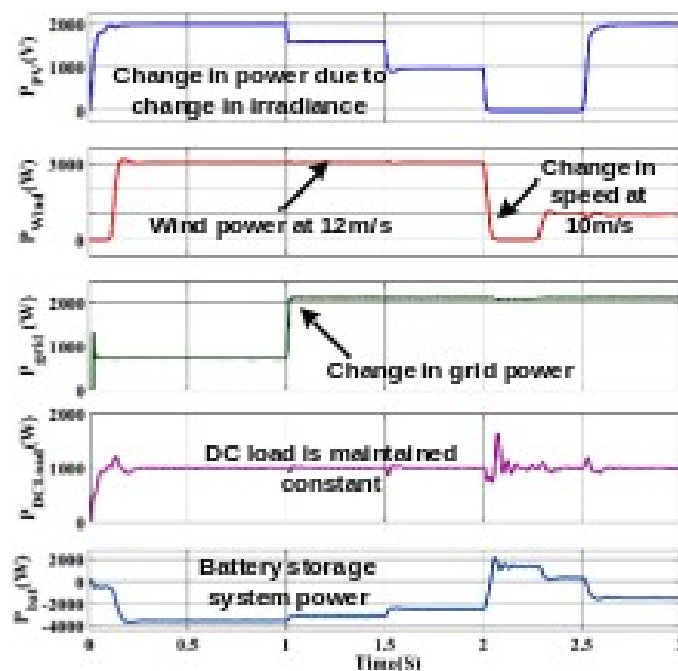


Fig.6 System performance during dynamic behaviour

The waveforms in fig. 5 illustrate the dynamic behaviour of a HRES comprising PV, battery, and grid. The PV current decreases abruptly when irradiance drops and returns to its rated level once sunlight is restored. Correspondingly, the grid current increases to support the load during PV power deficits. The VSC current adjusts in response to these variations, ensuring balanced power between the DC and AC sides. The battery current reverses its direction to supply or absorb power as per system requirements. Throughout the transient changes, the DC-link voltage is tightly regulated around 400 V. These responses highlight the effective coordination among PV, battery, VSC, and grid under fluctuating generation. Overall, the results demonstrate the stable and adaptive performance of the hybrid renewable energy system.

The fig.6 describes the power variations under different operating scenarios of a hybrid energy system. Initially, PV output is steady until irradiance drops, causing a sharp decrease and subsequent recovery in power. Wind power also fluctuates as wind speed transitions between 12 m/s to 10 m/s, leading to a corresponding drop in output. The grid supplies the shortfall, evident from its increasing power profile as renewables decrease. Throughout the simulation, the DC load is sustained at a nearly constant level, confirming effective power management. The battery storage alternates between charging and discharging states to support the energy balance. These coordinated variations ensure the DC-link remains stable despite significant renewable fluctuations. Overall, the system responds promptly to maintain power quality and continuous energy availability.

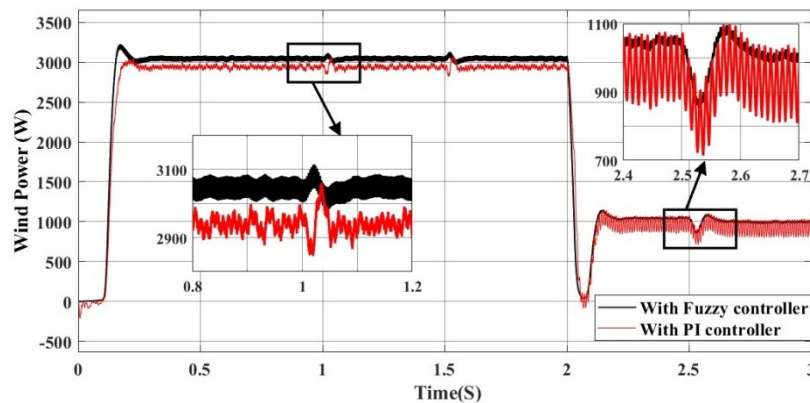


Fig.7 Wind power extraction

The graph compares wind power output using fuzzy and PI controllers over a 3-second interval. The fuzzy controller shows better steady-state stability with minimal oscillations around the rated power of 3000 W. During a disturbance at 2 seconds, the fuzzy controller maintains a smoother response. The PI controller gives larger fluctuations and slower recovery. This gives the better dynamic analysis of the fuzzy logic controller.

