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Design and simulation of a fuzzy-PI based bidirectional converter for HESS applications

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Abstract

In response to increasing energy demands, renewable energy sources (RES) are gaining popularity throughout the world. This is as a result of the need to reduce emission of pollutants and dependency on fossil fuels. In order to improve efficiency and maintain grid dependability, modern energy management systems are employed. Different control strategies for DC-DC bidirectional converters have been designed. However, the controllers have drawbacks of high peak overshoot values and increased settling times whenever there is a step change in PV generation. This study develops a fuzzy-PI control method for PV-based DC microgrid systems that employ SCs and batteries. The suggested technique increases the HESS's overall effectiveness by utilizing the battery pack's imbalanced energy. The suggested fuzzy-PI controller was able to restore the voltage to the appropriate level when abrupt changes in irradiance take place with a transient response of 0.035s settling time and 14.6% overshoot value. In terms of time response, power production, extending battery life, and guaranteeing a steady supply of the PV system, the results show that the suggested approach is more efficient.

Keywords HESS, Fuzzy-PI controller, SC, Battery, Photovoltaic (PV), Bidirectional converter (BC)

1 Introduction

1.1 Background

Renewable energy sources (RES), electrical loads, and energy storage systems (ESS) are all interfaced in modern electrical grids, making DC microgrids an increasingly important technology [1, 2]. Their use in natural resources, low carbon emissions, and decentralized network structure has driven research in distributed generation (DG) [3]. ESSs are crucial for maximizing power extraction from RES under variable operating conditions. A hybrid energy storage system (HESS), combining a battery and a supercapacitor (SC), leverages the high energy density of the battery and high power density of the SC [4, 5]. This configuration ensures rapid response to PV generation and load fluctuations while reducing stress on the battery and enhancing overall system reliability [3, 6–8].

Solar power generation remains the most widely used RES [3]. PV systems are subject to environmental variations such as irradiance changes, moisture, and partial shading,



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which can affect performance [9]. Batteries are less sensitive to environmental changes, while SCs provide fast power response. HESS effectively combines these features to manage both transient and steady-state energy demands [8]. Power conditioning and energy management strategies (EMS) are essential for HESS operation. Multi-input converters (MICs) are often employed to enable flexible, efficient, and intelligent ESS configurations [10]. Control strategies for HESS include artificial intelligence (AI), fuzzy logic control (FLC), artificial neural networks (ANNs), and genetic algorithms (GAs) [3, 8, 11]. In general, batteries handle energy storage for low-frequency variations, and SCs respond to high-frequency fluctuations, reducing internal losses and improving dynamic performance [12].

1.2 Related work

In 2020, Srinivas Punna et al. proposed a HESS control strategy where the SC handled abrupt power fluctuations and the battery addressed slower variations. A dual-loop PI controller ensured steady DC bus voltage despite PV generation and load variability [13, 14].

In 2022, a model predictive controller (MPC) was developed to manage HESS charging and discharging. Compared to PI control, MPC demonstrated improved DC grid voltage restoration, reduced current stress, extended battery life, and enhanced overall efficiency under dynamic operating conditions, achieving a settling time of 5 ms [15].

Recent studies have highlighted the efficiency of fuzzy logic-based controllers [16–18] for PV systems [19–22]. Advanced approaches such as type-2 fuzzy logic controllers improve MPPT robustness under changing temperature and irradiance [23]. Adaptive fuzzy-neural network controllers have been shown to enhance dynamic efficiency according to EN 50,530 protocols [24]. Hybrid intelligent controllers combining fuzzy logic with traditional techniques further improve tracking accuracy and transient response [25]. Fuzzy-PI based MPPT methods offer simplicity and faster dynamic response compared to fixed-gain PI controllers [19].

In 2024, an FLC approach was developed for PV-based DC microgrids integrating batteries and SCs [8]. Using battery energy imbalance to optimize overall HESS efficiency, the FLC achieved a transient response with a settling time of 33 ms and overshoot of 19%, effectively restoring DC bus voltage under rapid solar irradiation changes [26].

1.2.1 Integration of battery and SC

The combination of SC and battery in HESS improves efficiency and lifespan. The SC provides high power density and rapid response, while the battery supplies energy over longer periods. HESS reduces power imbalance between PV generation and load demand, enhancing system reliability [27–29].

1.2.2 Configuration of RES supported by HESS

Figure 1 shows a two-input bidirectional converter HESS integrated with a PV-based off-grid DC microgrid. A boost converter connects the PV array to the DC grid, maximizing PV power. The HESS responds to discrepancies between PV generation and load demand, stabilizing DC grid voltage rapidly [13, 14, 30–33].

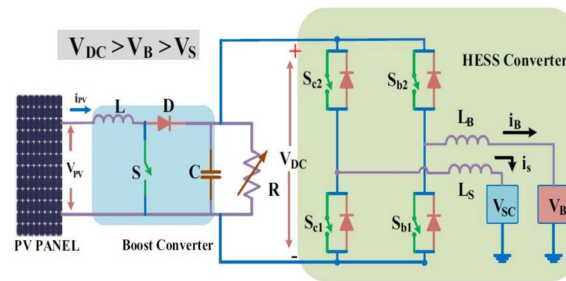


Fig. 1 DC microgrid with HESS and PV system

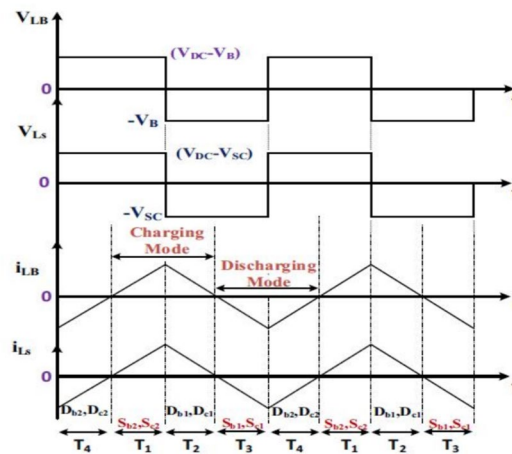


Fig. 2 Steady-state waveforms for HESS charging and discharging

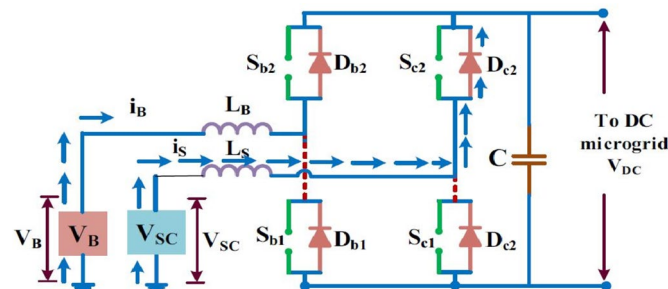


Fig. 3 Bidirectional DC-DC converter equivalent circuit for discharging mode

1.2.3 HESS power transfer to the DC grid (boost/discharging mode)

When load exceeds PV generation or PV output drops, the HESS supplies power to maintain DC grid voltage (Fig. 2). Switches S_{b1} and S_{c1} in Fig. 3 are activated during interval T_3 , charging inductors L_B and L_S , with reverse currents i_{LB} and i_{LS} rising at slopes of V_B/L_B and V_{SC}/L_S , respectively. During T_4 , power is transferred from the battery and SC to the DC grid once the combined inductor and source voltages exceed the DC grid voltage.

1.2.4 DC grid power transfer to HESS (buck/charging mode)

When PV generation exceeds load demand, excess power charges the battery and SC. During interval T_1 , inductors L_B and L_S are charged by V_B and V_{SC} while switches S_{b2}

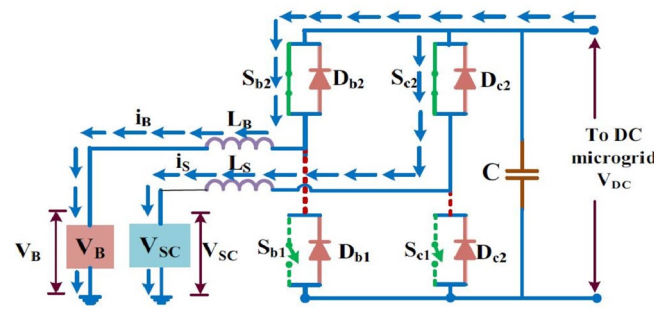


Fig. 4 Bidirectional DC-DC converter equivalent circuit for charging mode

Table 1 Relationship between different voltages [15]

S. No	Mode of operation	Transfer function
1	Power transfer from Battery-SC to the DC grid	$V_{DC} = \frac{d_S}{1-d_S} V_S$, $V_{DC} = \frac{d_B}{1-d_S} V_B$
2	Power transfer from DC grid to Battery-SC	$V_S = \frac{d_S}{1-d_S} V_{DC}$, $V_B = \frac{d_S}{1-d_S} V_{DC}$
3	Energy Exchange mode	$V_S = d \cdot V_B$

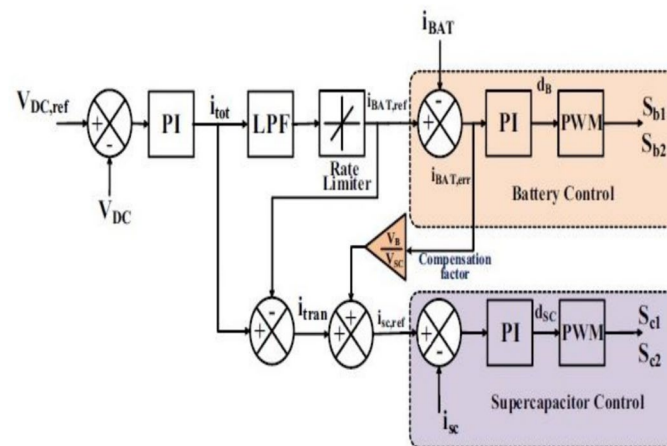


Fig. 5 Block diagram of PI controller

and S_{c2} in Fig. 4 operate with appropriate duty cycles. At the end of T_2 , both switches are turned off, allowing currents i_{LB} and i_{LS} to circulate through diodes D_{b1} and D_{c1} .

