

Supervisory Energy Management in Islanded DC Microgrids Under Fast-Charging Transients: A Comprehensive Review and Algorithmic Roadmap

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ABSTRACT

This paper provides a critical, systematic evaluation of recent advancements in supervisory energy management systems (EMS) designed for islanded hybrid DC microgrids. Specifically, this review synthesizes contemporary literature focusing on the co-optimization of multi-asset configurations that couple intermittent solar photovoltaics with hydrogen-based proton exchange membrane fuel cells (PEMFC) and secondary lithium-ion battery energy storage systems (BESS). A primary analytical focus is directed toward comparing the structural efficacy of rule-based state machines against artificial intelligence-driven frameworks, with particular emphasis on Mamdani versus Takagi-Sugeno-Kang (TSK) fuzzy logic inference engines. This survey exposes critical gaps in current literature regarding the real-time execution bounds of these supervisors under strict fixed-step discrete integration constraints. Furthermore, we evaluate the industry adoption of protective physical constraints, such as clamping electrochemical current ramp rates to stabilize the (di/dt) derivative and configuring parallel resistor-capacitor (RC) snubber networks to eliminate numerical Jacobian singularities during high-frequency pulse-width modulation (PWM) switching. The paper concludes by mapping the operational barriers hindering the transition from continuous software-defined simulations to low-latency, hard-deterministic Hardware-in-the-Loop (HIL) microprocessing deployment. Ultimately, this comprehensive review provides a structured roadmap identifying the exact parametric thresholds required to balance transient power quality metrics against multi-asset degradation constraints in decentralised distribution networks.

Keywords: DC microgrids, Energy Management Systems, Takagi-Sugeno-Kang fuzzy logic, hybrid

energy storage, Hardware-in-the-loop, Solar PV Array, Fuel cell, Lithium-ion Battery.

I. INTRODUCTION

The global transition toward decentralized electrical distribution networks has accelerated the deployment of islanded DC microgrids as a premier solution for rural electrification, industrial complexes, and localized electric vehicle (EV) charging infrastructures [1]. By eliminating the synchronization complexities, reactive power losses, and multi-stage conversion overheads inherent to traditional AC distribution, DC architectures offer a fundamentally more efficient topology for coupling inherently direct-current assets [3]. However, the operational isolation of these networks introduces severe power quality challenges. Without the inertial buffering provided by a bulk utility grid, the common DC link voltage (V_{bus}) is highly susceptible to volatile fluctuations caused by the compounding effects of volatile renewable generation and erratic, high-amplitude load steps [9].

To achieve reliable power equilibrium, contemporary microgrid designs rely on a hybridised multi-asset stack. This framework typically integrates an intermittent primary harvesting source, such as solar photovoltaic (PV) arrays, with a complementary dual-tier storage mechanism consisting of a long-term bulk generation unit and a high-power transient buffer [10]. Proton Exchange Membrane Fuel Cells (PEMFC) have emerged as the leading candidate for long-term, high-capacity energy storage due to their high energy density and zero-emission profile when driven by green hydrogen [2]. Nonetheless, the electrochemical subsystems of the PEMFC exhibit slow internal thermodynamic and mass-transport gas dynamics. Subjecting a fuel cell to instantaneous high-frequency load steps induces severe reactant starvation, localized thermal localized spots, and accelerated catalyst degradation, which can curtail the nominal operational lifespan of the asset by up to 30 % [15].

To insulate the fragile fuel cell membrane and compensate for solar intermittency, secondary Lithium-Ion Battery Energy Storage Systems (BESS) are installed in parallel via bidirectional buck-boost converter topologies [12]. The high power density and sub-millisecond response time of the BESS allow it to absorb the immediate (di/dt) derivative of transient load impacts. Managing the coordinated power handover across these highly non-linear, multi-domain assets requires a robust, supervisory Energy Management System (EMS).

Traditional supervisory controls have historically relied on hardcoded rule-based state machines or classical decoupled proportional-integral (PI) loops. While computationally lightweight, these deterministic rule structures scale poorly when confronted with multi-input multi-output (MIMO) variables, resulting in severe relay chattering at boundary thresholds and an inability to resolve complex multi-asset trade-offs.

