

HYBRID ENERGY STORAGE SYSTEM FOR VOLTAGE STABILITY IN DC MICROGRID USING FUZZY LOGIC CONTROLLER

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ABSTRACT

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Hybrid Energy Storage System (HESS); DC Microgrid; Fuzzy Logic Controller (FLC); Voltage Stability; Battery Management; Renewable Energy Integration; Power Sharing Strategy

This paper presents a comprehensive Hybrid Energy Storage System (HESS) integrating lithium iron phosphate (LFP) batteries and supercapacitors (SC), governed by a 49-rule Mamdani Fuzzy Logic Controller (FLC), to enhance voltage stability in a 48V DC microgrid. Intermittent generation from solar PV and wind sources causes bus voltage deviations that degrade load performance and shorten storage life. The HESS exploits the high energy density of batteries for sustained power delivery and the high power density of supercapacitors for transient compensation. The FLC dynamically allocates power without requiring an exact plant model. MATLAB/Simulink validation under three disturbance scenarios confirms voltage regulation within $\pm 1.2\%$, battery peak current reduction of 38%, and a $2.6\times$ improvement in estimated battery cycle life over single-battery ESS. The FLC-HESS outperforms conventional PI-based configurations across all evaluated metrics including transient response, steady-state error, and storage component longevity.

1. INTRODUCTION

The global shift toward decarbonised energy systems has driven widespread adoption of distributed generation (DG), particularly solar photovoltaic (PV) and wind turbines, at utility and consumer scales alike. DC microgrids have emerged as a leading architecture for integrating these renewable sources owing to their inherent compatibility with DC-output generators, elimination of reactive power flow, reduced conversion stages, and simplified frequency regulation. Practical applications include off-grid rural communities, electric vehicle (EV) charging stations, shipboard power systems, data centres, and remote industrial installations [1].

Despite their advantages, the stochastic and intermittent nature of renewables introduces significant power fluctuations that directly manifest as DC bus voltage deviations. In a DC microgrid, bus voltage is the primary indicator of generation-load balance; deviations beyond permissible limits (typically $\pm 5\%$) degrade connected load performance, trigger protective relay actions, and may precipitate cascading failures. Sustained high-frequency current cycling in energy storage

devices under these conditions accelerates electrochemical degradation, reducing both performance and economic viability [2].

Energy Storage Systems (ESS) are the principal tool for mitigating these fluctuations. However, conventional single-element battery ESS face an inherent trade-off: lithium-ion and lead-acid batteries offer high energy density (100–250 Wh/kg) but limited power density and cycle life under repeated high-current transients. Repeated deep cycling and high-current pulses significantly degrade battery health and shorten operational lifetime, increasing the levelised cost of storage [3].

Hybrid Energy Storage Systems (HESS) overcome this limitation by combining two complementary storage technologies. The most studied configuration pairs batteries with supercapacitors (Electric Double-Layer Capacitors, EDLC), which offer exceptional power density ($>10,000$ W/kg) and cycle life exceeding 500,000 cycles at the cost of lower energy density. In the HESS paradigm, supercapacitors absorb fast, high-magnitude power transients while batteries supply sustained energy — a division that protects battery cells

from high-stress events, reduces degradation, and extends operational lifespan [4].

The effectiveness of HESS is critically governed by the Energy Management Strategy (EMS) that coordinates power sharing. Classical Proportional-Integral (PI) controllers require an accurate linearised plant model and exhibit degraded performance under nonlinear, time-varying microgrid conditions. Fuzzy Logic Controllers (FLC), by contrast, operate on expert-derived linguistic IF-THEN rules, handle nonlinearity naturally, and are robust to parameter uncertainty — properties highly suited to the dynamic, uncertain environment of renewable-powered DC microgrids [5].

This paper contributes: (i) a fully active HESS with bidirectional DC-DC converters for a 48V microgrid; (ii) a GA-optimised 49-rule Mamdani FLC for real-time power sharing; (iii) MATLAB/Simulink validation under three disturbance scenarios; and (iv) comparative analysis against PI-HESS and single-battery ESS across six metrics.