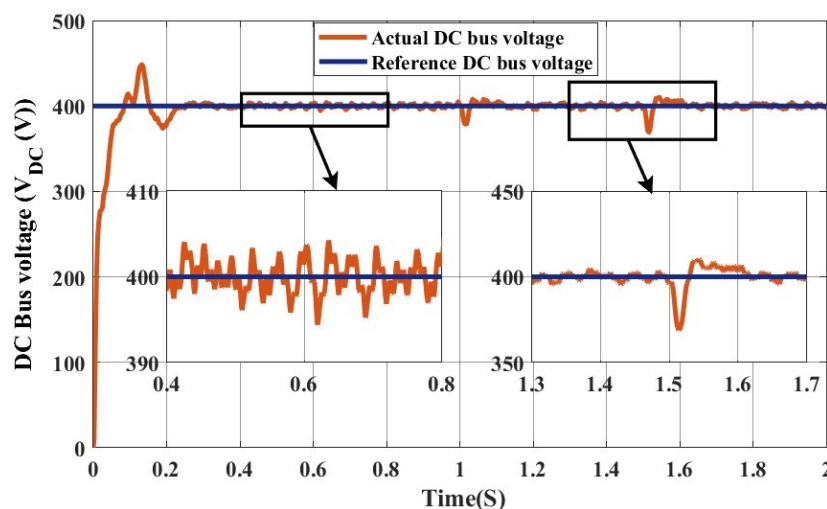


Fig.8 Comparison of the DC bus voltage with the reference voltage

Fig.8 shows the performance of DC bus voltage regulation compared to a constant reference of 400 V. Initially, the actual DC voltage exhibits a transient overshoot before stabilizing near the reference. Between 0.4 s to 0.8 s, minor oscillations are observed, indicating dynamic adjustment. A voltage dip occurs around 1.45 s, but the system quickly recovers to its nominal value. The overall performance shows effective voltage tracking with occasional deviations. These responses reflect the system's ability to maintain voltage stability under varying operating conditions. Figure 9 illustrates the total harmonic distortion (THD) of the grid current during a transient demand for power transfer to the battery storage system. The measured THD of the grid current is 1.48%,

indicating minimal harmonic distortion and demonstrating that power quality is effectively maintained under dynamic operating conditions.