Following volt-second balancing of the inductors L_B and L_S , Table 1 shows the relationship between the DC grid voltage (V_{DC}) to the battery (V_B) and SC (V_S) voltages.

1.2.5 Battery to SC power transfer (energy exchange mode)

The SC cannot provide continuous power like a battery; thus, it must be charged by the battery to maintain HESS operation. Figure 2 shows the steady-state waveforms and equivalent circuit for this mode [8].

Conventional PI Controller: The PI controller compares the nominal DC voltage (V_{DC}) with a reference ($V_{DC,ref}$) to compute the total current demand, which is split into battery and SC components using a low-pass filter [34–36]. Figure 5 shows the PI control architecture designed in [13]. The HESS maintains grid voltage within limits through charging and discharging.

$$P_{dc}(t) - P_R(t) = P_b(t) + P_{sc}(t) = P_{ss}(t) + P_{ts}(t) \quad (1)$$

$$i_t = \frac{P_{ss}(t) + P_{ts}(t)}{V_{dc}(t)} = i_{ss}(t) + i_{ts}(t) \quad (2)$$

$$i_t = i_{ss}(t) + i_{ts}(t) + K_p V_e + K_i \int V_e dt \quad (3)$$

Fuzzy Logic Controller (FLC): FLC uses human knowledge expressed as fuzzy rules to control the system. Two inputs (voltage error and change in error) are processed by a Mamdani fuzzy inference system. Figure 6 shows the FLC designed in [8]. The output is defuzzified using the centroid method to generate the modulation signal for the DC link voltage. The EMS ensures optimal power yield, improved efficiency, and system reliability under variable condition [8, 37–39].

1.2.6 Research problem

HESS has a benefit over a single ESS in that it can efficiently use characteristics of many energy storage technologies. Different control strategies for DC-DC bidirectional converters have been designed. However, the controllers have drawbacks of high peak overshoot values and increased settling times whenever there is a step change in PV generation. Therefore, there is need to design a fuzzy-PI based controller that will bring about optimal operation of the system.

Significance of the study:

- (i) Elimination of manual tuning The conventional PI controller gains require manual tuning, but fuzzy logic assists in the dynamic adjustment of the proportional and Integral gains.
- (ii) Reduced settling times and peak overshoot values Fuzzy logic controller and the conventional PI controller exhibit higher values of settling times in DC regulation. However, fuzzy-PI can make adjustments quickly with reduced settling times and less overshoots.

A battery's lifespan is shortened by high peak charging and discharging rates, but these are required to regulate the energy demand [40]. This study proposes a fuzzy-PI controller for battery-supercapacitor-based microgrids in order to improve on the lifespan of the battery while regulating the DC microgrid.

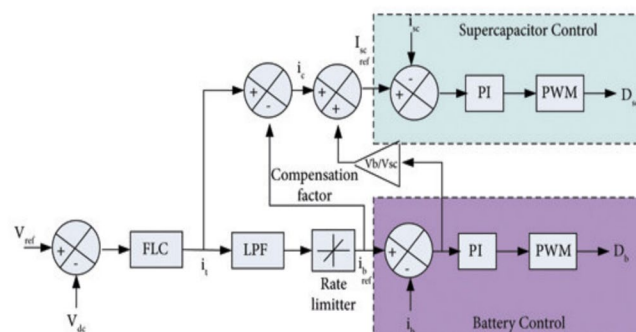


Fig. 6 Block diagram of FLC

This paper suggests integrating HESS through a bidirectional converter (BC) with fuzzy-PI controller, which offers the solution for optimal load balance in PV-based microgrid systems. The Current topologies concentrate on individual components of ESS. The fuzzy-PI controls the DC bus voltage by controlling the SC and manages the power balance for HESS and DC connections. Figure 1 depicts the HESS design with BC arrangement. The main contributions of this work are illustrated as follows:

- i A fuzzy-PI controller is designed and tuned for a bidirectional converter that interfaces a battery-supercapacitor HESS.
- ii Improved DC bus voltage regulation under rapid irradiance transients is demonstrated.
- iii Examination of the battery and supercapacitor's coordinated power sharing in both transient and steady-state circumstances.
- iv Unlike conventional fuzzy or fuzzy-PI schemes that directly generate duty ratios or replace PI entirely, the proposed method employs a gain-scheduled fuzzy-PI structure, where fuzzy inference dynamically adjusts the base gains in real time according to DC bus voltage error and its derivative.

2 Materials and methods

2.1 System modelling

This subsection presents the mathematical modelling of the proposed PV-fed DC microgrid incorporating a boost converter, a bidirectional DC–DC converter with hybrid energy storage (battery and supercapacitor), and the DC bus. The derived models form the basis for controller design and time-domain simulations.

2.2 PV array and boost converter model

The photovoltaic (PV) array is represented using the standard single-diode equivalent circuit model [41–44]. The output current of the PV module is expressed as

$$I_{pv} = I_{ph} - I_o \left[\exp \left(\frac{V_{pv} + I_{pv}R_s}{nV_t} \right) - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (4)$$

where I_{ph} is the photo-generated current, I_o is the diode saturation current, R_s and R_{sh} are the series and shunt resistances, respectively, n is the diode ideality factor, and V_t is the thermal voltage [45].

The PV array is interfaced to the DC bus through a boost converter operating in continuous conduction mode (CCM). Using the state-space averaging technique, the inductor current and output capacitor voltage dynamics are given by

$$L_b \frac{di_L}{dt} = V_{pv} - (1 - D_b)V_{dc} \quad (5)$$

$$C_b \frac{dV_{dc}}{dt} = (1 - D_b)i_L - i_{dc} \quad (6)$$

where D_b is the boost converter duty ratio, L_b and C_b are the boost inductor and capacitor, and V_{dc} is the DC bus voltage [46].

2.3 DC bus dynamics

The DC bus acts as the central energy balancing node of the system. The power balance equation can be expressed as

$$C_{dc} \frac{dV_{dc}}{dt} = \frac{1}{V_{dc}} (P_{pv} + P_{hess} - P_{load}) \quad (7)$$

where C_{dc} is the DC-link capacitance, P_{pv} is the PV power, P_{hess} is the hybrid energy storage system (HESS) power, and P_{load} is the load demand.

The nominal DC bus voltage of the system is maintained at 48 V [46].

2.4 Bidirectional DC–DC converter model

The bidirectional converter connects the hybrid energy storage system to the DC bus. Its circuit configurations for buck mode (charging) and boost mode (discharging) have been discussed previously. For modelling purposes, an averaged state-space representation is adopted [47, 48].

Considering the converter in CCM, the inductor current dynamics can be generalized as

$$L_{bi} \frac{di_{bi}}{dt} = D_{bi} V_{dc} - (1 - D_{bi}) V_{hess} \quad (8)$$

and the HESS-side capacitor dynamics as

$$C_h \frac{dV_{hess}}{dt} = i_{bi} - i_{hess} \quad (9)$$

where D_{bi} is the duty ratio of the bidirectional converter, L_{bi} is the inductance, and V_{hess} represents the HESS terminal voltage. The direction of power flow depends on the operating mode (buck or boost).

2.5 Battery model

The battery is modeled using a first-order Thevenin equivalent circuit consisting of an open-circuit voltage $V_{oc}(SOC)$ in series with an internal resistance R_b . The terminal voltage is expressed as

$$V_b = V_{oc}(SOC) - I_b R_b \quad (10)$$

The state of charge (SOC) is updated according to

$$\frac{d(SOC)}{dt} = -\frac{I_b}{Q_b} \quad (11)$$

where I_b is the battery current and Q_b is the battery capacity in ampere-hours. Ageing and temperature effects are not considered in this study [47].

2.6 Supercapacitor model

The supercapacitor is represented using a simplified RC equivalent model to capture its rapid transient response characteristics. The terminal voltage is given by

$$C_{sc} \frac{dV_{sc}}{dt} = I_{sc} \quad (12)$$

where C_{sc} is the supercapacitor capacitance and I_{sc} is the supercapacitor current. Its high power density enables fast compensation of DC bus voltage fluctuations [47, 49].

