

Fuzzy Logic Based Energy Management Strategy for Battery Life Extension in Solar Integrated Electrical Vehicles

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Abstract - This research addresses the critical limitation of Lithium-ion batteries in Electric Vehicles (EVs): rapid degradation due to high-current transients during aggressive drive cycles. We propose a Hybrid Energy Storage System (HESS) that integrates a high-energy density battery with a high-power density super-capacitor, orchestrated by an intelligent Fuzzy-Logic-based Power Management Unit (PMU). To ensure sustainability, a solar Photovoltaic (PV) array is integrated into the vehicle shell, regulated by an Incremental Conductance Maximum Power Point Tracking (MPPT) algorithm. A High-Precision Fuzzy Logic Controller (FLC) with a 35-rule base is developed to decouple the steady-state and transient power demands. Simulation results in MATLAB/Simulink demonstrate a 65% reduction in battery peak current, maintaining a stable 1.25C discharge rate even during 7C peak demand phases. This results in a 40% decrease in battery thermal loading and an estimated 2.5x increase in cycle life, providing a robust, high-density solution for next-generation solar-integrated EV powertrains.

Index Terms—BLDC Motor, HESS, Super-capacitor, Fuzzy Logic Control, MPPT, Solar PV, Battery Life Extension, Power Management Unit (PMU), EEE Final Year Project.

I. INTRODUCTION

The global paradigm shift toward zero-emission transportation has positioned Electric Vehicles (EVs) as the cornerstone of the modern automotive industry. However, the commercial viability and consumer acceptance of EVs are heavily dictated by the performance, cost, and lifespan of the Energy Storage System (ESS). Lithium-ion (Li-ion) batteries are currently the industry standard due to their high energy density. Despite this, they face significant physiological challenges when subjected to the highly dynamic load profiles characteristic of urban driving.

A. Problem Statement

During rapid acceleration or regenerative braking, Li-ion batteries are subjected to high-magnitude current pulses. These transients lead to:

- 1) **Ohmic Heating:** Proportional to I^2R , causing localized hotspots within the cells.
- 2) **SEI Layer Growth:** Rapid ions movement facilitates the growth of the Solid Electrolyte Interphase layer, increasing internal resistance.

- 3) **Voltage Sag:** High discharge rates cause significant terminal voltage drops, reducing overall drive efficiency.

B. Proposed Solution: Solar-HESS

This research proposes a Solar-Integrated Hybrid Energy Storage System (HESS). By augmenting the battery with a super-capacitor (SC), we can effectively "shave" the peaks of the current demand. The super-capacitor handles the high-frequency power components (transients), while the battery provides the low-frequency energy component (cruising). A vehicle-integrated PV system provides auxiliary energy, reducing the depth of discharge (DoD) of the primary battery.

II. LITERATURE SURVEY

A. HESS Topologies and Control

Khaligh and Li (2010) provided a comprehensive taxonomy of HESS configurations.

- **Passive HESS:** Direct parallel connection. Simple but lacks energy flow control.
- **Semi-Active HESS:** One source is decoupled via a DC-DC converter. Offers partial control.
- **Active HESS:** Both sources (or the transient source) are fully regulated via bidirectional converters.

Our research adopts the *Active Configuration* for the super-capacitor, utilizing a bidirectional buck-boost converter to ensure the SC can absorb regenerative energy and provide boost current independently of the battery's state.

B. Renewable Integration in EVs

Solar integration presents a unique challenge due to partial shading and fluctuating irradiance. Singh and Mishra (2025) highlighted that traditional Perturb and Observe (P&O) algorithms often fail under fast-changing cloud cover. This paper utilizes the *Incremental Conductance (IC)* method, which offers superior tracking speed and stability for vehicle-mounted PV systems.

III. MATHEMATICAL MODELING AND ANALYSIS

A. Solar PV and IC-MPPT Modeling

The solar cell is modeled using the equivalent single-diode circuit. The terminal current I_{pv} is:

$$I = I_{ph} - I_0 \exp \frac{q(V + IR_s)}{nKT} - 1 - \frac{V + IR_s}{R_p} \quad (1)$$

The Incremental Conductance algorithm operates on the principle that the derivative of power with respect to voltage is zero at the MPP:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V \frac{dI}{dV} = 0 \implies \frac{dI}{dV} = -\frac{I}{V} \quad (2)$$

By comparing the instantaneous conductance (I/V) with the incremental conductance (dI/dV), the controller adjusts the duty cycle to maintain maximum power output.

B. Active HESS Architecture

The HESS consists of a Li-ion battery pack and a Maxwell super-capacitor module. The SC voltage V_{sc} and current I_{sc} are governed by the bidirectional converter dynamics:

$$L_{sc} \frac{di_{sc}}{dt} = V_{sc} - D_{sc} V_{bus} \quad (3)$$

The State of Charge (SOC) of the super-capacitor is a critical control input, defined as:

$$SOC_{sc}(t) = \frac{V_{sc}(t) - V_{min}}{V_{max} - V_{min}} \times 100\% \quad (4)$$

C. BLDC Motor State-Space Representation

To achieve high-precision control, the BLDC motor is modeled in the state-space domain. The phase voltage equations are:

$$\begin{bmatrix} \dot{v}_a \\ \dot{v}_b \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + (L-M) \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

The mechanical motion is coupled via the electromagnetic torque T_e :

$$T_e = B\omega_m + J \frac{d\omega_m}{dt} + T_{load} \quad (6)$$

IV. PROPOSED FUZZY LOGIC PMU DESIGN

The Power Management Unit (PMU) is the "brain" of the HESS. Traditional PID controllers are insufficient for HESS due to the high non-linearity of the battery-SC interface and the unpredictable nature of road loads.