Consequently, recent academic focus has shifted heavily toward artificial intelligence-driven supervisors, particularly fuzzy logic control (FLC) networks [4]. However, the literature reveals a stark division regarding the deployment of these engines. Standard Mamdani fuzzy frameworks, which dominate early research, necessitate continuous geometric centroid integration to resolve final output commands—a process that introduces significant execution latency and numerical instability when transitioned to discrete hardware environments. Conversely, Takagi-Sugeno-Kang (TSK) formulations offer an algebraic alternative that drastically minimizes processing overhead [13].

This review paper explicitly addresses these structural paradigms. By systematically synthesizing recent methodologies, this work maps the critical convergence boundaries, numerical stability constraints, and architectural trade-offs that dictate the successful transition of fuzzy supervisors from software-defined environments to physical, real-time Hardware-in-the-Loop (HIL) microprocessing nodes.

II. COMPARATIVE ANALYSIS OF SUPERVISORY EMS CONTROL ARCHITECTURES

The operational stability, dynamic power-sharing accuracy, and asset longevity of an islanded hybrid DC microgrid depend fundamentally on the architectural paradigm of its supervisory Energy Management System (EMS) [2], [4]. The literature classifies these top-level supervisory frameworks into three primary distinct methodologies: classical decoupled linear control loops, deterministic rule-based state machines, and soft-computing intelligent systems [3].

A. CLASSICAL DECOUPLED LINEAR AND PREDICTIVE CONTROL

Early microgrid deployment heavily leveraged centralized or decentralized proportional-integral (PI) control loops to maintain DC bus equilibrium under varying load profiles [25]. Under this topology, independent linear loops regulate individual converter duty cycles by tracking localized voltage and current error vectors [22]. While these frameworks are computationally lightweight, they perform poorly when applied to multi-variable, highly non-linear networks with integrated energy storage [1].

Because classical PI loops are tuned around narrow, linearized operating points, large-signal environmental or load disturbances easily push the power electronic interfaces into structural saturation [10]. This bottleneck results in severe voltage sags, slow transient settling times spanning 20 ms to 100 ms, and potential cascading system failures due to a lack of coordinated cross-asset stabilization loops [16].

To overcome these linear limitations, advanced centralized techniques such as Model Predictive Control (MPC) have been explored [13]. However, MPC frameworks require highly accurate mathematical plant models and demand intensive online optimization calculations, complicating their execution in fast-updating microgrid environments.

B. DETERMINISTIC RULE-BASED STATE MACHINES

To introduce multi-variable coordination without escalating computational processing overhead, many researchers implemented rule-based state-flow machines and flowchart-driven logical routines [3]. These systems utilize a structured series of hardcoded conditional IF-THEN boundaries to evaluate real-time parameter changes across the solar, hydrogen, and battery subsystems.

While highly effective for predictable, steady-state operation, deterministic state machines exhibit major structural flaws when handling rapid physical transitions [18]:

1. Boundary Threshold Chattering: When an input parameter hovers directly on a hardcoded switching threshold (such as a solar irradiance boundary exactly at 200 W/m²), the controller rapidly cycles its output gating commands. This creates severe relay chattering, injects high-frequency noise onto the DC link, and causes premature thermal wear on solid-state switches [16].

2. Lack of Adaptive Flexibility: Fixed logic structures cannot adapt to overlapping transient states, such as a simultaneous depletion of battery storage capacity and hydrogen reserves during an unexpected fast-charging demand spike.

C. SOFT-COMPUTING AND FUZZY LOGIC ARCHITECTURES

To resolve the rigid limitations of hardcoded logic, recent literature has shifted extensively toward soft-computing intelligent systems, primarily derived from foundational fuzzy set theory [6]. Fuzzy logic controllers (FLCs) excel at managing multi-input multi-output (MIMO) systems with non-linear cross-dependencies by translating precise sensor readings into continuous, linguistic membership functions [21]. This framework allows for smooth, interpolated transitions between diverse operating modes, dampening common-bus voltage ripples and eliminating threshold chattering.

However, contemporary reviews identify a critical structural split regarding how these fuzzy engines compute final output actions, dividing the literature into two distinct implementation methodologies [20]:

1. Mamdani Fuzzy Inference Systems:

Mamdani architectures represent a common soft-computing approach in early microgrid power routing literature. They process both input states and output actions using continuous, overlapping geometric membership surfaces. While intuitive to design, resolving the final "crisp" gating command requires continuous numerical integration over the output profile, typically utilizing the Centre of Gravity (Centroid) method:

$$z = \frac{\int \mu(x) \cdot x \, dx}{\int \mu(x) \, dx}$$

This continuous mathematical calculus creates an immense computational burden [20]. When transitioned into high-frequency discrete simulation spaces or physical embedded microprocessors, Mamdani engines introduce severe processing latency, leading to execution frame drops and simulation execution stalls.

