International Transactions on Parametric Engineering Simulations (ITPES)

ISSN: XXXX-YYYY | Volume 01 | Issue 01 | January 2026

Research Article

Design and Energy Management of a Hybrid Fuel Cell–Battery–Supercapacitor Power System for Electric Vehicles

R. Essaki Raj

Electrical and Electronics Engineering, Rajalakshmi Engineering College, Chennai, India
Corresponding Author: essakiraj.r@rajalakshmi.edu.in

Received: 29-10-2025; Accepted: 27-01-2026; Published: 31-01-2026

Abstract

This research addresses the critical challenge of balancing power and energy densities in Electric Vehicles (EVs) by proposing a multi-source Hybrid Energy Storage System (HESS). While Proton Exchange Membrane Fuel Cells (PEMFCs) provide high energy density for extended range, their inherent slow dynamic response leads to "oxygen starvation" and membrane degradation during high-frequency power transients. By integrating a Lithium-ion battery and a supercapacitor (SC), this study develops a multi-converter architecture capable of mitigating the degradation of primary sources under dynamic load cycling fatigue. Central to this integration is a State Machine Control (SMC) strategy that manages power allocation based on the battery's State of Charge (SoC) and the non-linear demands of a variable drive cycle. Simulation results in MATLAB/Simulink demonstrate that the HESS effectively maintains DC-link voltage stability within a 265–285V window and optimizes fuel consumption, recorded in both Liters Per Minute (LPM) and Grams Per Second (GS). The supercapacitor successfully provides "peak shaving" for high-frequency transients, while the battery and fuel cell operate within constrained di/dt limits to ensure system longevity and robust power delivery for next-generation electric mobility.

Keywords

Hybrid Energy Storage System, State Machine Control, Proton Exchange Membrane Fuel Cell, Lithium-ion Battery, Supercapacitor.

Citation:
Essaki Raj, R (2026), Design and Energy Management of a Hybrid Fuel Cell–Battery–Supercapacitor Power System for Electric Vehicles, International Transactions on Parametric Engineering Simulations (ITPES), Volume 1, Issue 1, 2026010105.

I. Introduction

The global shift toward electric transportation is motivated by the need to reduce greenhouse gas emissions, improve energy efficiency, and decrease dependence on fossil fuels. Despite significant advancements in battery technology, standalone battery-based EVs still face challenges, particularly in terms of range anxiety, long charging times, and accelerated degradation due to high power cycling in urban driving conditions.

Fuel cell electric vehicles (FCEVs) offer an alternative by converting hydrogen directly into electrical energy, providing high energy density and fast refueling. However, PEM fuel cells exhibit slow electrochemical dynamics, making them unsuitable for rapid power variations. Sudden current changes can cause oxygen starvation, thermal stress, and membrane degradation, severely reducing fuel cell lifespan. Fig. 1 illustrate common DC bus structure.

