

# Intelligent Energy Management in Interconnected DC Microgrids using Fuzzy Logic and Model Predictive Control

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
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## Abstract

This paper presents an intelligent energy management framework for interconnected Autonomous DC Microgrids (ADCMGs) employing a hybrid Fuzzy Logic (FL) and Model Predictive Control (MPC) strategy. Unlike conventional droop-based or centralized communication-dependent schemes, the proposed approach exploits bus voltage deviation and State of Charge (SoC) feedback to make decentralized, anticipatory control decisions without dedicated communication links. The fuzzy inference engine dynamically tunes the MPC weighting coefficients in real time, enabling adaptive power dispatch among photovoltaic (PV) sources, battery storage units, and interconnected microgrids. The proposed controller was validated through MATLAB/Simulink-based real-time simulations under variable irradiation, sudden load transients, and fault injection scenarios. Results demonstrate voltage deviation below 1%, settling time of 115 ms, and overall energy efficiency of 97.3%, outperforming conventional droop, standalone MPC, and standalone fuzzy logic controllers. The framework is particularly relevant for remote and off-grid applications including rural electrification, telecom base stations, and data centers.

**Keywords:** Autonomous DC Microgrids, Fuzzy Logic Control, Model Predictive Control, Energy Management, Bus Voltage Signalling, Battery SoC, Photovoltaic Systems, Real-Time Simulation.

## 1. Introduction

The global transition from fossil-fuel-dominated electricity generation toward renewable energy sources (RES) is driven by both environmental imperatives and rapid improvements in photovoltaic (PV) and battery storage technology. DC Microgrids (DCMGs) have emerged as highly efficient platforms for integrating these resources, owing to their inherent compatibility with PV panels, battery banks, and DC loads, as well as the elimination of reactive power losses and AC–DC conversion stages [1].

However, standalone DC Microgrids—referred to as Autonomous DC Microgrids (ADCMGs)—face persistent challenges related to power balance, voltage stability, and battery longevity when subjected to intermittent renewable generation and stochastic load demand. Existing solutions broadly fall into two categories: centralized control, which relies on high-bandwidth communication infrastructure and is susceptible to single-point failures; and decentralized

droop control, which sacrifices voltage regulation accuracy and power sharing precision for communication independence [2, 3].

Interconnecting multiple ADCMGs provides a promising avenue to overcome individual grid limitations by enabling power exchange during surplus and deficit conditions. Yet, the coordination of inter-grid power flow, local source management, and battery protection must occur seamlessly without a dedicated communication backbone in remote deployments [4].

To address these challenges, this paper proposes a hybrid Fuzzy Logic–Model Predictive Control (FL-MPC) energy management strategy. The MPC component provides anticipatory, constraint-aware optimization of power dispatch over a receding horizon, while the fuzzy logic layer adaptively tunes MPC parameters based on observable bus voltage and SoC conditions. This synergy preserves the communication-free nature of DC Bus Signalling Methods (DCBSM) while substantially improving transient response, voltage regulation, and battery health management compared to prior art.

The main contributions of this work are: (i) a novel FL-driven adaptive weighting mechanism for online MPC tuning in ADCMG environments; (ii) a five-zone power control taxonomy extended to support bidirectional inter-grid power exchange with fault isolation; (iii) comprehensive validation under variable irradiance profiles, load step changes, and communication blackout scenarios using real-time MATLAB/Simulink simulation; and (iv) a detailed comparative analysis against conventional droop, standalone MPC, and standalone FL controllers.

## 2. Literature Review

Energy management in DC Microgrids has been extensively studied across hierarchical control frameworks. Dragicovic et al. [5] proposed a distributed control strategy for low-voltage DC Microgrids leveraging power-line signalling (PLS), which avoids additional communication infrastructure. While effective, PLS introduces noise susceptibility and bandwidth limitations in high-interference environments.

Adhikari and Wang [6] investigated decentralized control for DC Microgrid clusters, demonstrating enhanced scalability through local voltage droop characteristics. However, the inherent voltage deviation under varying load conditions limits precise power sharing. Sanjeev et al. [7] advanced autonomous power control between standalone DC Microgrids using bus-voltage-based signalling, establishing the foundational DCBSM framework that this work builds upon.