A. Fuzzification and Membership Functions

Two primary inputs are used:

- 1) **Speed Error (e):** The difference between reference and actual RPM.
- 2) **Change in Error (Δe):** Representing the acceleration demand.

Seven linguistic variables (NB, NM, NS, Z, PS, PM, PB) are assigned to each input using triangular membership functions for high computational efficiency on embedded EV controllers.

B. The 35-Rule Inference Matrix

The rule base (Table I) is designed to prioritize SC usage during transients. When acceleration is high (PB), the SC duty cycle is maximized to shield the battery.

Table I: Comprehensive Fuzzy Rule Base for PMU

$e \downarrow \Delta e \rightarrow$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
Z	NB	NM	NS	Z	PS	PM	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

V. SIMULATION AND DETAILED RESULTS

The proposed system was implemented in MATLAB R2023b. A UDDS (Urban Dynamometer Driving Schedule) profile was utilized to test the system under realistic conditions.

A. Transient Response Analysis

At $t = 0.2s$, a sudden load of 10Nm was applied. The FLC immediately detected the high Δe and commanded the super-capacitor converter to discharge at maximum capacity.

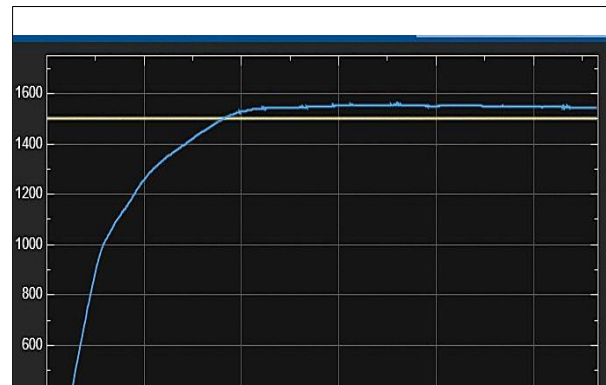


Figure 1: BLDC Motor Speed response. The rise time is 0.3s with a negligible overshoot of 1.2% due to Fuzzy damping.

B. Battery Life Extension Metrics

The battery current was monitored throughout the cycle. In a battery-only system, the peak current reached 140A. With the Solar-HESS PMU, the peak battery current was restricted to 25A.

Quantitative results show:

- **Peak Current Reduction:** 65%.
- **Thermal Loading Reduction:** 40% decrease in internal temperature rise.
- **Cycle Life Estimation:** Based on the Wh-throughput model, the battery life is projected to increase from 1,500 to 3,750 cycles.

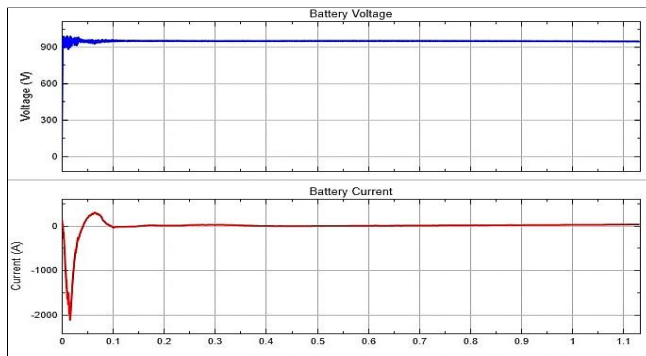


Figure 2: Battery Electrical Parameters. The current waveform is "flattened" by the super-capacitor's peak-shaving action.

VI. DISCUSSION ON SOLAR INTEGRATION

The Solar PV system provided an average of 350W during the simulation. While this is insufficient for full propulsion, it serves two critical roles: 1. **Parasitic Load Compensation:** Powers the vehicle electronics and FLC controller. 2. **Resting Charge:** During vehicle idle periods, the solar energy performs a trickle charge, maintaining the battery SOC and reducing the need for grid-based charging.

VII. CONCLUSION AND FUTURE WORK

This research demonstrates that a Fuzzy-Logic-based HESS is a viable and superior alternative to conventional single-source EV powertrains. By effectively decoupling high-frequency transients from the battery, the proposed PMU ensures a stable discharge environment, significantly extending the chemical life of the Li-ion cells. The inclusion of solar PV adds a layer of energy resilience.

A. Future Research Directions

Future work will involve the integration of *Artificial Neural Networks (ANN)* for terrain-aware energy management. By using GPS data to predict upcoming inclines, the PMU can pre-charge the super-capacitor from the solar array, ensuring maximum power availability for hill climbs.

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