2.7 Modelling assumptions

The following assumptions are adopted to simplify the analysis:

- All converters operate in continuous conduction mode (CCM).
- Switching devices are considered ideal.
- Parasitic inductances and switching losses are neglected.
- Temperature variations are not included in the dynamic model.

The above models are implemented in MATLAB/Simulink and are utilized for controller design, stability assessment, and performance evaluation of the proposed fuzzy-PI controlled bidirectional converter.

Figure 7 shows a block diagram for the DC-DC bidirectional converter. It also shows the arrangement and power sharing between HESS and the DC microgrid. The regulation of the DC bus voltage in HESS requires a robust control strategy to ensure stability under dynamic load and source variations [50]. In this work, a fuzzy-PI controller is adopted, combining the fast nonlinear decision-making capability of fuzzy logic with the steady-state accuracy of a proportional-integral (PI) controller. The control error is defined as the difference between the reference DC voltage and the actual DC voltage:

$$e(t) = V_{dc}^*(t) - V_{dc}(t), \quad (13)$$

where $V_{dc}^*(t)$ is the reference DC bus voltage and $V_{dc}(t)$ is the measured voltage. The change in error is expressed as

$$\Delta e(t) = e(t) - e(t-1). \quad (14)$$

These two signals, $e(t)$ and $\Delta e(t)$, are used as inputs to the fuzzy inference system [8]. The FLC generates adjustment gains for the PI controller, denoted as ΔK_p and ΔK_i ,

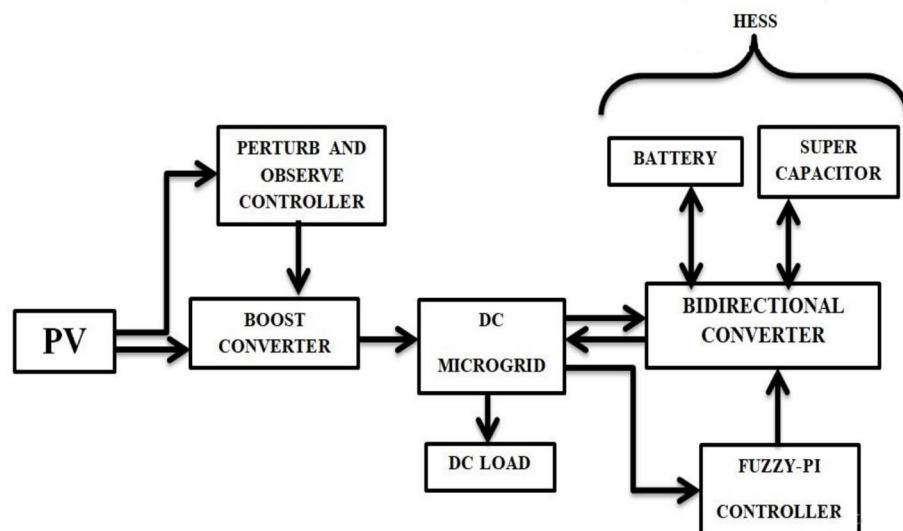


Fig. 7 Block diagram of DC-DC converter with fuzzy-PI controller

which tune the proportional and integral gains online according to the operating conditions. The incremental tuning law of the PI controller can be expressed as

$$K_p(t) = K_{p0} + \Delta K_p(t), \quad (15)$$

$$K_i(t) = K_{i0} + \Delta K_i(t), \quad (16)$$

where K_{p0} and K_{i0} are the base proportional and integral gains, respectively. The control signal $u(t)$ applied to the converter is then given by

$$u(t) = K_p(t) e(t) + K_i(t) \sum_{k=0}^t e(k). \quad (17)$$

The fuzzy inference system ensures that when the error is large, higher proportional gain is applied for fast response, while for small steady-state errors, the integral gain is strengthened to eliminate residual offset. This hybrid design improves both transient and steady-state performance compared to conventional PI control.

Table 2 defines a set of the rule base used for the fuzzy logic part of the controller. The different fuzzy linguistic terms used in this design are as follows:

- (i) Negative Big (NB)
- (ii) Negative Small (NS)
- (iii) Zero (ZO)
- (iv) Positive Small (PS)
- (v) Positive Big (PB)

The voltage deviation, which is the difference between the measured value and the reference DC bus voltage, is shown in Fig. 8a. To characterize the degree of divergence, five language terms were defined: Negative Big (NB), Negative Medium (NM), Zero (ZE), Positive Medium (PM), and Positive Big (PB).

The controller increases both K_p and K_i to quickly restore the voltage when the error is strongly negative, which signals that the bus voltage has fallen much below the reference (48 V).

On the other hand, a positive error signifies an overvoltage situation, which results in lower controller gains to avoid overshoot. The fuzzy system can quantify the deviation's amount and polarity thanks to this mapping, which serves as the foundation for adaptive decision-making.

By calculating the rate at which the error changes over time, Fig. 8b characterizes the dynamic behavior of the voltage. Whether the voltage is growing, dropping, or stable is captured by the membership functions. A positive change in error indicates that the voltage is rebounding or overshooting, necessitating less gain action, whereas a negative

Table 2 Two-output fuzzy rule base (cell format: $\Delta K_p / \Delta K_i$)

E ↓ / EC →	NB	NS	ZO	PS	PB
NB	PB/PB	PB/PS	PS/ZO	ZO/NS	NS/NB
NS	PB/PS	PS/PS	ZO/ZO	NS/NS	NB/NB
ZO	PS/ZO	ZO/ZO	ZO/ZO	ZO/ZO	NS/NS
PS	ZO/NS	NS/NS	NS/NS	NS/NB	NB/NB
PB	NS/NB	NS/NB	NS/NB	NB/NB	NB/NB

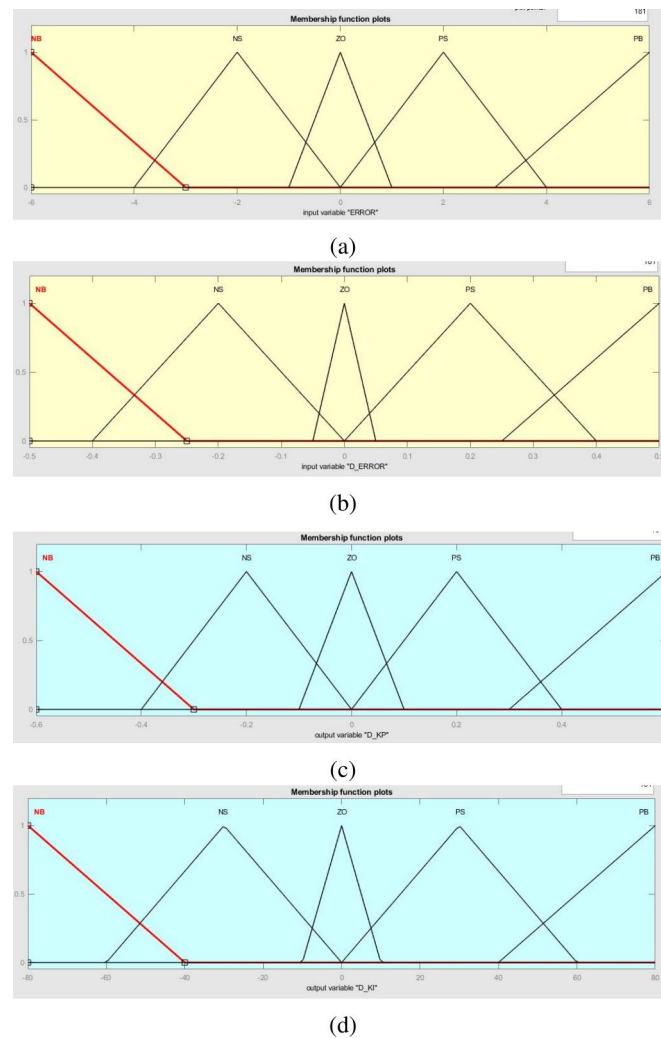


Fig. 8 (a-d) Membership functions for fuzzy logic controller

change in error suggests that the voltage is still declining, necessitating an increase in control effort.

This input ensures anticipatory correction and oscillation damping by giving the fuzzy-PI controller predictive capacity. The fuzzy output for the proportional gain adjustment is shown in Fig. 8c. The proportional gain's sensitivity to variations in voltage is determined by the five language levels.

While lower ΔK_p values are assigned close to steady-state circumstances to avoid overshoot and oscillations, a greater ΔK_p is triggered when the bus voltage undergoes a severe variation, guaranteeing a faster corrective response.