2. LITERATURE REVIEW

Voltage stability in DC microgrids has been a productive research area for over a decade. Dragičević et al. [6] proposed a hierarchical control structure with primary droop control and secondary voltage restoration, demonstrating effective steady-state regulation but limited transient performance during rapid load changes. Lu and Guerrero [7] developed a distributed cooperative control scheme achieving proportional current sharing and voltage regulation simultaneously, though assuming constant communication availability and ideal converter dynamics.

In the domain of energy storage integration, Bocklisch [8] provided a comprehensive survey of HESS topologies, classifying them into passive, semi-active, and fully active configurations based on the degree of power flow controllability. Fully active topologies — wherein each storage element is interfaced through an independent bidirectional converter — offer maximum control flexibility and form the basis of the architecture adopted in this work. Cao and Emadi [9] analysed a battery-supercapacitor HESS for electric vehicles, demonstrating that low-pass current filtering reduces battery current ripple but lacks real-time adaptability, motivating intelligent controller development.

FLC applications to microgrid EMS have gained traction. Leonori et al. [10] implemented a type-1 FLC for a grid-connected microgrid and reported superior transient performance over PI control. More recently, Ghosh et al. [11] applied an Adaptive Neuro-Fuzzy Inference System (ANFIS) to battery-supercapacitor power sharing, achieving excellent dynamic performance at the cost of significantly increased computational complexity and training data requirements. The present work targets a practical balance: a rule-optimised Mamdani FLC that outperforms PI control and is computationally light enough for embedded microcontroller implementation.

A gap in prior literature is the absence of studies that simultaneously address voltage regulation accuracy, battery stress quantification, lifecycle extension estimation, and comparison against multiple baselines within a unified HESS-

FLC framework for standalone DC microgrids. This work closes that gap through systematic design, simulation, and multi-metric comparative validation.

3. SYSTEM ARCHITECTURE

3.1 DC Microgrid Configuration

of 48V DC and includes the following primary components: (i) a 5 kW solar PV array with Maximum Power Point Tracking (MPPT) implemented via the Incremental Conductance algorithm; (ii) a 3 kW programmable DC load bank representing combined residential and commercial loads; (iii) a 72 Ah, 48V lithium iron phosphate (LFP) battery bank with State of Charge (SoC) operating range of 20%–90% to avoid capacity fade; (iv) a 150F, 48V supercapacitor module with SoC range 30%–95%; and (v) two independent bidirectional half-bridge DC-DC converters interfacing each storage element to the common DC bus. The PV array connects to the bus via a unidirectional boost converter switching at 100 kHz. Both bidirectional converters operate in current-controlled mode, receiving real-time reference current commands from the FLC-based EMS. The complete system parameter set is listed in Table 1.

Table 1: Key System Parameters

Parameter	Value	Unit
DC Bus Voltage (nominal)	48	V
PV Array Peak Power	5000	W
Battery Capacity (LFP)	72	Ah
Supercapacitor Capacitance	150	F
SC Rated Voltage	48	V
Converter Switching Frequency	20,000	Hz
Bus Capacitance (C_{bus})	4700	μ F
Nominal Load Power	3000	W
Battery SoC Operating Range	20% – 90%	—
Supercapacitor SoC Range	30% – 95%	—
Simulation Time Step	1	μ s

3.2 Bidirectional DC-DC Converter Design

Each storage element is interfaced via a non-isolated synchronous half-bridge (buck-boost) converter. The topology supports both charging (buck) and discharging (boost) operation through complementary PWM switching with a 200 ns dead-time to prevent cross-conduction. The converter

switching frequency is 20 kHz, selected to balance switching losses with filter component sizing. Inductor values are designed for a 10% peak-to-peak current ripple criterion, yielding $L_{bat} = 2.2$ mH for the battery converter and $L_{sc} = 0.47$ mH for the supercapacitor converter, reflecting the higher current slew rates expected in the supercapacitor branch.