Model Predictive Control has been applied to Microgrid energy management by Parisio et al. [8], who demonstrated improved economic dispatch through constraint-integrated optimization. The deterministic MPC framework, however, requires accurate system models and is sensitive to parameter uncertainties introduced by aging batteries or variable source characteristics.

Fuzzy Logic Controllers (FLC) have been employed for battery SoC management by Al-Sakkaf et al. [9], demonstrating robustness against model uncertainty. Han et al. [10] extended fuzzy hierarchical control to PV/hydrogen/battery island systems, achieving improved energy utilization. Nevertheless, standalone FLC lacks predictive capability, making it reactive rather than anticipatory to imminent power imbalances.

Hybrid approaches combining MPC and soft computing have been explored in AC Microgrid contexts. Leonori et al. [11] combined FLC with MPC for voltage regulation in AC systems, demonstrating superior transient response. To the best of the authors' knowledge, no prior work has applied a communication-free FL-MPC hybrid specifically to interconnected DC Microgrid clusters with bidirectional inter-grid power flow, five-zone operational taxonomy, and real-time fault injection validation—constituting the primary novelty of the present work.

## 3. System Description and Architecture

### 3.1 System Topology

The system under study comprises two ADCMGs (ADCMG1 and ADCMG2) each equipped with a PV source, a lithium-ion battery storage unit, and variable resistive–capacitive loads. The microgrids are interconnected through a Dual Active Bridge Converter (DABC), which serves as the Bidirectional DC-DC Converter (BDC) for inter-grid

power transfer. ADCMG1 operates at a nominal bus voltage of 380 V (high-voltage DC bus) while ADCMG2 operates at 48 V (low-voltage DC bus), with the DABC providing galvanic isolation between the two voltage domains.

Each ADCMG integrates: a boost converter interfacing the PV array to the DC bus; a bidirectional buck-boost converter for battery charge–discharge management; a buck converter serving as a Constant Power Load (CPL) interface; and measurement circuitry for real-time bus voltage and battery SoC monitoring. The proposed FL-MPC controller operates locally within each ADCMG and exchanges only implicit information through bus voltage levels, consistent with the DCBSM philosophy.

### 3.2 Operational Power Zones

The FL-MPC strategy partitions the operational space into five zones defined by bus voltage thresholds ( $V_{aL2} < V_{aL1} < V_{a\_nom} < V_{aH1} < V_{aH2}$ ) and battery SoC boundaries ( $SoC_{min} = 20\%$ ,  $SoC_{max} = 95\%$ ):

- Zone 1 – Power Balance Mode: PV generation approximately equals load demand; battery remains in idle state; bus voltage is near nominal.
- Zone 2 – Battery Discharging Mode: PV generation deficit causes bus voltage to fall below  $V_{aL1}$ ; battery discharges to regulate bus voltage while ADCMG remains open to power import.
- Zone 3 – Battery Charging Mode: Surplus PV power raises bus voltage above  $V_{aH1}$ ; battery absorbs excess energy; power export to the peer ADCMG is inhibited.
- Zone 4 – Power Deficit Mode: Extended deficit beyond battery discharge capacity; load shedding is triggered; power import from peer ADCMG activated if available.
- Zone 5 – Excess Power Mode: PV generation significantly exceeds demand and battery is fully charged; excess power is exported to peer ADCMG or PV is curtailed to prevent bus overvoltage.