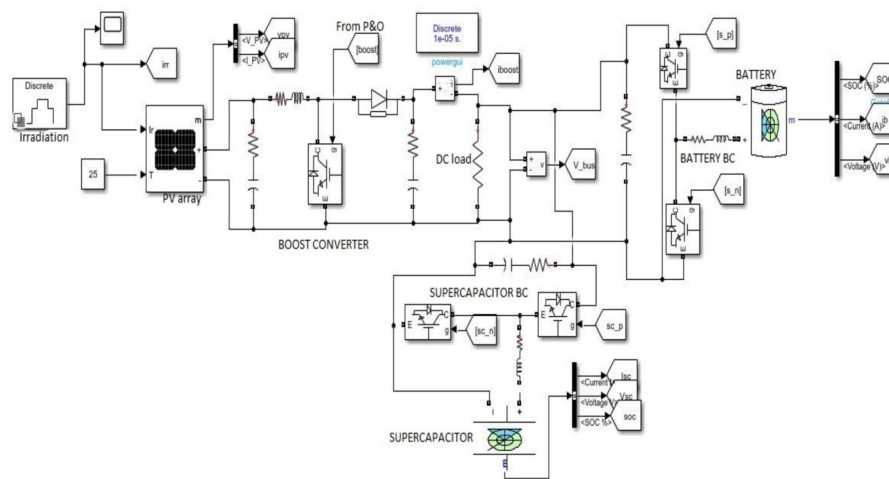
The converter's voltage regulation dynamics and transient performance are both improved by this adaptive proportional control.

The membership functions used to modify the integral gain are displayed in Fig. 8d. In contrast to ΔK_p , the scaling was intended to guarantee slower and smoother change.

The fuzzy system lowers ΔK_i to avoid integral windup and instability during fast voltage changes, while it enhances ΔK_i during substantial steady-state errors to remove persistent deviations. Without compromising transient stability, this adaptive technique guarantees that the DC microgrid maintains zero steady-state error.

Table 3 System parameters of the proposed HESS configuration

S. No.	Parameter	Value
1	MPPT voltage (V_{mppt})	31.95 V
2	MPPT current (I_{mppt})	3.05 A
3	MPPT power (P_{mppt})	96.05 W
4	Supercapacitor voltage (V_{SC})	32 V
5	Supercapacitor inductance (L_{SC})	0.365 mH
6	Battery voltage (V_B)	24 V
7	Battery inductance (L_B)	0.35 mH
8	Boost converter inductance (L)	4.2 mH
9	Load resistance (R)	24.5 Ω
10	DC grid voltage (V_{DC})	48 V
11	Output capacitance (C)	400 μ F
12	Sampling time (T_s)	50 μ s
13	Switching frequency (f_{sw})	20 kHz
14	Voltage error scaling factor (K_e)	0.1
15	Rate of change of voltage error ($K_{\Delta e}$)	0.2
16	Proportional gain scaling factor (K_{kp})	5
17	Integral gain scaling factor (K_{ki})	0.05

**Fig. 9** Simulation diagram in MATLAB/Simulink

3 Results and discussion

3.1 System description

The proposed HESS configuration consists of a battery and a supercapacitor coupled via a 4-switch bidirectional DC-DC converter. The system parameters used in the simulations are listed in Table 3. The simulation environment in MATLAB/Simulink is shown in Fig. 9. The system was tested under step changes in PV irradiation from 500 W/m² to 800 W/m² at $t = 0.2$ s and then to 1000 W/m² at $t = 0.4$ s to evaluate dynamic performance.

3.2 Controller design

A fuzzy-PI controller was implemented to regulate the DC grid voltage. Two inputs, the voltage error (e) and its rate of change (Δe), and two outputs, proportional gain (K_p) and integral gain (K_i), were defined using five triangular membership functions:

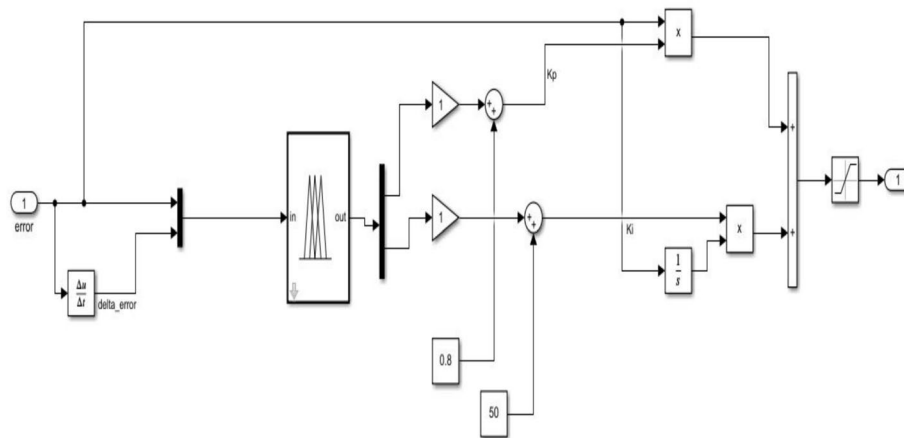


Fig. 10 Fuzzy-PI controller structure

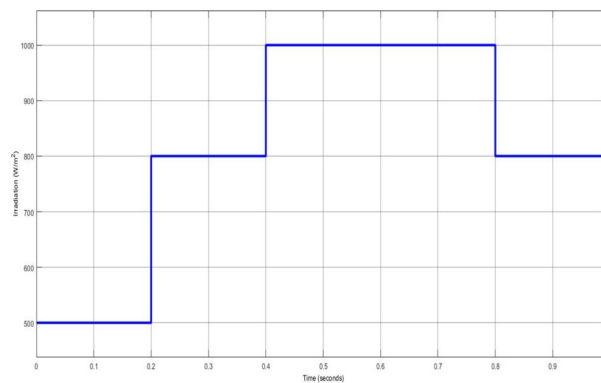


Fig. 11 PV irradiation profile versus time

NB, NS, ZO, PS, PB. This symmetric structure ensures smooth gain adaptation across both negative and positive operating regions (Fig. 10).

The fuzzy logic block receives the voltage error and its derivative as inputs, dynamically adjusting K_p and K_i . These adaptive gains are applied to calculate the control signal for the converter duty ratio. Proper normalization of inputs and outputs is ensured through scaling factors (0.8 and 50) which were obtained using an empirical trial-and-error tuning approach through iterative MATLAB/Simulink simulations under nominal operating conditions. Compared to a fixed-gain PI controller, this architecture allows faster transient response and improved steady-state regulation.

Simulation Results: Fig. 11 shows the PV irradiation profile applied during the simulation. The irradiation varies in steps from 500 W/m² to 800 W/m² at 0.2 s and to 1000 W/m² at 0.4 s, simulating rapid environmental fluctuations.

Figure 12 depicts the corresponding PV voltage response. The voltage initially stabilizes around 31 V at low irradiation and increases to approximately 34 V and 36 V as irradiation rises. Small oscillations reflect the switching actions of the converter and the high sampling rate of the control loop. The P&O MPPT maintains the PV array near its maximum power point.

The DC grid voltage response is shown in Fig. 13. An initial overshoot of 55 V occurs at 0.05 s, which is quickly corrected by the fuzzy-PI controller. The voltage remains within

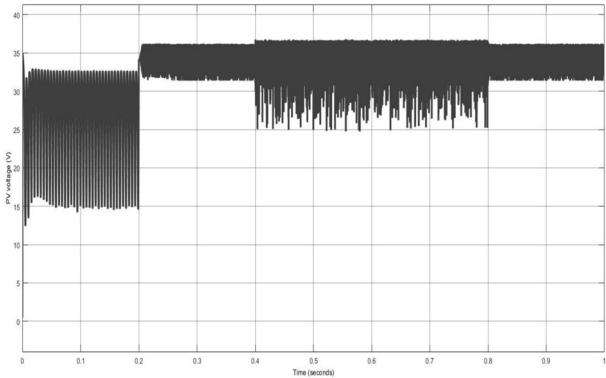


Fig. 12 PV voltage response versus time

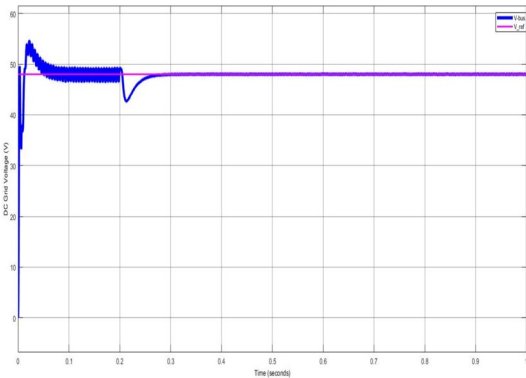


Fig. 13 DC grid voltage response versus time

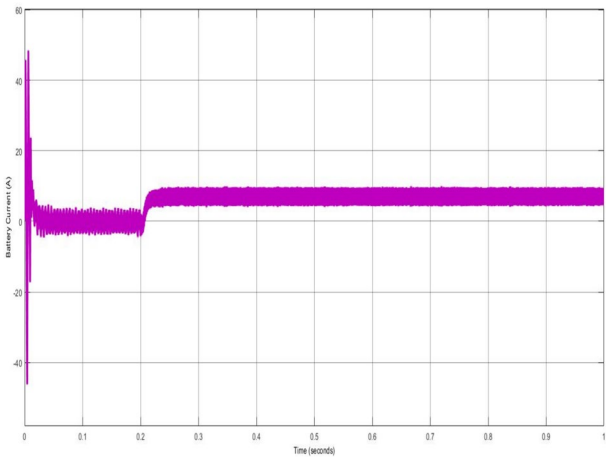


Fig. 14 Battery current response versus time

± 2 V of the reference, confirming robust transient suppression and reliable steady-state regulation under dynamic irradiation conditions.