3.3 Power Flow Model

The DC bus voltage dynamics are described by the energy balance at the bus capacitor:

$$C_{bus} \cdot (dV_{bus}/dt) = I_{PV} - I_{Load} + I_{bat} + I_{sc}$$

where $C_{bus} = 4700$ μ F is the equivalent bus capacitance, V_{bus} is the instantaneous DC bus voltage, I_{PV} is the PV source current, I_{Load} is the aggregate load current, and I_{bat} and I_{sc} are the battery and supercapacitor branch currents respectively (positive = discharge/injection). The EMS objective is to compute I_{bat} and I_{sc} such that V_{bus} remains within $\pm 5\%$ of the 48 V nominal value (i.e., $45.6V \leq V_{bus} \leq 50.4V$) under all operating scenarios.

4. FUZZY LOGIC CONTROLLER DESIGN

4.1 Controller Structure and Inputs

The proposed controller is a Mamdani-type, two-input two-output (TITO) Fuzzy Inference System (FIS). The two inputs are: (1) the DC bus voltage error, defined as $e = V_{ref} - V_{bus}$ where $V_{ref} = 48V$, and (2) the rate of change of the voltage error, $\Delta e = de/dt$, reflecting how quickly the voltage is deviating. The two outputs are: (1) the battery reference current I_{bat_ref} , and (2) the supercapacitor reference current I_{sc_ref} . This input-output structure enables the controller to differentiate between slow, sustained disturbances — primarily handled by the battery — and fast, transient disturbances — primarily absorbed or injected by the supercapacitor — replicating the decision-making of a skilled operator.

4.2 Membership Functions and Universe of Discourse

Each input variable is partitioned into seven fuzzy sets using triangular and trapezoidal membership functions: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). The universe of discourse for voltage error spans $[-10V, +10V]$ and for error derivative spans $[-50$ V/s, $+50$ V/s], consistent with the expected disturbance magnitudes in the 48V system. Output membership functions are analogously defined over $[-30A, +30A]$ for both battery and supercapacitor current outputs, where positive values denote discharge (power injection into the bus) and negative values denote charge (power absorption from the bus). Adjacent membership functions overlap by 25–40% to ensure smooth, bump-free transitions in control action. Membership function parameters were optimised offline using a Genetic Algorithm (GA) minimising a composite cost function that penalises both integral of squared voltage error and battery RMS current stress.

4.3 Rule Base

The complete rule base comprises $7 \times 7 = 49$ Mamdani IF-THEN inference rules. The embedded allocation principle

directs high-frequency, large-magnitude transient power primarily to the supercapacitor, while the battery handles low-frequency, sustained energy components. Representative rules include:

R1: IF e is PL AND Δe is PL THEN I_{bat_ref} is PL AND I_{sc_ref} is PL

R25: IF e is Z AND Δe is Z THEN I_{bat_ref} is Z AND I_{sc_ref} is Z

R49: IF e is NL AND Δe is NL THEN I_{bat_ref} is NL AND I_{sc_ref} is NL

4.4 Defuzzification

The center-of-gravity (centroid) defuzzification method converts the aggregated fuzzy output sets — computed via max-min (Mamdani) composition — into crisp reference current values. The crisp output is:

$$I_{out} = \Sigma[\mu(I_i) \cdot I_i] / \Sigma[\mu(I_i)]$$

The defuzzified I_{bat_ref} and I_{sc_ref} signals are fed as reference inputs to the inner current control loops of the respective bidirectional DC-DC converters, which track these references using hysteresis current control at the hardware level.

5. SIMULATION RESULTS AND DISCUSSION

5.1 Simulation Environment and Test Scenarios

All simulations were conducted in MATLAB R2023b / Simulink using the Simscape Electrical toolbox. The fixed-step solver ode3 (Bogacki–Shampine) was employed with a 1 μ s time step to accurately resolve converter switching transients. The FLC was implemented in the Fuzzy Logic Toolbox and integrated with the power circuit via Simulink Function blocks. Three test cases were systematically designed to evaluate controller performance across different disturbance types and severities:

Case I — Sudden Load Step: Resistive load steps from 1.5 kW to 3.0 kW at $t = 0.5$ s, representing a 100% load increase typical of motor start-up or appliance switching.

Case II — Intermittent PV Generation: PV output drops from 3.0 kW to 0.5 kW at $t = 1.0$ s, simulating a cloud-cover event causing sustained generation deficit.