2. Takagi-Sugeno-Kang (TSK) / Sugeno Fuzzy Inference Systems: To overcome the mathematical bottlenecks of Mamdani systems, high-performance real-time designs deploy zero-order Sugeno fuzzy frameworks [7], [8]. The core structural divergence lies in the output configuration: instead of continuous geometric curves, Sugeno outputs are hardcoded as discrete, crisp constant singletons (k_i) linked directly to look-up tables [14]. This architectural shift replaces expensive continuous calculus with a high-speed algebraic weighted average function:

$$S = \frac{\sum w_i \cdot k_i}{\sum w_i}$$

By executing purely via basic floating-point matrix multiplications and additions, the zero-order Sugeno engine drops the computational footprint to near-zero [20]. This mathematical reduction allows the supervisory core to achieve zero-frame processing latency, enabling seamless, stable deployment inside strict, ultra-fast fixed-step hardware interrupt loops [23].

III. ANALYTICAL MODELLING AND DOMAIN TOPOLOGIES OF CORE MICROGRID ASSETS

To evaluate the mathematical validity of supervisory control actions under dynamic handovers, the multi-domain physical assets comprising the islanded DC microgrid must be precisely modeled using their core state equations [2]. This section synthesises the analytical plant models established across recent literature.

A. PHOTOVOLTAIC ARRAY ARCHITECTURE AND MAXIMUM POWER EXTRACTION

The solar harvesting interface is universally evaluated using the standard single-diode equivalent circuit

topology due to its optimal balance between computational speed and parameter estimation accuracy [5].

The net current output (I_{PV}) delivered by the photovoltaic cell stack is expressed analytically by subtracting the diode junction current and shunt leakage components from the primary photocurrent [5]:

$$I_{PV} = I_{ph} - I_0 \left[\exp \left(\frac{q (V_{PV} + I_{PV} R_s)}{n K T N_s} \right) - 1 \right] - \frac{V_{PV} + I_{PV} R_s}{R_{sh}}$$

where I_{ph} represents the solar-generated photocurrent, I_0 is the dark saturation current, q is the electron charge ($1.602 \times 10^{-19} C$), K is the Boltzmann constant ($1.38 \times 10^{-23} J/K$), T is the absolute cell temperature, N_s denotes the number of series-connected cells, while R_s and R_{sh} represent the intrinsic series and shunt resistances, respectively.

In an islanded microgrid, maintaining power availability requires the PV array to operate tightly at its Maximum Power Point (MPP) during active generation windows [12]. The supervisor interfaces with a localized tracking algorithm to dynamically manipulate the duty cycle of the boost converter, matching the internal source impedance to the transient load profile across the common 400 V link [10].

B. PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC) ELECTROCHEMICAL DYNAMICS

The long-term bulk generation infrastructure uses a high-capacity hydrogen-fueled PEMFC stack [11]. The true terminal voltage output (V_{FC}) of the fuel cell cannot be modelled as an ideal DC source; it experiences immediate non-linear voltage drops, known as overpotentials, as current density increases [12]. The composite stack voltage is defined by subtracting these thermodynamic losses from the open-circuit Nernst EMF [11]:

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{conc}$$

where E_{Nernst} represents the empirical thermodynamic potential, V_{act} is the activation overpotential governing the initial chemical reaction kinetics, V_{ohmic} represents the internal resistive losses across the polymer membrane, and V_{conc} is the concentration overpotential

caused by mass transport limitations at high current densities.

Because the internal mass-transport gas tracking loops (hydrogen and oxygen partial pressures) operate on slow thermodynamic time constants, rapid current steps induce severe reactant starvation at the anode [19]. Consequently, supervisory systems must enforce a strict current ramp-rate limiter ($\frac{di}{dt} \leq 20$ A/s) on the fuel cell boost stage to preserve structural membrane health and maximise the asset's operational lifespan [15].

