Power Quality Improvement and Fuzzy Logic MPPT Control of a Grid-Integrated Solar–Wind–Battery Hybrid Energy System

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Abstract: A multifunctional hybrid energy system integrating solar photovoltaic (PV) modules, a wind energy conversion unit, and a battery storage component is developed in this work. To overcome the limitations of conventional maximum power point tracking (MPPT) approaches such as slow convergence and inadequate performance under rapidly changing environmental conditions, a Mamdani-type fuzzy logic-based MPPT controller is proposed. This controller adaptively regulates the duty cycles of the DC–DC boost converters, enabling the system to extract maximum available power from both PV and wind sources in real time. The coordination of multiple energy sources is achieved without reliance on linearized models, enhancing system robustness under diverse operating scenarios. A phase-locked loop (PLL) mechanism ensures grid synchronization by aligning frequency and phase, while an LCL filter is introduced at the point of common coupling to suppress switching harmonics and maintain power quality within grid standards. The proposed control strategy improves transient response, reduces power fluctuations, and ensures efficient energy sharing among sources. Simulation results obtained using MATLAB/Simulink confirm the superior performance of the system in terms of stability, responsiveness, and harmonic reduction. The novelty of this work lies in the intelligent coordination of hybrid sources using a real-time fuzzy inference-based control framework, which ensures enhanced adaptability, efficiency, and power quality in grid-connected renewable energy systems.

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 significant increase in the share 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 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 Maximum Power Point Tracking (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 point of common coupling. This underscores the potential of fuzzy logic-driven MPPT control to significantly enhance power quality and stability in grid-connected renewable energy systems.

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 flowbatteries [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 penetration of hybrid renewable energy resources, Hybrid Energy Systems (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 anotherpower 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 discusses the MATLAB/simulation setup along with the obtained results. Finally, Section V summarizes the key findings and concludes the study.

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. 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.

Control Methodology

Modelling of Solar PV cell:

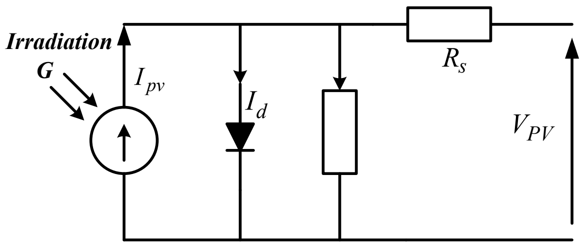

Fig. 2 circuit of a PV cell

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

$$I = I_{pv} - I_d \tag{1}$$

whereI$_{pv}$ is the solar cell current and I$_d$ is the diode equation. The Schottky diode equation can be written as

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

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

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

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

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

I_{pv} is the solar current, while I_o is the saturation current. R_p denotes parallel equivalent resistance, R_s denotes series equivalent resistance, and $V_t$denotes the thermal voltage of a solar PV cell with N_s cells linked in series. The PV cell current is affected by sun irradiation and temperature. The temperature-diode current may be expressed as:

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

Here, $E_g$represents the semiconductor band gap.

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 generated by the 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 is the swept area, V_W is the 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 is the rotor speed of the wind turbine and R is the 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 model produced by the generator is given as

$$T_{em} = \frac{3}{2} p \lambda_m i_q \tag{10}$$

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

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, power quality, and system responsiveness in the hybrid energy system.

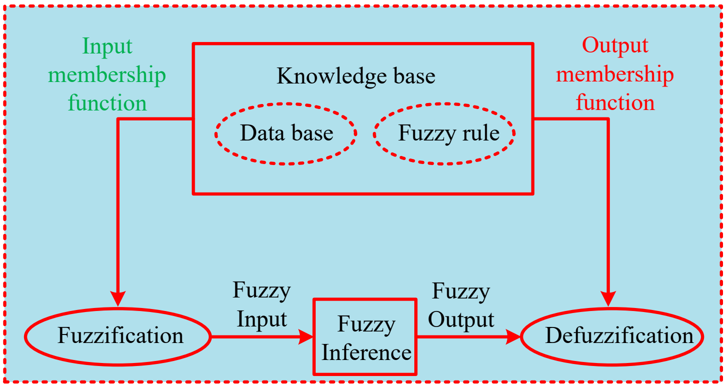

Fig.3 Fuzzy based logic controller block diagram

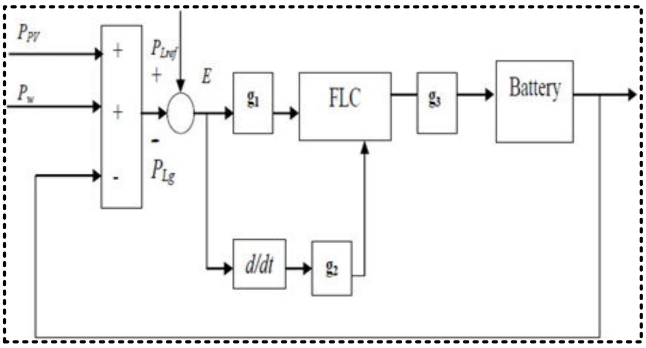

Fig. 4 Control block diagram of hybrid energy system

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 (EEE). 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.