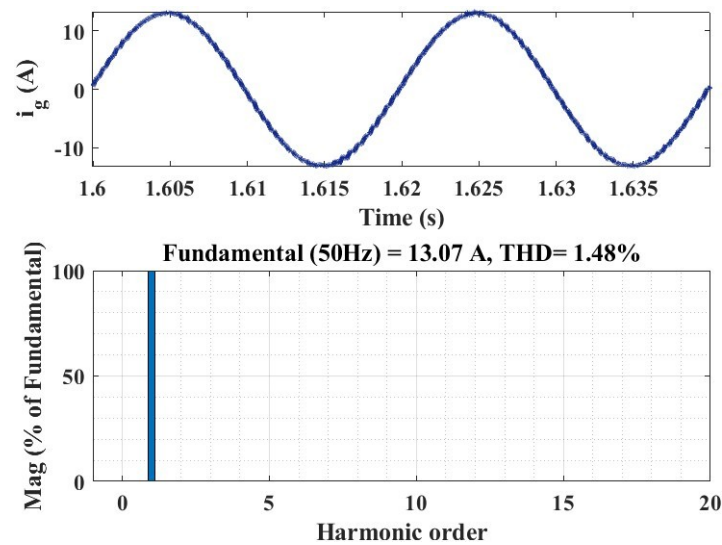


Fig.9 THD of grid current

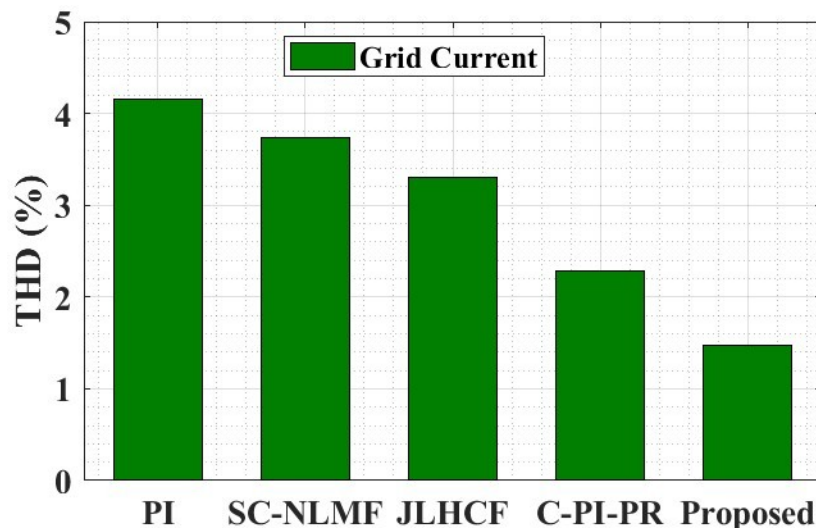


Fig.10 THD Comparison of Grid current

Figure 10 presents a comparison of grid current total harmonic distortion (THD) across different control strategies. The X-axis represents various control methods along with the proposed one, while the Y-axis denotes the corresponding THD values, limited to a maximum of 5%. Among the evaluated techniques, the proposed Fuzzy Logic Controller (FLC) demonstrates superior performance by achieving the lowest THD, thereby indicating enhanced power quality. Although all control methods maintain THD within acceptable limits, the FLC-based approach clearly outperforms the others in terms of harmonic mitigation.

5. Conclusion

A MATLAB-based implementation of fuzzy logic-controlled HES incorporating a 3 kW wind energy system and a 2 kW solar photovoltaic array has been designed to optimize power quality in grid-integrated applications. The system integrates a battery energy storage unit to support energy balancing and improve dynamic performance. Comparative analysis with conventional control strategies demonstrates the superiority of the proposed configuration in mitigating power quality issues. The fuzzy logic controller significantly reduces grid current THD to 1.48%, which is markedly lower than that observed in existing hybrid energy systems. These

results confirm the proposed approach as an effective solution for advanced microgrid control and quality enhancement.