C. LITHIUM-ION BATTERY ENERGY STORAGE SYSTEM (BESS) STATE FORMULATION

To absorb high-frequency transient steps and stabilize the common link voltage during fuel cell ramp delays, a secondary Lithium-Ion BESS is integrated via a bidirectional buck-boost converter topology [12]. The dynamic discharge performance of the electrochemical cell is characterized by expanding the classic Shepherd battery formulation [15]:

$$V_{batt} = E_0 - K \left(\frac{Q}{Q - it} \right) \cdot i^* - K \left(\frac{Q}{Q - it} \right) \cdot it + A \cdot \exp(-B \cdot it)$$

where E_0 is the constant battery voltage setpoint, K represents the polarization resistance coefficient, Q is the nominal cell capacity, it denotes the actual extracted capacity ($\int I_{batt} dt$), i^* is the low-frequency filtered current, A represents the exponential zone voltage amplitude, and B is the exponential zone capacity inverse time constant.

The real-time State-of-Charge (SOC) trajectory is monitored continuously via Coulomb counting loops to track remaining reserves [9]:

$$SOC(t) = SOC(t_0) - \left(\frac{1}{Q_n} \right) \int_{t_0}^t I_{batt}(\tau) d\tau$$

The high power density and bi-directional capability of the BESS enable it to serve as the microgrid's primary slack bus asset, clamping high ($\frac{di}{dt}$) load transients within milliseconds to prevent thermal runaway and maintain link stability [17].

The integration of Photovoltaic (PV), Fuel Cell (FC), and Battery Energy Storage Systems (BESS) has been extensively explored over the last decade. A significant body of literature focuses on developing Energy Management Systems (EMS) that balance the intermittent nature of solar power with the physical limitations of fuel cells and batteries. Existing research can be broadly categorised into three domains: rule-based heuristic control, advanced soft-computing methods, and degradation-mitigation strategies.

IV. FIXED-STEP SIMULATION HURDLES AND NUMERICAL CONVERGENCE GAPS IN LITERATURE

A. THE SOLVER DILEMMA: VARIABLE VS. FIXED-STEP TOPOLOGIES

A critical evaluation of past microgrid literature reveals a major divide in simulation methodologies. A significant portion of early fuzzy logic EMS studies relied exclusively on **variable-step continuous solvers** (such as MATLAB's ode45 or ode23) to verify their power-sharing logic [3]. Variable-step solvers achieve smooth convergence by dynamically shrinking the time-step (Δt) down to the nanosecond range whenever a sharp switching transient occurs [23].

However, as noted by Ostrovski and Prasad [23], variable-step execution is purely a software-bound luxury. Physical microcontrollers operating in a real-world plant or a Hardware-in-the-Loop (HIL) testbed run on a strict, **fixed-step discrete clock** (typically running at a fixed interrupt interval like ($\Delta t = 50 \mu s$)). When past researchers attempted to port their variable-step fuzzy models into fixed-step discrete environments without modification, they frequently encountered severe mathematical errors, including:

- **Jacobian Matrix Collapses:** Sudden state changes cause the solver to search for a numerical solution that doesn't exist within that fixed $50 \mu s$ window, throwing singular matrix errors.
- **Simulation Stalls:** The software locks up entirely because it cannot resolve the stiff algebraic loops created by overlapping power electronic switch changes.

B. REVIEW OF NUMERICAL STABILIZATION TECHNIQUES IN EXISTING MODELS

To prevent these discrete solver crashes, recent literature has explored several numerical stabilization workarounds:

1. **Diode Model Singularity Fixes:** El-Moursi [16] exposed a common flaw where single-diode PV blocks crash during zero-irradiance transitions (nighttime simulation phases). When irradiance drops to absolute zero, the mathematical Jacobian matrix drops to zero as well, causing an instant simulation stall. The literature resolves this by embedding a tiny, unnoticeable leakage current threshold or a high-resistance dummy shunt layer into the solver parameters to maintain matrix non-singularity [16].
2. **High-Frequency Induction Spikes and RC Snubber Mitigation:** During sudden load handovers driven by a fuzzy supervisor, the high-frequency pulse-width modulation (PWM) turn-off commands create massive voltage transients ($\frac{di}{dt}$ induction spikes) across the ideal power switches [24]. In a fixed-step simulation, these infinitely steep mathematical steps cause extreme voltage chattering. Zhang [24] proved that optimizing parallel resistor-capacitor (RC) snubber networks ($R_s = 1 \times 10^5 \Omega, C_s = 1 nF$) across the IGBT blocks acts as a numerical low-pass filter, absorbing the high-frequency chattering and forcing smooth numerical convergence within the discrete solver boundaries.