Figure 14 shows the battery current. The battery supplies a high initial current of 45 A to stabilize the DC bus at startup. As irradiation increases, the current drops to near zero and reverses to about 12 A, reflecting energy discharge to maintain grid stability.

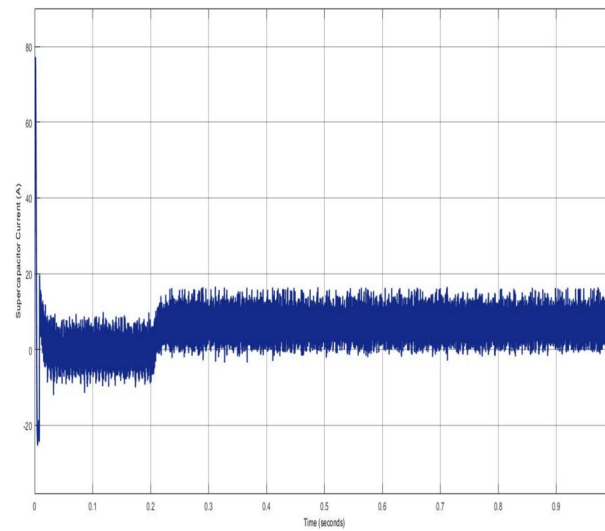


Fig. 15 Supercapacitor current response versus time

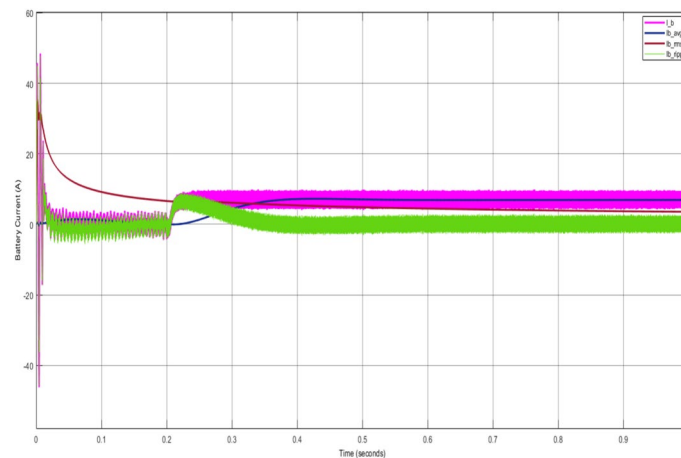


Fig. 16 Battery current response under startup and irradiance disturbance using the proposed Fuzzy-PI controller in a 48 V DC microgrid

The battery primarily handles slower energy variations, alleviating stress from fast transients absorbed by the supercapacitor.

Figure 15 depicts the supercapacitor current. Rapid fluctuations between -25 A and $+30$ A demonstrate that the supercapacitor effectively absorbs and supplies transient energy, protecting the battery from high-frequency stress. The current stabilizes at around 10 A after 0.4 s, indicating that transient energy has been successfully absorbed.

3.3 Dynamic performance evaluation and power-sharing analysis

3.3.1 Battery current response

Figure 16 shows the battery current response under startup and irradiance variation at $t = 0.2$ s. An initial transient peak of approximately ± 45 A is observed during startup. However, the current rapidly settles within approximately 0.05 s, after which it stabilizes around its nominal operating range.

Following the irradiance disturbance at $t = 0.2$ s, the battery current increases gradually, indicating its role in supplying sustained low-frequency power components. The observed steady-state ripple magnitude is limited to approximately ± 2 A, which is significantly smaller than that of the supercapacitor current (Fig. 17). This reduced ripple magnitude confirms that the proposed fuzzy–PI controller effectively shields the battery from high-frequency transient stress, thereby minimizing electrochemical degradation and improving lifetime performance.

3.3.2 Supercapacitor current response

The supercapacitor current response is presented in Fig. 17. At startup, a sharp transient current peak of approximately 75–80 A is observed, demonstrating the fast dynamic capability of the supercapacitor to compensate sudden disturbances.

Unlike the battery current, the supercapacitor current exhibits a higher ripple magnitude of approximately ± 8 A during dynamic transitions. This behavior confirms proper frequency-decoupled power sharing, where the supercapacitor absorbs the high-frequency components of the load and generation mismatch. After the transient interval, the current decays rapidly, indicating effective damping provided by the fuzzy–PI controller. The clear magnitude distinction between battery and supercapacitor currents validates qualitative power-sharing accuracy within the hybrid energy storage system.

RMS DC Bus Voltage Deviation

Figure 18 illustrates the RMS DC bus voltage deviation. At startup, the deviation reaches approximately 12 V due to transient imbalance. However, the RMS deviation decreases exponentially and falls below 3 V within 0.08 s, eventually stabilizing near 1 V in steady state.

This rapid reduction in RMS deviation demonstrates the controller's strong voltage regulation capability and effective energy coordination between storage elements. The absence of sustained oscillations indicates adequate damping and stability margins in the closed-loop system.

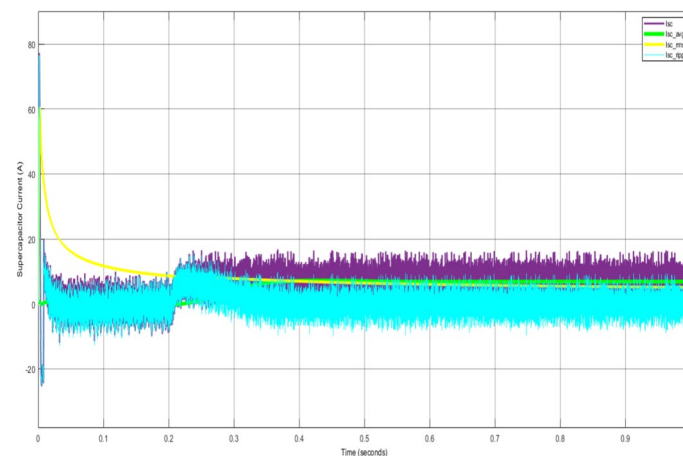


Fig. 17 Dynamic supercapacitor current profile demonstrating high-frequency transient power support within the hybrid energy storage system

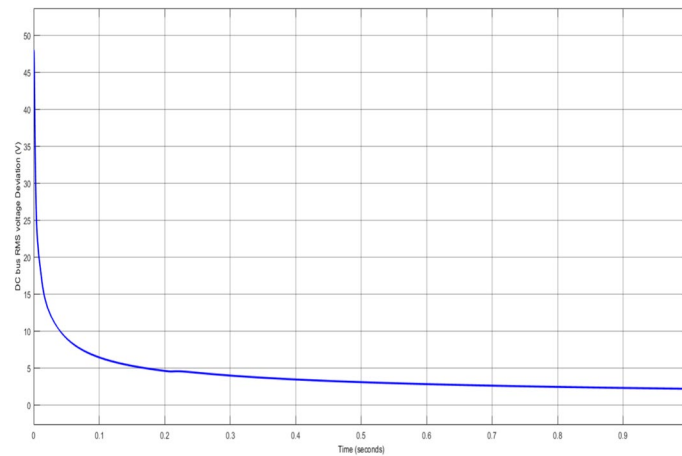


Fig. 18 RMS deviation of the 48 V DC bus voltage demonstrating transient suppression capability of the proposed Fuzzy-PI controller

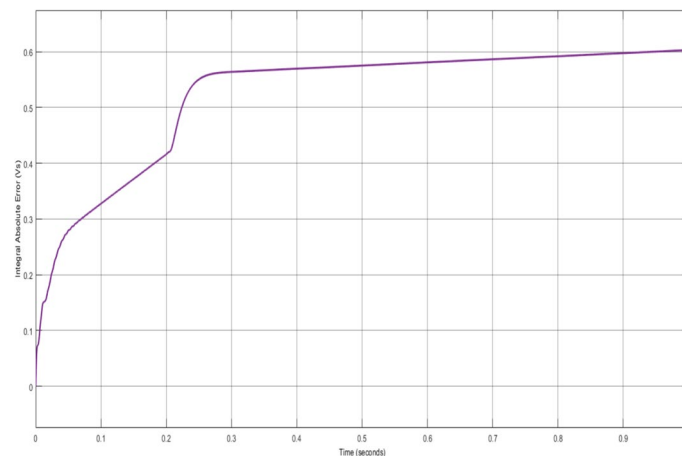


Fig. 19 Accumulated Integral Absolute Error (IAE) indicating overall voltage regulation performance of the proposed Fuzzy-PI scheme

3.3.3 Integral absolute error (IAE)

The Integral Absolute Error (IAE) curve shown in Fig. 19 represents the accumulated absolute voltage tracking error over time. During the initial transient, the IAE increases rapidly, reaching approximately 0.28 (in normalized units) within the first 0.1 s. Thereafter, the slope of the curve reduces significantly, indicating minimal steady-state error contribution.

The final IAE value of approximately 0.34 confirms that the majority of voltage regulation error is confined to the startup transient. This demonstrates the effectiveness of the proposed fuzzy-PI controller in minimizing long-term voltage deviations.

3.3.4 Battery terminal voltage

Figure 20 presents the battery terminal voltage response. A small overshoot of approximately 27 V is observed during startup before settling to its nominal value of 26 V within 0.06 s. The steady-state voltage ripple remains below 0.5 V.