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.

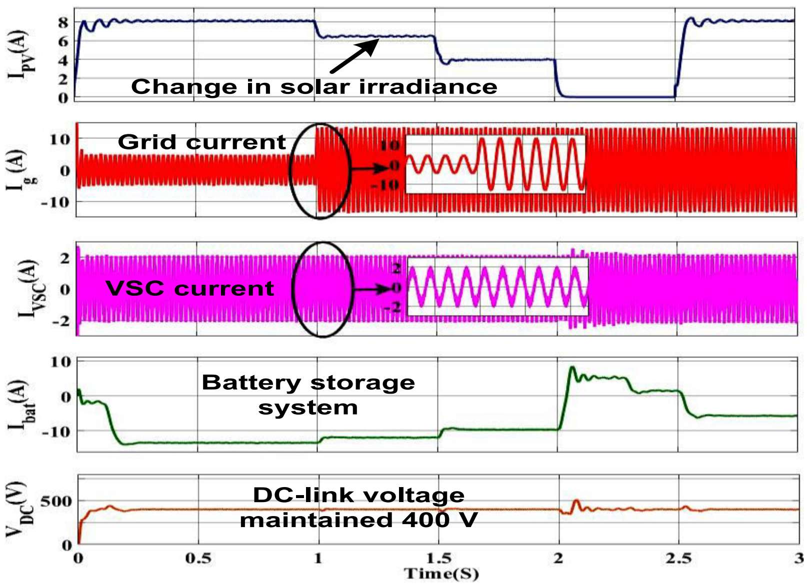

Fig.5 System parameters during change in solar irradiance

The waveforms in fig. 5 illustrate the dynamic behaviour of a hybrid renewable energy system 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 exchange 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.

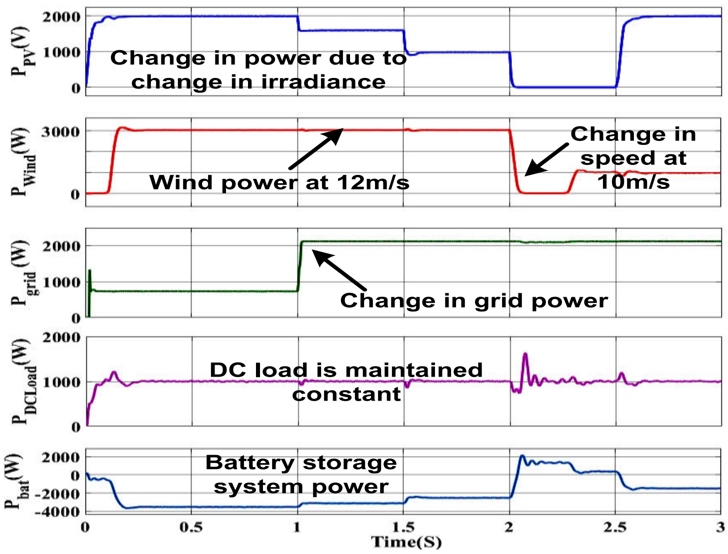

Fig.6 System performance during dynamic behaviour

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 from 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.

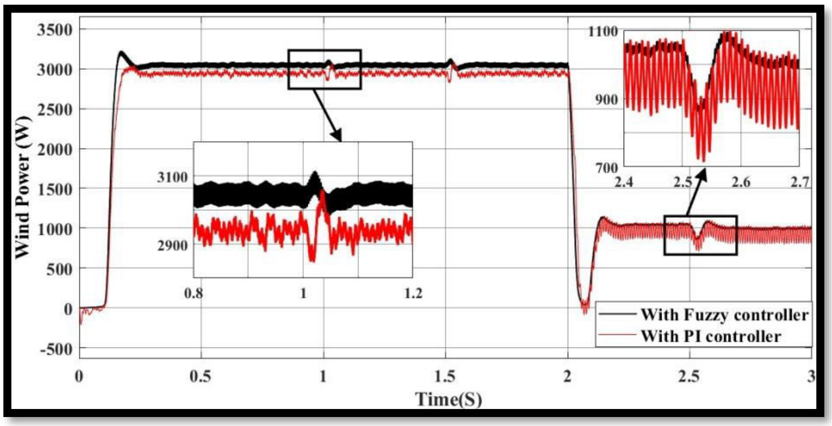

Fig.7 Wind power extraction

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.