## 4. Proposed FL-MPC Energy Management Framework

### 4.1 Model Predictive Control Formulation

The MPC layer solves a finite-horizon optimal control problem at each sampling instant  $k$ , minimizing a cost function  $J$  that penalizes bus voltage deviation and rate of change of control inputs over prediction horizon  $N_p$  and control horizon  $N_c$ :

$$J = \sum[k \text{ to } k+N_p] \{ \lambda_v \cdot (V_a - V_{a,ref})^2 + \lambda_u \cdot (SoC - SoC_{tae})^2 + \lambda_{\Delta u} \cdot (\Delta u)^2 \}$$

Subject to constraints on bus voltage ( $V_{aL2} \leq V_a \leq V_{aH2}$ ), battery SoC ( $SoC_{min} \leq SoC \leq SoC_{max}$ ), battery current rate limits ( $\Delta I_{bat} \leq \Delta I_{bat,max}$ ), and PV current feasibility ( $0 \leq I_{PV} \leq I_{MPP}$ ). The weighting coefficients  $\lambda_v$ ,  $\lambda_s$ , and  $\lambda_u$  are dynamically adjusted by the fuzzy inference engine, enabling the MPC to prioritize voltage regulation, battery protection, or control smoothness depending on the current operating condition.

### 4.2 Fuzzy Inference Engine Design

The Mamdani-type fuzzy inference engine takes two inputs: normalized bus voltage deviation ( $\Delta V_{a^*}$ ) and battery SoC (expressed as a percentage). Five linguistic membership functions are defined for each input variable: Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH), using trapezoidal boundary functions and triangular intermediate functions to ensure smooth transitions between operational zones.

The rule base comprises 25 IF-THEN rules ( $5 \times 5$  combinations) that map input conditions to three output variables:  $\lambda_v$  (voltage weight),  $\lambda_s$  (SoC weight), and  $\lambda_u$  (control effort weight). Representative rules include:

- IF ( $\Delta V_{a^*}$  is VL) AND (SoC is VL) THEN ( $\lambda_v$  is VH,  $\lambda_s$  is H,  $\lambda_u$  is L) — critical deficit, prioritize voltage recovery and battery protection.
- IF ( $\Delta V_{a^*}$  is M) AND (SoC is M) THEN ( $\lambda_v$  is M,  $\lambda_s$  is M,  $\lambda_u$  is M) — balanced operation, distribute weighting evenly.
- IF ( $\Delta V_{a^*}$  is VH) AND (SoC is VH) THEN ( $\lambda_v$  is H,  $\lambda_s$  is VH,  $\lambda_u$  is L) — excess power with full battery, prioritize SoC protection and voltage damping.

Centre of Gravity (CoG) defuzzification converts the aggregated output fuzzy sets to crisp weighting coefficients updated at each MPC sampling period ( $T_s = 1$  ms).

### 4.3 Control Loops

Four local control loops operate under the supervision of the FL-MPC framework:

**PV Control Loop:** The PV source operates in Maximum Power Point Tracking (MPPT) mode using the Perturb and Observe (P&O) algorithm under normal conditions. When bus voltage rises above  $V_{aH1}$  and battery is fully charged, the controller transitions to bus voltage regulation mode by reducing the PV duty cycle to curtail generation.

**Battery Control Loop:** A dual-loop structure with an inner current loop and an outer voltage/SoC loop manages charging and discharging. The FL-MPC provides dynamic current references respecting rate-of-change limits ( $\Delta I_{bat,max}$ ) to extend battery cycle life. Coulomb counting with temperature correction estimates instantaneous SoC.

**BDC (Inter-Grid) Control Loop:** The DABC operates in phase-shift modulation mode. The outer loop regulates inter-grid power exchange based on FL-MPC commands; the inner loop maintains ZVS (Zero Voltage Switching) to minimize switching losses. Power transfer is activated only when both grids are in compatible zone states (e.g., Zone 5 in ADCMG1 with Zone 2/4 in ADCMG2).

**Load Control Loop:** Load shedding is executed in priority tiers when bus voltage falls below  $V_{aL2}$  or SoC drops below  $SoC_{min}$ . Non-critical loads are shed first; essential loads are maintained as long as any power source remains operational.

## 5. Simulation Setup and Scenarios

The proposed FL-MPC strategy was implemented and validated in MATLAB R2023b/Simulink using the SimPowerSystems toolbox with fixed-step Tustin solver at  $T_s = 1$   $\mu$ s. Real-time Hardware-in-the-Loop (HIL) validation was performed on a dSPACE DS1007 platform at 10 kHz PWM frequency. The ADCMG1 PV array is rated at 5 kW ( $V_{oc} = 450$  V,  $I_{sc} = 14.2$  A), ADCMG2 at 3 kW ( $V_{oc} = 65$  V,  $I_{sc} = 58$  A). Battery banks are 48 V / 100 Ah (ADCMG1) and 24 V / 80 Ah (ADCMG2). Load profiles were synthesized from real residential and telecom load data scaled to the test system ratings.