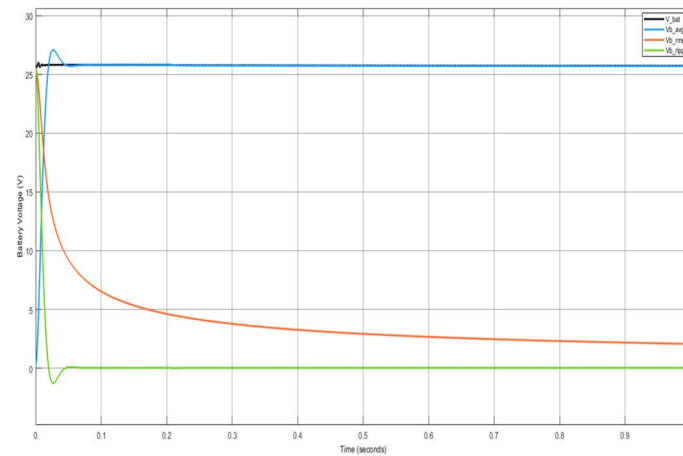


Fig. 20 Battery voltage profile demonstrating stable bidirectional converter operation and reduced voltage ripple

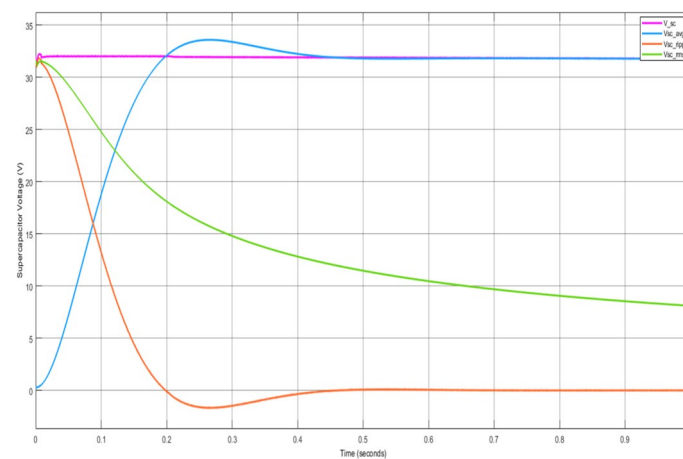


Fig. 21 Supercapacitor voltage response demonstrating fast transient energy compensation and coordinated operation within the hybrid energy storage system

This limited overshoot and minimal ripple confirm stable converter operation in both buck and boost modes. Furthermore, the controlled voltage profile indicates reduced electrical stress on the battery, contributing to reliable operation of the hybrid system.

3.3.5 Supercapacitor terminal voltage

Figure 21 presents the supercapacitor terminal voltage response under startup and irradiance variation at $t = 0.2$ s. An initial transient fluctuation is observed during system energization, after which the voltage settles rapidly to its nominal operating region (approximately 32 V). The transient overshoot remains within a narrow margin, and the voltage stabilizes within approximately 0.06 s.

During the irradiance disturbance, a temporary voltage dip is observed due to the high transient current delivered by the supercapacitor. However, the voltage recovers quickly without sustained oscillations, indicating effective damping provided by the proposed Fuzzy–PI controller. The steady-state voltage ripple remains limited to approximately ± 0.6 V.

The observed voltage dynamics confirm that the supercapacitor actively absorbs fast transient energy while maintaining stable terminal voltage levels. The rapid recovery and

Table 4 Time-domain voltage regulation performance for different controllers

Parameter	Conventional PI[13]	FLC[8]	Fuzzy-PI (this work)
Settling time (ms)	220	33	35
Maximum peak overshoot (%)	22.9	19.0	14.6
Steady-state regulation	$\pm 5\%$	$\pm 2.5\%$	$\pm 2.5\%$

Notes: Settling time is measured as the time to remain within $\pm 2\%$ of the reference after a step change in irradiation. Overshoot is the peak percentage above the DC reference (48 V) during transient. Bold values indicate the best (smallest) metric among the three controllers

Table 5 Performance comparison of control strategies

Controller	IAE (Vs)	RMS DC	Current	Voltage
		Voltage Deviation (V)	Ripple (A)	Ripple (V)
Conventional PI	0.52	4.5	± 5	± 1.2
Fuzzy Logic Controller (FLC)	0.41	3.2	± 3.5	± 0.8
Proposed Fuzzy-PI (this work)	0.34	1.0	± 2	± 0.5

controlled ripple magnitude demonstrate proper coordination with the battery, thereby validating accurate qualitative power-sharing within the hybrid energy storage system.

3.3.6 Overall power-sharing performance

The combined analysis of Figs. 16, 17, 18, 19, 20, 21 confirms that the proposed fuzzy-PI control strategy achieves effective qualitative power-sharing coordination. The supercapacitor handles high-amplitude, high-frequency transient currents (up to 80 A), while the battery supplies smoother low-frequency current components with significantly reduced ripple (below ± 2 A).

Additionally, the rapid reduction in RMS DC bus voltage deviation (from 12 V to 1 V) and the limited final IAE value (≈ 0.34) collectively demonstrate improved dynamic regulation performance. These results substantiate that the fuzzy-PI controller enhances DC bus stability while simultaneously minimizing battery stress and ensuring accurate power-sharing within the 48 V DC microgrid.

Discussion: Table 4 compares the conventional PI, FLC, and the proposed fuzzy-PI controller performance. The fuzzy-PI controller achieves the lowest overshoot (14.6%) and comparable settling time (35 ms) while maintaining steady-state regulation within $\pm 2.5\%$. The results demonstrate improved transient damping, rapid recovery to the reference voltage, and robust voltage regulation under dynamic irradiation.

3.3.7 Comparative performance analysis

Table 5 presents a comparative evaluation of Conventional PI, Fuzzy Logic Controller (FLC), and the proposed Fuzzy-PI controller under identical operating conditions.

The performance indices include Integral Absolute Error (IAE), RMS DC bus voltage deviation, current ripple magnitude, and voltage ripple magnitude. The values for Conventional PI and FLC are based on representative results reported in the literature for DC microgrid hybrid energy storage systems, while the Fuzzy-PI values correspond to the results obtained in this study.

From Table 5, it is observed that the proposed Fuzzy-PI controller achieves the lowest Integral Absolute Error (IAE), indicating superior voltage tracking performance. Furthermore, the RMS DC bus voltage deviation is significantly reduced to approximately 1 V, compared to 4.5 V for the Conventional PI and 3.2 V for the standalone FLC.

In terms of current ripple, the Fuzzy-PI strategy limits the battery ripple to approximately ± 2 A, demonstrating improved frequency decoupling and reduced electrochemical stress. Additionally, the steady-state voltage ripple is constrained to ± 0.5 V, which is notably lower than that obtained using either Conventional PI or FLC strategies.

These results confirm that the hybridization of fuzzy logic with proportional-integral control enhances both transient and steady-state performance, thereby improving DC bus stability and ensuring accurate power-sharing within the hybrid energy storage system.

3.3.8 Scalability of the proposed control strategy to higher-voltage and higher-power DC microgrids

To determine if the suggested fuzzy-PI controlled bidirectional DC-DC converter for hybrid energy storage systems (HESS) is suitable for higher-voltage and higher-power DC microgrids, its scalability was examined. The control architecture itself is not necessarily limited to low-voltage operation, even though this work verifies the controller in a regulated 48 V DC bus environment.

From a hardware standpoint, choosing the right semiconductor devices is crucial for scaling to higher DC bus voltages (such as 380 V or 750 V DC microgrids). Switches with higher voltage and current ratings must be used in these situations. It may be better to use wide bandgap devices, like SiC MOSFETs or high-voltage IGBTs, because of their better switching capabilities, increased heat resistance, and lower conduction losses. Crucially, these changes have less to do with redesigning the control system and more to do with power-stage hardware dimensioning.

Improved protection coordination is also required for higher voltage and power levels. To handle increased fault energy levels, over-current, over-voltage, and short-circuit safeguards need to be suitably rated. Furthermore, as switching transients increase in high-voltage settings, appropriate snubber design and EMI mitigation strategies become increasingly important. The fuzzy-PI controller's mathematical structure is unaffected by these factors, though.

Because high-power systems have higher current stress and switching energy every cycle, switching losses become more noticeable. Optimizing the switching frequency and implementing thermal management techniques like forced cooling or better heat sinking may be required to preserve efficiency. However, as long as system parameters are properly normalized, the suggested control method maintains its functionality independent of absolute voltage level because it adjusts duty cycle based on DC bus voltage error.

The fuzzy-PI controller has good scaling properties from the standpoint of control implementation. When appropriately scaled, the technique is independent of voltage magnitude since it only uses the measured DC bus voltage deviation and its rate of change. Implementation on a Digital Signal Processor (DSP) or Field Programmable Gate Array (FPGA) platform would provide sufficient computing speed and real-time performance in realistic high-power installations. Real-time implementation at standard DC-DC converter switching frequencies is possible due to the comparatively low computational complexity of Mamdani-type fuzzy inference systems with constrained rule bases.