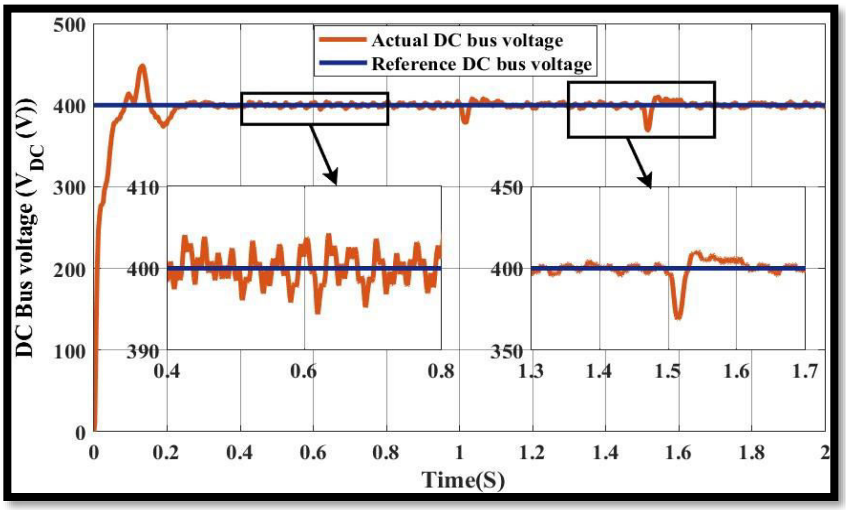

Fig.8 Comparison of the DC bus voltage with the reference voltage

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.

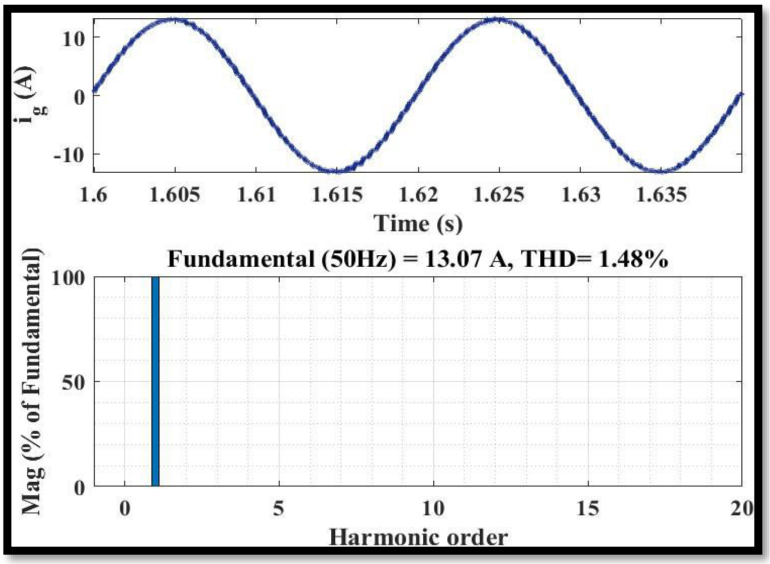

Fig.9 THD of grid current

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.

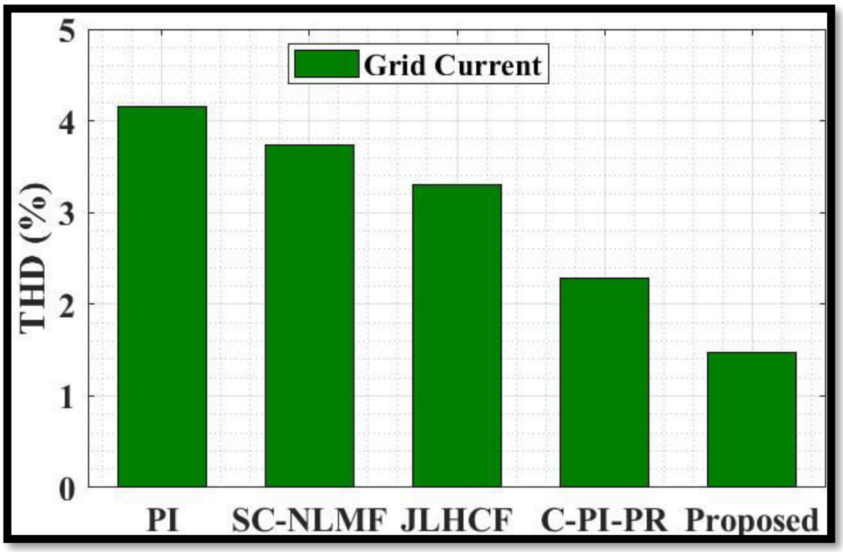

Fig.10 Comparative analysis of Grid current THD

Figure 10 presents a comparative analysis 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.

Conclusion

A MATLAB-based implementation of a fuzzy logic-controlled hybrid energy storage system incorporating a 3 kW wind energy conversion system and a 2 kW solar photovoltaic array has been developed to enhance power quality in grid-connected 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 harmonics, achieving a Total Harmonic Distortion (THD) of 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.

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