6. Reference

- [1] J. Nunez Forestieri and M. Farasat, "Integrative Sizing/Real-Time Energy Management of a Hybrid Supercapacitor/Undersea Energy Storage System for Grid Integration of Wave Energy Conversion Systems," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 4, pp. 3798-3810, Dec. 2020, doi: 10.1109/JESTPE.2019.2926061.
- [2] J. Zhu, et.al, "Boom Potential Energy Regeneration Method for Hybrid Hydraulic Excavators," in *IEEE Access*, vol. 12, pp. 51450-51462, 2024, doi: 10.1109/ACCESS.2024.3386741.
- [3] P. Roy, J. He, T. Zhao and Y. V. Singh, "Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation: A Review," in *IEEE Open Journal of the Industrial Electronics Society*, vol. 3, pp. 81-104, 2022, doi: 10.1109/OJIES.2022.3144093.
- [4] Ahmad Khan, et.al, "Techno-Economic Feasibility and Reliability Analysis of Hybrid Renewable Energy System: A Systematic Review of Energy Storage Systems' Integration," in *IEEE Access*, vol. 13, pp. 59198-59226, 2025, doi: 10.1109/ACCESS.2025.3535520.
- [5] M. Lingamaiah, A. Mittal and S. Kumar, "A Grid-Connected 30 kW 5-Level Bidirectional Multilevel Converter for Electric Vehicle Charging," 2025 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), Bhopal, India, 2025, pp. 1-5, doi: 10.1109/SCEECS64059.2025.10940661.
- [6] S. Zhou, Z. et.al, "Model Prediction and Rule Based Energy Management Strategy for a Plug-in Hybrid Electric Vehicle With Hybrid Energy Storage System," in *IEEE Transactions on Power Electronics*, vol. 36, no. 5, pp. 5926-5940, May 2021, doi: 10.1109/TPEL.2020.3028154.
- [7] T. Wang, et.al, "Coordinated modulation strategy considering multi-HVDC emergency for enhancing transient stability of hybrid AC/DC power systems," in *CSEE Journal of Power and Energy Systems*, vol. 6, no. 4, pp. 806-815, Dec. 2020, doi: 10.17775/CSEEJPES.2019.02000.
- [8] M. Lingamaiah, A. Mittal and S. Kumar, "Reliable Power Flow Management and Control in Solar PV Based Electric Vehicle Charging System with G2V and V2G Integration," 2024 IEEE Silchar Subsection Conference (SILCON 2024), Agartala, India, 2024, pp. 1-6, doi: 10.1109/SILCON63976.2024.10910855.
- [9] Z. Zhang, et.al, "Market-oriented optimal dispatching strategy for a wind farm with a multiple stage hybrid energy storage system," in *Journal of Power and Energy Sys*, vol. 4, no. 4, pp. 417-424, Dec. 2018, doi: 10.17775/CSEEJPES.2018.00130.
- [10] M. B. Abdelghany, A. Al-Durra and F. Gao, "A Coordinated Optimal Operation of a Grid-Connected Wind-Solar Microgrid Incorporating Hybrid Energy Storage Management Systems," in *IEEE Transactions on Sustainable Energy*, vol. 15, no. 1, pp. 39-51, Jan. 2024, doi: 10.1109/TSTE.2023.3263540.
- [11] Q. Gao, et.al, "Analysis of Wave Energy Conversion for Optimal Generator Sizing and Hybrid System Integration," in *IEEE Trans. on Sus. Energy*, vol. 15, no. 1, pp. 609-620, Jan. 2024, doi: 10.1109/TSTE.2023.3318010.
- [12] M. Amir, et.al, "Enhancement of Frequency Regulation by TFOID Controller in Hybrid Renewable Energy With Battery Storage System-Based Multi-Area Microgrids," in *IEEE Access*, vol. 12, pp. 110813-110828, 2024, doi: 10.1109/ACCESS.2024.3439738.
- [13] V. I. Herrera, et.al, "Design and Experimental Comparison of Energy Management Strategies for Hybrid Electric Buses Based on Test-Bench Simulation," in *IEEE Transactions on Industry Applications*, vol. 55, no. 3, pp. 3066-3075, May-June 2019, doi: 10.1109/TIA.2018.2886774.
- [14] M. J. O'Malley et al., "Multicarrier Energy Systems: Shaping Our Energy Future," in *Proceedings of the IEEE*, vol. 108, no. 9, pp. 1437-1456, Sept. 2020, doi: 10.1109/JPROC.2020.2992251.
- [15] Malle, L, et.al, "OSG-PLL-based method of a solar PV grid-interfaced CHB multilevel inverter for power quality enhancement. *Electr Eng* (2024). <https://doi.org/10.1007/s00202-024-02460-2>.

- [16] Y. Zhang, L. Diao, Z. Jin and C. Xu, "Topologies, Configuration Scheme Optimization, and Energy Management Strategies of Vehicular Hybrid Power Systems: An Overview," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 2, pp. 6453-6471, April 2025, doi: 10.1109/TTE.2024.3510057.
- [17] S. Gangatharan, et.al, "A Novel Battery Supported Energy Management System for the Effective Handling of Feeble Power in Hybrid Microgrid Environment," in *IEEE Access*, vol. 8, pp. 217391-217415, 2020, doi: 10.1109/ACCESS.2020.3039403.
- [18] R. Singh, et.al, "Multi-Objective Optimization of Hybrid Renewable Energy System Using Reformed Electric System Cascade Analysis for Islanding and Grid Connected Modes of Operation," in *IEEE Access*, vol. 6, pp. 47332-47354, 2018, doi: 10.1109/ACCESS.2018.2867276.
- [19] S. Mehdi Rakhtala Rostami and Z. Al-Shibaany, "Intelligent Energy Management for Full-Active Hybrid Energy Storage Systems in Electric Vehicles Using Teaching–Learning-Based Optimization in Fuzzy Logic Algorithms," in *IEEE Access*, vol. 12, pp. 67665-67680, 2024, doi: 10.1109/ACCESS.2024.3399111.
- [20] L. Malle, et.al, "A Single Phase Grid-Integrated PV System Using Cascaded PI and PR Controller for Power Quality Improvement," 2022 IEEE 10th PIICON, New Delhi, India, 2022, pp. 1-6, doi: 10.1109/PIICON56320.2022.10045224.