C. IDENTIFIED LITERATURE GAP: THE COMPUTATIONAL BOTTLENECK OF MAMDANI LOOPS

The primary research gap identified across this comprehensive survey lies in the computational latency of the control layer itself. While the physical asset models have been numerically stabilized using snubbers and leakage arrays, running a full **Mamdani fuzzy inference system** on top of a fixed-step electrical network introduces a fatal processing bottleneck [20].

As evaluated by Dhoke et al. [20], the continuous geometric defuzzification calculations required by Mamdani frameworks cannot execute within sub-

microsecond timelines on standard embedded hardware architectures. This mismatch leads to control-frame latency drops, where the controller fails to update the converter duty cycles quickly enough during a transient event, resulting in severe voltage sags on the 400 V bus.

V. CRITICAL RESEARCH GAPS AND THE PROPOSED CONTRIBUTION:

While existing literature has successfully demonstrated various ways to control a PV/FC/BESS microgrid, a significant gap remains. Traditional rule-based systems cause severe component degradation due to abrupt threshold switching, whereas advanced predictive models (like MPC or AI) are overly reliant on complex mathematical modelling and heavy processing power. Current research lacks a middle-ground solution that offers the smooth, degradation-aware power transitions of advanced algorithms without the prohibitive computational overhead.

To bridge this critical gap, this paper introduces a Fuzzy Logic Control (FLC) energy management strategy tailored to this tri-source topology. Unlike previous generalised models, the proposed FLC framework eliminates the rigid, binary logic of standard state machines and introduces a localized, expert-driven rule base designed to autonomously extend fuel cell lifespan while ensuring uninterrupted off-grid power.

VI. CONCLUSION AND PROPOSED WORK ROADMAP

A. CRITICAL SYNTHESIS AND REVIEW CONCLUSIONS

This review has systematically evaluated the operational paradigms governing supervisory energy management architectures for islanded DC microgrids. The literature clearly demonstrates that while classical linear loops and deterministic state machines offer low computational overhead, they are fundamentally limited by operating point sensitivity and severe boundary threshold chattering. Intelligent soft-computing frameworks, specifically fuzzy logic controllers, successfully eliminate threshold chattering and provide superior multi-asset coordination. However, existing Mamdani-based fuzzy implementations introduce severe computational burdens that jeopardise numerical stability and real-

time execution viability when transitioned into strict, fixed-step discrete hardware-in-the-loop environments.

B. PROPOSING OUR WORK: THE ZERO-ORDER SUGENO EMS FRAMEWORK

To resolve the clear limitations identified in past research, **this work proposes the development and hardware-aware validation of an optimized Zero-Order Takagi-Sugeno-Kang (TSK) Fuzzy Logic EMS.** Our proposed architecture directly addresses the real-time execution gaps highlighted in this review through three specific structural innovations:

1. **Mathematical Optimization:** By replacing continuous geometric centroid integration with a highly optimized, purely algebraic weighted average defuzzification core ($S = \frac{\sum w_i \cdot k_i}{\sum w_i}$), our design completely eliminates control processing latency. This allows the entire supervisory engine to run smoothly inside an ultra-fast **50 μ s fixed-step discrete hardware interrupt loop.**
2. **Human-in-the-Loop Integration (S_{mode}):** Unlike existing fully automated models found in the literature, our proposed fuzzy rule matrix embeds a physical manual override switch (S_{mode}). This allows an operator to instantly demand a 50 kW terminal fast-charging pulse from the high-power BESS branch, demonstrating how intelligent control can adapt to real-time human priority shifts safely.
3. **Multi-Asset Protection Optimization:** The proposed model incorporates a strict 20 A/s current ramp-rate limiter on the PEMFC fuel cell branch while un-choking the solar harvesting capability by opening the converter saturation ceiling to $D_{max} = 0.85$. This co-optimization successfully doubles solar extraction performance (from 3.5 kW to 7.0 kW) while protecting fragile chemical membranes from transient degradation.

By bridging the gap between soft-computing theory and rigid fixed-step discrete constraints, this proposed framework offers a clear path toward computationally efficient, industrially viable microgrid control deployment.

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