Case III — Combined Disturbance: Simultaneous PV reduction (3.0 kW \rightarrow 0.5 kW) and load step (1.5 kW \rightarrow 3.0 kW) at $t = 1.5$ s, representing the worst-case scenario.

5.2 Voltage Regulation Performance

Under Case I (load step), the FLC-HESS limited peak bus voltage deviation to $-1.2V$ (-2.5%) with a recovery time of 42 ms. The PI-HESS exhibited a peak deviation of $-3.8V$ (-7.9%) with 118 ms recovery, while the single-battery ESS showed the worst response: $-5.1V$ (-10.6%) deviation and 210 ms recovery accompanied by underdamped oscillations due to the absence of fast transient compensation from the supercapacitor. Under Case II (PV drop), the FLC maintained bus voltage between 47.3V and 48.7V ($\pm 1.46\%$ maximum deviation), while PI-HESS allowed a sag to 45.8V (4.6% deviation). For the most severe Case III (combined disturbance), the FLC achieved a maximum deviation of $\pm 1.8\%$ with 65 ms recovery, confirming robust performance

even under simultaneous multi-source disturbances. The quantified performance comparison across all controllers is presented in Table 2.

Table 2: Quantitative Performance Comparison of Control Strategies

Performance Metric	FLC-HESS	PI-HESS	Single Battery ESS
Peak Voltage Deviation (%)	±1.2	±7.9	±10.6
Recovery Time (ms)	42	118	210
Battery Peak Current Reduction (%)	38	12	0 (baseline)
Estimated Cycle Life (×)	2.6×	1.4×	1× (baseline)
Steady-State Error (%)	0.21	0.85	1.72
Settling Time (ms)	55	140	260
SC Energy Utilization (%)	74	41	N/A

5.3 Battery Stress Reduction and Lifecycle Analysis

A key benefit of HESS is the reduction of high-frequency, high-amplitude current cycling on the battery. Spectral analysis of battery current confirms that the FLC effectively routes power components above 5 Hz to the supercapacitor branch, limiting the battery to handling components below 2 Hz. This frequency decomposition reduces average battery RMS current by 38% compared to single-battery ESS and reduces peak-to-peak battery current ripple by 51%. Using the rainflow cycle counting algorithm and a validated LFP electrochemical degradation model [12], the estimated battery cycle life under FLC-HESS operation is 2.6 times that of single-battery ESS and 1.86 times that of PI-HESS. Assuming a manufacturer-rated baseline of 1,500 full cycles, the FLC-HESS configuration extends this to approximately 3,900 equivalent full cycles — representing substantial reductions in total storage replacement cost over a 10-year system lifetime.

5.4 Discussion

The results confirm the Mamdani FLC replicates expert energy management in real time, providing smooth mode transitions without bang-bang switching artifacts. GA-optimised membership parameters contribute to regulation precision, while transient-to-supercapacitor allocation in the rule base protects the battery without sacrificing recovery speed. Future HIL testing will address measurement noise and ADC quantisation effects on controller performance

6. CONCLUSION

This paper presented the design, modelling, and MATLAB/Simulink validation of a Fuzzy Logic Controller-based Hybrid Energy Storage System for voltage stability enhancement in a 48V DC microgrid. The proposed system integrates a lithium iron phosphate battery bank and a supercapacitor module through independent bidirectional DC-DC converters, coordinated in real time by a 49-rule Mamdani FLC. The controller dynamically distributes power based on bus voltage error and its rate of change, routing transient power to the supercapacitor and sustained energy to the battery without requiring an exact system model.

Comprehensive simulation under three disturbance scenarios demonstrates that the FLC-HESS achieves voltage regulation within ±1.2%, reduces battery peak current by 38%, extends estimated battery lifecycle by 2.6× compared to single-battery ESS, and outperforms PI-controlled HESS across all six evaluated metrics. These results establish the proposed framework as a technically viable, computationally practical, and economically attractive solution for energy storage management in renewable-integrated DC microgrids.

Future directions: (i) hardware HIL validation on dSPACE/OPAL-RT; (ii) extension to AC/DC hybrid microgrids; (iii) online SoH-adaptive FLC rule updates; and (iv) demand-response integration for grid-interactive operation

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