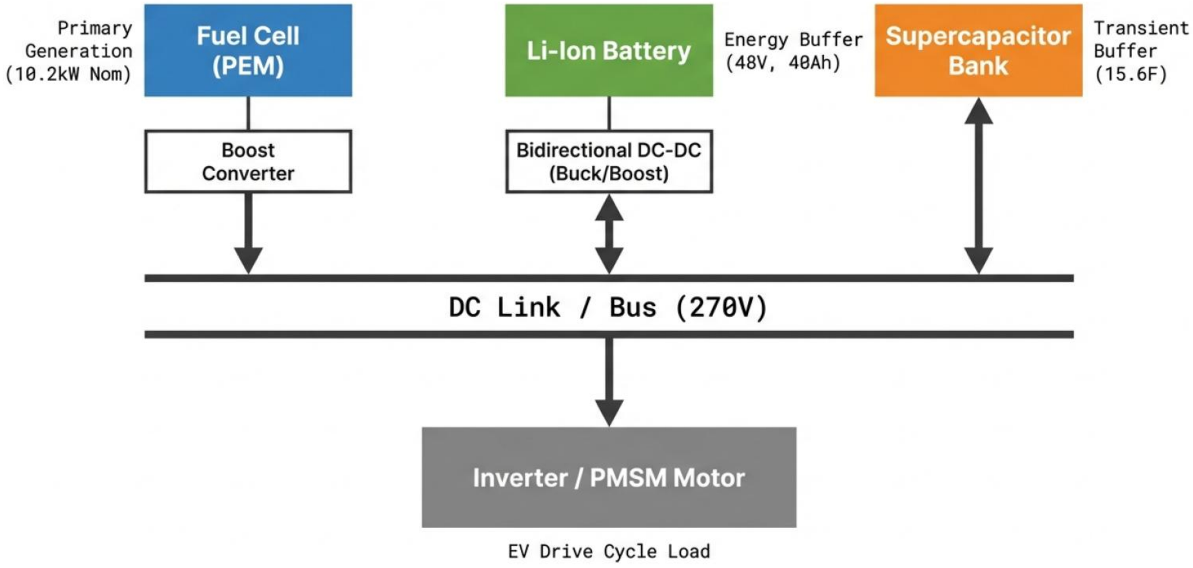


Fig. 1 Common DC Bus Structure

To address these issues, multi-source hybrid power architectures have gained attention. By combining energy sources with complementary characteristics, it is possible to distribute power demands intelligently. In such architectures:

- The fuel cell supplies the average or steady-state power,
- The battery manages medium-term load variations,
- The supercapacitor absorbs high-frequency transients.

This paper focuses on the modelling, control, and performance analysis of a hybrid fuel cell–battery–supercapacitor system connected to a Permanent Magnet Synchronous Motor (PMSM) drive. The main emphasis is on energy management using State Machine Control and its validation through MATLAB/Simulink simulations under realistic drive cycles.

Mounica and Obulesu [1] proposed a hybrid power management strategy for a fuel cell–battery–supercapacitor-based hybrid electric vehicle with the primary objective of improving fuel economy. Their study demonstrated that assigning the fuel cell to supply the average load demand, while allowing the battery and supercapacitor to handle transient and peak power requirements, significantly reduced hydrogen consumption. Simulation results validated improved overall efficiency under standard driving cycles. However, the study placed limited emphasis on DC-link voltage regulation and converter-level dynamic interactions, which are critical for maintaining power quality in traction applications.

Rahman *et al.* [2] introduced a variable structure-based control strategy for a fuel cell–battery–supercapacitor hybrid electric vehicle. The proposed method dynamically switched between multiple control modes depending on operating conditions, enabling effective handling of load disturbances and reducing fuel cell stress during rapid transients. While the results indicated improved dynamic response and robustness, the frequent switching between control structures increased control complexity, potentially affecting real-time implementation in embedded automotive systems.

Zhang *et al.* [6] developed an adaptive energy management strategy for fuel cell/battery/supercapacitor hybrid energy storage systems used in electric vehicles. Their approach adjusted power distribution rules in real time based on system states and driving conditions. The adaptive nature of the strategy enhanced energy utilization efficiency and reduced battery aging. Nevertheless, the work primarily focused on adaptive power sharing and did not explicitly address the issue of strict DC-link voltage stability under high-frequency load variations.

Kamel *et al.* [5] investigated a hybrid energy management strategy for a multi-source renewable energy system incorporating fuel cell, photovoltaic array, battery, and supercapacitor. Their results demonstrated improved operational efficiency and enhanced system reliability through coordinated energy management. Although the strategy proved effective for renewable-integrated systems, the inclusion of photovoltaic sources increased system complexity, making the approach less directly applicable to traction-focused electric vehicle powertrains.

Benhammou *et al.* [4] proposed an accurate and efficient EMS for hybrid electric vehicles integrating fuel cell, battery, supercapacitor, and both AC and DC generators. Their work emphasized precise power coordination and minimization of energy losses across multiple sources. Simulation results confirmed improved vehicle performance and smoother power transitions. However, the EMS relied on relatively complex coordination algorithms, which may impose higher computational requirements for real-time automotive controllers.