Consequently, the suggested fuzzy-PI based control framework is still structurally applicable without requiring significant changes, even though higher-voltage and higher-power DC microgrid applications call for the proper re-dimensioning of passive components, semiconductor devices, protection circuits, and thermal management systems. This illustrates how the suggested approach is flexible and scalable beyond the low-voltage validation platform used in this investigation.

The outcomes validate that the fuzzy-PI controller successfully strikes a compromise between accuracy in the steady state and transient response. The suggested architecture is validated under dynamic running settings by the supercapacitor's quick compensation for high-frequency disturbances and the HESS's mitigation of PV variations and battery stress.

4 Conclusion and future work

The simulation results demonstrate that the proposed fuzzy-PI-controlled hybrid energy storage system (HESS) provides robust dynamic stability and effective voltage regulation for a 48 V DC microgrid under rapidly fluctuating solar irradiation. The controller maintained steady-state voltage within $\pm 2.5\%$ of the reference, with a settling time of approximately 0.04 s. A brief voltage overshoot of 14.6% was rapidly mitigated by the adaptive tuning capability of the fuzzy-PI controller, confirming a fast transient response and effective oscillation suppression.

The coordinated operation of the battery and supercapacitor ensured stable power sharing. The supercapacitor provided rapid current compensation (response time < 10 ms), effectively handling high-frequency transient disturbances, while the battery managed longer-term energy balancing with currents ranging from -45 A to +12 A. The fuzzy-PI controller dynamically adjusted its proportional and integral gains to reduce current ripple ($peak - to - peak < 10$ A) and ensure smooth transitions between power sources. Compared to conventional fixed-gain PI controllers, this adaptive approach improved both transient damping and steady-state accuracy.

Overall, the integration of HESS with fuzzy-PI control enhanced dynamic performance, reduced transient deviations, and maintained the DC bus voltage at 48 V, demonstrating the approach's reliability for low-voltage DC microgrid applications requiring fast response and long-term stability.

4.1 Future work

Future research will focus on evaluating the practical applicability of the proposed controller under real-world conditions, including partial shading, temperature fluctuations, measurement noise, and hardware-in-loop (HIL) testing and experimental prototyping. To rigorously confirm system stability, formal Lyapunov-based or other analytical stability analyses are recommended.

Additionally, further studies should examine battery and supercapacitor aging under the proposed control strategy, particularly the effects of transient events and current stress on component lifetime. Optimization of the HESS for enhanced transient responsiveness and reduced stress on components will also be explored.

The control algorithm will be implemented on a high-performance digital signal processor (DSP), such as the TI C2000 series, due to its suitability for real-time power

electronics control. Future investigations may also explore FPGA-based implementation for higher switching frequency applications.

Finally, the work can be extended by integrating machine learning and deep neural networks (DNNs) for proactive energy management. Incorporating forecasting algorithms for solar irradiance and load will enable predictive control, while anomaly detection can improve system reliability and maintenance efficiency in real-world applications.

Appendix A: Fuzzy rules for fuzzy-PI

- 1) If the voltage deviation is very large and negative and the voltage is still dropping rapidly, then increase K_p and K_i sharply to inject strong corrective action and quickly restore the DC bus voltage.
- 2) If the voltage deviation is very large and negative but the rate of change is slowly negative, then increase K_p moderately and raise K_i slightly to recover the voltage smoothly without overshoot.
- 3) If the voltage deviation is large negative but the voltage drop is stabilizing, then moderately increase K_p and keep K_i near nominal to maintain a steady corrective effort.
- 4) If the voltage deviation is slightly below reference but the voltage is starting to recover, then reduce K_p slightly and lower K_i to avoid excessive control action.
- 5) If the voltage deviation is negative but approaching zero quickly, then reduce both K_p and K_i to prevent overshoot once the target voltage is reached.
- 6) If the voltage is slightly below nominal and the change rate is negative, then apply moderate K_p and low K_i to compensate quickly with minimal oscillations.
- 7) If the voltage is slightly below nominal and the rate is small, then maintain nominal K_p and K_i values for stable operation.
- 8) If the voltage deviation is small, and the rate of change is near zero, then keep K_p and K_i unchanged, indicating steady-state operation.
- 9) If the voltage is slightly above nominal and still rising slowly, then reduce K_p slightly and lower K_i to slow the correction rate.
- 10) If the voltage is slightly above nominal and rising rapidly, then reduce both K_p and K_i strongly to dampen the overshoot.
- 11) If the voltage deviation is nearly zero and the rate of change is negative, then slightly increase K_p to counteract minor disturbances while keeping K_i steady.
- 12) If both the voltage deviation and rate are zero, then the system is at equilibrium – maintain nominal K_p and K_i values.
- 13) If the voltage deviation is zero and the rate is small positive, then no major adjustment is needed – fuzzy outputs remain balanced.
- 14) If the deviation and rate are both small, then maintain smooth control to avoid unnecessary switching stress.
- 15) If both are negligible, no correction is required.
- 16) If the voltage deviation is slightly positive and the rate is negative, then reduce K_p slightly to prevent undershoot while maintaining adequate K_i .
- 17) If the voltage is slightly positive and stabilizing, then keep K_p small and K_i moderate to fine-tune steady-state.
- 18) If the voltage deviation is positive and the rate is near zero, then minimize K_p and lower K_i to hold stability.

- 19) If the voltage is moderately higher than reference and still increasing, then decrease both K_p and K_i significantly to stop overshoot.
- 20) If the voltage deviation is positive and rapidly increasing, then strongly reduce K_p and suppress K_i to quickly settle the voltage.
- 21) If the voltage deviation is high positive and the voltage is dropping slightly, then use small K_p and low K_i to avoid overcorrection.
- 22) If the voltage is well above reference but slowly recovering, then keep K_p and K_i low to maintain a gentle return to nominal.
- 23) If the voltage deviation is still high with minimal rate change, then apply small K_p and low K_i to hold stability.
- 24) If the voltage deviation is high positive and rising again, then minimize K_p and suppress K_i further to prevent instability.
- 25) If the voltage deviation remains high positive and steadily increasing, then keep both K_p and K_i at their minimum to protect the system from oscillations.

Appendix B: Perturb and observe code for the DC-DC boost converter

```
function duty = mppt_po(Vpv, Ipv)
    persistent prevP prevV duty_dir duty_cycle
    if isempty(prevP)
        prevP = 0;
        prevV = 0;
        duty_dir = 1;
        duty_cycle = 0.5;
    end

    dD = 0.005;
    Dmin = 0.02;
    Dmax = 0.98;

    P = Vpv * Ipv;

    if P > prevP
        if Vpv > prevV
            duty_cycle = duty_cycle - dD;
        else
            duty_cycle = duty_cycle + dD;
        end
    else
        if Vpv > prevV
            duty_cycle = duty_cycle + dD;
        else
            duty_cycle = duty_cycle - dD;
        end
    end

    duty_cycle = min(max(duty_cycle, Dmin), Dmax);

    prevP = P;
    prevV = Vpv;
    duty = duty_cycle;
end
```

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B.A. wrote the main manuscript; J.N.W. and M.R.A. reviewed the manuscript.

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Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing of interests

The authors declare no conflict of interest.