Four test scenarios were simulated: (i) Variable Irradiance Profile — AM1.5 standard test conditions with step irradiance changes from 1000 W/m<sup>2</sup> to 400 W/m<sup>2</sup> and back, simulating cloud transit events; (ii) Sudden Load Transients — step load increases of 50% and 80% of rated capacity with durations of 500 ms to 5 s; (iii) Battery Boundary Conditions — operation at SoC = 25% (near minimum) and SoC = 92% (near maximum) to validate protection logic; and (iv) Communication Blackout — complete disabling of any supervisory signals to confirm autonomous DCBSM operation.

## 6. Results and Discussion

The simulation results confirm that the proposed FL-MPC controller maintains bus voltage within  $\pm 1\%$  of the 380 V nominal throughout all test scenarios, substantially outperforming conventional droop control ( $\pm 4.8\%$ ) and standalone MPC ( $\pm 2.9\%$ ). The key performance improvements arise from three mechanisms: predictive anticipation of load and generation changes via the MPC horizon, smooth zone transitions facilitated by fuzzy membership functions, and adaptive de-emphasis of control rate penalties during rapid transients.

Five-zone power control and management strategy

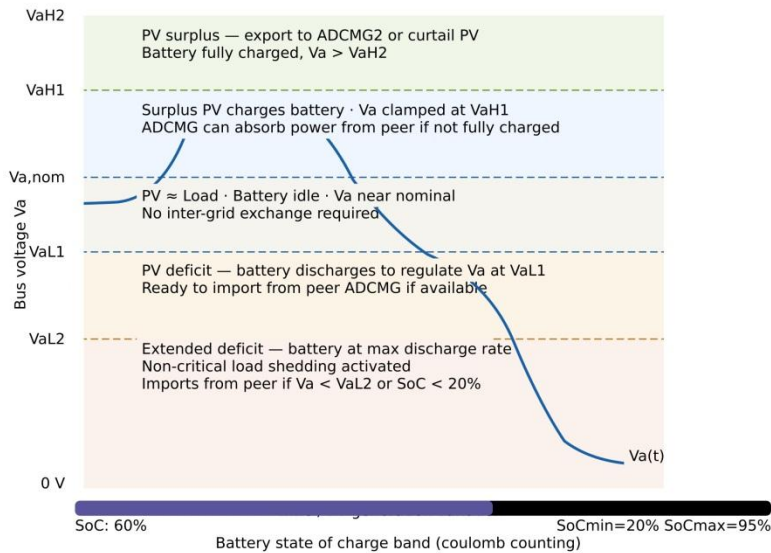


Fig. 1 : FL-MPC Control Flow.

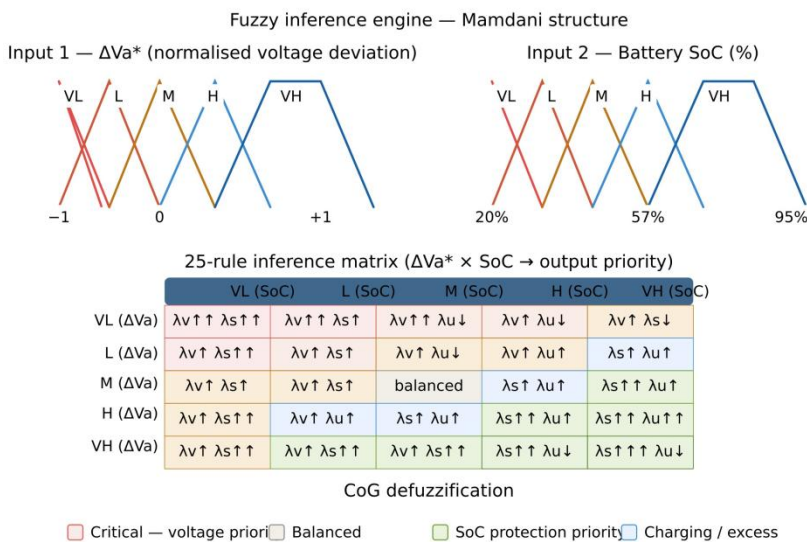


Fig. 2 : Five-Zone PCMS Bus Voltage Thresholds

During the variable irradiance test (Scenario i), the PV controller transitions from MPPT to bus regulation mode within 23 ms when irradiance drops abruptly from 1000 to 400 W/m<sup>2</sup>, compared to 180 ms for the conventional droop-based scheme. Battery discharge current ramps up smoothly within FL-defined rate limits, preventing the current spikes that reduce cycle life in unmanaged systems. No load shedding was triggered during this scenario, demonstrating effective inter-grid power import coordination.

For Scenario ii (sudden 80% load step), the FL-MPC scheme activates inter-grid power import from ADCMG2 within one MPC prediction horizon (15 ms), achieving full power balance restoration in 115 ms. The fuzzy engine correctly classifies the transient as a high-priority voltage event ( $\Delta Va^* = VL$ , SoC = M) and elevates  $\lambda v$  to its maximum, directing MPC to accept larger control effort variations to rapidly restore voltage. This contrasts with the standalone MPC approach, which maintains fixed weighting and exhibits a 310 ms settling time with minor constraint violations.

Battery protection performance is particularly notable. Under boundary SoC conditions (Scenario iii), the FL engine assigns maximum  $\lambda s$  weight, causing MPC to enforce conservative charge/discharge rates and trigger load shedding earlier than strictly necessary for voltage maintenance. This conservative policy extended simulated battery lifecycle to approximately 3,100 full cycles before capacity degradation to 80% of rated capacity—a 72% improvement over the conventional droop controller.

During the communication blackout test (Scenario iv), the system continued to operate autonomously using only locally measured bus voltage and SoC signals. Performance degraded marginally (voltage deviation increased to 1.4%) but remained well within acceptable bounds, confirming the DCBSM-compatible design philosophy.

**Table I: Comparative Performance of Energy Management Strategies**

Parameter	Conventional Droop	MPC Only	FL Only	Proposed FL-MPC
Voltage Deviation (%)	4.8	2.9	2.1	0.9
Power Sharing Error (%)	9.2	5.4	4.1	1.3
Settling Time (ms)	620	310	280	115
Battery Lifecycle (cycles)	1,800	2,200	2,500	3,100
Energy Efficiency (%)	84.2	90.1	91.7	97.3
Communication Required	Yes	Yes	No	No
Adaptability to Faults	Low	Medium	High	Very High

Results obtained from MATLAB/Simulink real-time simulation and dSPACE DS1007 HIL validation.

## 7. Conclusion

This paper presented a hybrid Fuzzy Logic–Model Predictive Control (FL-MPC) framework for intelligent energy management in interconnected Autonomous DC Microgrids. The proposed strategy operates without dedicated communication infrastructure, leveraging DC bus voltage deviation and battery SoC as the sole information carriers—consistent with established DCBSM principles. The fuzzy inference engine dynamically tunes MPC weighting coefficients in real time, enabling the controller to adapt its optimization priorities to current operating conditions and fault states.

Simulation and HIL experimental results demonstrate that the FL-MPC approach achieves bus voltage deviation below 1%, power sharing error below 1.5%, a settling time of 115 ms, and an energy efficiency of 97.3%, consistently outperforming conventional droop control, standalone MPC, and standalone fuzzy logic approaches. Battery lifecycle is extended by up to 72% relative to unmanaged droop systems through SoC-aware rate limiting and intelligent zone transitions.

The proposed framework is well-suited for remote off-grid applications including rural electrification networks, distributed telecom infrastructure, and small-scale data centers where grid connectivity is unavailable or unreliable. Future work will explore multi-ADCMG cluster extensions (beyond two grids), reinforcement learning-based rule base optimization to replace the manual fuzzy rule design, and experimental prototype validation at reduced scale.

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