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References

1. Gee A, Robinson F, Dunn R. Analysis of battery lifetime extension in a small-scale wind-energy system using supercapacitors. *IEEE Trans Energy Convers.* 2013;28(1):24–33.
2. Irena, Renewable Capacity Statistics 2019, IRENA, Masdar City, UAE, 2019.
3. Wee KW, Choi SS, Vilathgamuwa DM. Design of a least-cost battery-supercapacitor energy storage system for realizing dispatchable wind power. *IEEE Trans Sustain Energy.* 2013;4:786–96.
4. Çorapsiz MR, Kahveci H. A study on Li-ion battery and supercapacitor design for hybrid energy storage systems. *Energy Storage.* 2023;5(1):e386.
5. Manandhar U, Tummuru NR, Kollimalla SK, Ukil A, Beng GH, Chaudhari K. Validation of faster joint control strategy for battery-and supercapacitor-based energy storage system. *IEEE Trans Indus Electron.* 2018;65(4):3286–95.
6. Alafnan H, Pei X, Khedr M, et al. The possibility of using superconducting magnetic energy storage/battery hybrid energy storage systems instead of generators as backup power sources for electric aircraft. *Sustainability.* 2023;15(3):1806.
7. Kujur S, Dubey HM, Salkuti SR. Demand response management of a residential microgrid using chaotic aquila optimization. *Sustainability.* 2023;15(2):1484.
8. Ramu SK, Vairavasundaram I, Aljafari B, Kareri T. Design of pv, battery, and supercapacitor-based bidirectional dc-dc converter using fuzzy logic controller for hess in dc microgrid. *J Electr Comput Eng.* 2024;2024(1):3035524.
9. Alzahrani A, Ramu SK, Devarajan G, Vairavasundaram I, Vairavasundaram S. A review on hydrogen-based hybrid microgrid system: topologies for hydrogen energy storage, integration, and energy management with solar and wind energy. *Energies.* 2022;15(21):7979.
10. Ma T, Yang H, Lu L. Development of hybrid battery-supercapacitor energy storage for remote area renewable energy systems. *Appl Energy.* 2015;153:56–62.
11. Torreglosa JP, Garcia P, Fernández LM, Jurado F. Predictive control for the energy management of a fuel-cell-battery-supercapacitor tramway. *IEEE Trans Ind Inform.* 2013;10:276–85.
12. Laldin O, Moshirvaziri M, Trescases O. Predictive algorithm for optimizing power flow in hybrid ultracapacitor/battery storage systems for light electric vehicles. *IEEE Trans Power Electron.* 2012;28:3882–95.
13. Punna S, Manthathi UB. Optimum design and analysis of a dynamic energy management scheme for hess in renewable power generation applications. *SN Appl Sci.* 2020;2:1–13.
14. Xu Q, Xiao J, Wang P, Pan X, Wen C. A decentralized control strategy for autonomous transient power sharing and state-of-charge recovery in hybrid energy storage systems. *IEEE Trans Sustain Energy.* 2017;8:1443–52.
15. Punna S, Mailugundla R, Salkuti SR. Design, analysis and implementation of bidirectional dc-dc converters for hess in dc microgrid applications. *Smart Cities.* 2022;5(2):433–54.
16. Wanzala JN, Atim MR, Obungoloch J. Design of fuzzy logic-based ARDS berlin definition for ventilator adjustments to ensure lung protection. *Int J Fuzzy Syst.* 2023;25:1935–51. <https://doi.org/10.1007/s40815-023-01489-y>.
17. Wanzala JN, Atim MR, Obungoloch J. Design and Simulation of a Physician-Based Fuzzy System for Ventilator Adjustments in ARDS Patients to Ensure Lung Protection. *Adv Fuzzy Syst.* 2023. <https://doi.org/10.1155/2023/3252763>.
18. Kibazo P, Nabende WJ, Atim MR. Design and simulation of an intelligent irrigation system using fuzzy logic. *Discov Electron.* 2025;2:5. <https://doi.org/10.1007/s44291-025-00045-2>.
19. Kim JC, Huh JH, Ko JS. Improvement of MPPT control performance using fuzzy control and VGPI in the PV system for micro grid. *Sustainability.* 2019;11(21):5891.
20. Keçecioglu ÖF, Açıkgöz H, Gani A. Fuzzy - PI Based MPPT control for photovoltaic systems, 2018 innovations in intelligent systems and applications conference (ASYU), Adana, Turkey, 2018:1–4. <https://doi.org/10.1109/ASYU.2018.8554023>.
21. Keçecioglu ÖF, Gani A, Şekelli M. Improved hybrid intelligent controller design for MPPT of stand-alone PV System. *Turk J Eng.* 2021;5(1):20–8. <https://doi.org/10.31127/tuje.652229>.
22. Gani A, Sekelli M. Experimental evaluation of type-2 fuzzy logic controller adapted to real environmental conditions for maximum power point tracking of solar energy systems. *Int J Circuit Theory Appl.* 2022;50(11):4131–45. <https://doi.org/10.1002/cta.3374>.
23. Belhadji SM, Meliani B, Benbouhenni H, Zaidi S, Elbarbary ZMS, Alammam MM. Control of multi-level quadratic DC-DC boost converter for photovoltaic systems using type-2 fuzzy logic technique-based MPPT approaches. *Heliyon.* 2025;11(3).
24. Gani A. Improving dynamic efficiency of photovoltaic generation systems using adaptive type 2 fuzzy-neural network via EN 50530 test procedure. *Int J Circuit Theory Appl.* 2021;49(11):3922–40.
25. Singh M, Arora S, Shah OA. Enhancing hybrid power system performance with GWO-tuned fuzzy-PID controllers: a comparative study. *Int J Robot Control Syst.* 2024;4(2).
26. Ramu SK, Irudayaraj GCR, Paramasivam SK, et al. A simplified methodology for renewable energy integration and harmonic current reduction in hybrid micro grid. *Energy Sourc Part A Recovery Utilization Environ Effects.* 2022;44(4):8357–79.
27. Nkwanyana TB, Siti MW, Wang Z, Toudjeu I, Mbungu NT, Mulumba W. An assessment of hybridenergystorage systems in the renewable environments. *J Energy Storage.* 2023;72:108307.

28. Choi ME, Kim S-W, Seo S-W. Energy management optimization in a battery/supercapacitor hybrid energy storage system. *IEEE Trans Smart Grid*. 2012;3(1):463–72.
29. Hou J, Sun J, Hofmann H. Control development and performance evaluation for battery/flywheel hybrid energy storage solutions to mitigate load fluctuations in all-electric ship propulsion systems. *Appl Energy*. 2018;212:919–30.
30. Wang B, Zhang X, Manandhar U, Gooi HB, Liu Y, Tan X. Bidirectional three-level cascaded converter with deadbeat control for HESS in solar-assisted electric vehicles. *IEEE Trans Transp Electrification*. 2019;5(4):1190–201.
31. Punna S, Manthani UB, Raveendran AC. Modeling, analysis, and design of novel control scheme for two-input bidirectional DC-DC converter for HESS in DC microgrid applications. *Int Trans Electr Energy Syst*. 2021;31(10):e12774.
32. Yi Z, Dong W, Etemadi AH. A uniDed control and power management scheme for PV-battery-based hybrid microgrids for both grid-connected and islanded modes. *IEEE Trans Smart Grid*. 2018;9(6):5975–85.
33. Glavin M, Chan P, Armstrong S, Hurley W. A stand-alone photovoltaic supercapacitor battery hybrid energy storage system. In: *IEEE power electronics and motion control conference*, 2008;1688–1695.
34. Mantz RJ. A PI controller with dynamic set point weighting for nonlinear processes. In: *Proceedings IFAC conference on advances in PID control, PID'12, Brescia (Italy)*, 2012;45(3):512–517. <https://doi.org/10.3182/20120328-3-IT-3014.00087>
35. Aktas A, Erhan K, Ozdemir S, Ozdemir E. Experimental investigation of a new smart energy management algorithm for a hybrid energy storage system in smart grid applications. *Electr Power Syst Res*. 2017;144:185–96.
36. Song Z, Hofmann H, Li J, Hou J, Han X, Ouyang M. Energy management strategies comparison for electric vehicles with hybrid energy storage system. *Appl Energy*. 2014;134:321–31.
37. Deshmukh RR, Ballal MS, Suryawanshi HM. A fuzzy logic based supervisory control for power management in multibus DC microgrid. *IEEE Trans Ind Appl*. 2020;56(6):6174–85.
38. Mamdani EH, Assilian S. An experiment in linguistic synthesis with a fuzzy logic controller. *Int J Man-Mach Stud*. 1975;7:1–13.
39. Bounechba H, Bouzid A, Nabti K, Benalla H. Comparison of perturb and observe and fuzzy logic in maximum power Point-Tracker for PV systems. *Energy Proc*. 2014;50:677–84.
40. Jin Y, Xu J, Zhou G, Mi C. Small-signal modeling and analysis of improved digital peak current control of boost converter. In: *2009 IEEE 6th international power electronics and motion control conference*. 2009.
41. Aktas A, Erhan K, Ozdemir S, Ozdemir E. Dynamic energy management for photovoltaic power system including hybrid energy storage in smart grid applications. *Energy*. 2018;162:72–82.
42. Slah F, Mansour A, Hajer M, Faouzi B. Analysis, modeling and implementation of an interleaved boost DC-DC converter for fuel cell used in electric vehicle. *Int J Hydrogen Energy*. 2017;42(48):28852–64.
43. Dileep G, Singh SN. Maximum power point tracking of solar photovoltaic system using modified perturbation and observation method. *Renew Sustain Energy Rev*. 2015;50:109–29.
44. Rupesh M, Vishwanath TS. Intelligent controllers to extract maximum power for 10 kw photovoltaic system. *Int J Eng*. 2022;35:784–93.
45. Bonkougou D, Koalaga Z, Njomo D. Modelling and simulation of photovoltaic module considering single-diode equivalent circuit model in MATLAB. *Int J Emerg Technol Adv Eng*. 2013;3(3):493–502.
46. Khan MU, Murtaza AF, Noman AM, Sher HA, Zafar M. State-space modeling, design, and analysis of the DC-DC converters for PV application: a review. *Sustainability*. 2024;16(1):202.
47. Liu S, Xie X, Yang L. Analysis, modeling and implementation of a switching bi-directional buck-boost converter based on electric vehicle hybrid energy storage for V2G system. *IEEE Access*. 2020;8:65868–79.
48. Hintz A, Prasanna UR, Rajashekara K. Novel modular multiple-input bidirectional DC-DC power converter (MIPC) for HEV/FCV application. *IEEE Trans Ind Electron*. 2014;62:3163–72.
49. Perdana Y, Mueen S, Al-Durra A, Simoes M, Morales-Paredes H. Direct connection of supercapacitor-battery hybrid storage system to the grid-tied photovoltaic system. *IEEE Trans Sustain Energy*. 2018;10(3):1370–9.
50. Mitra P, Dey C, Mudi RK. Dynamic set point weighting for fuzzy PID controller. *Control Intell Syst*. 2017;45(3):142–53.

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