More recently, Kalaivani and Joice [3] presented a neural network-based energy management system for a hybrid electric vehicle powered by solar PV, fuel cell, battery, and ultracapacitor. The proposed artificial intelligence-based approach demonstrated superior adaptability and improved energy utilization under varying operating conditions. Despite its performance advantages, neural network-based EMS approaches require extensive training data and higher computational resources, which can limit their deployment in safety-critical and cost-sensitive EV applications.

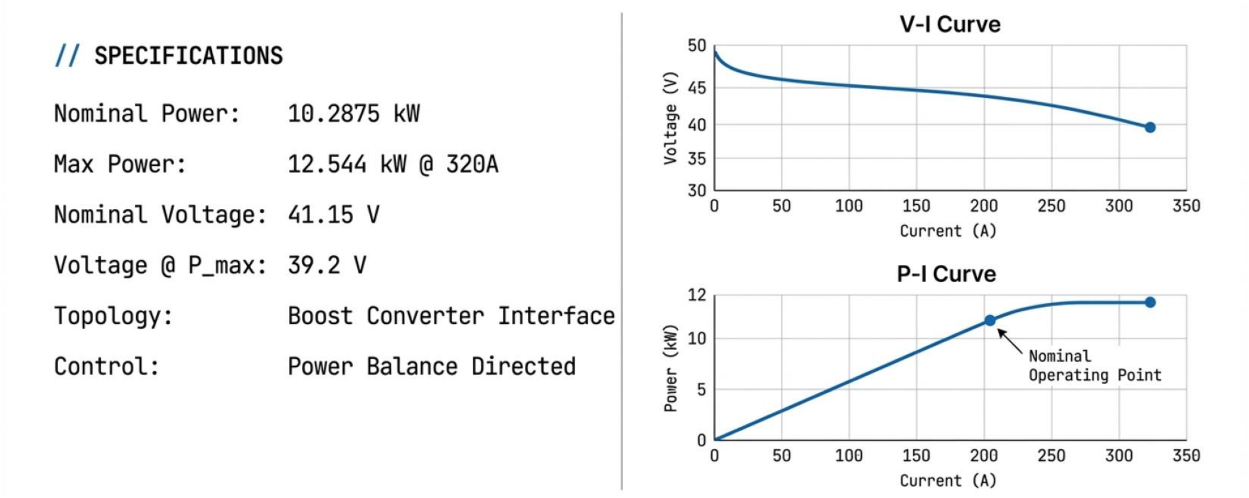
II. System Modeling and Methodology

3.1 Overall HESS Configuration

The proposed HESS integrates three energy sources into a common DC-link architecture, enabling coordinated power sharing. This topology ensures that each source operates within its optimal operating region while collectively satisfying the non-linear and time-varying power demands of an EV drivetrain.

3.2 Fuel Cell System Modelling

The primary energy source is a PEM fuel cell stack with a nominal power rating of 10.2875 kW and a maximum power capability of 12.544 kW. The fuel cell operates at a relatively low nominal voltage of 41.5 V and delivers up to 320 A at maximum power. Fig. 2 Characteristics of Fuel Cell.



// SPECIFICATIONS

Nominal Power:	10.2875 kW
Max Power:	12.544 kW @ 320A
Nominal Voltage:	41.15 V
Voltage @ P_max:	39.2 V
Topology:	Boost Converter Interface
Control:	Power Balance Directed

Fig. 2 Characteristics of Fuel Cell

Since the EV DC-link operates at a much higher voltage, a DC–DC boost converter is employed. The relationship between the fuel cell voltage and DC-link voltage is given by:

$$V_{DC} = \frac{V_{fc}}{1 - D}$$

where $D$is the duty cycle of the boost converter.

The fuel cell converter is controlled using a power balance approach, which limits rapid current changes and ensures smooth power ramping. This strategy prevents fuel starvation and mitigates thermal and electrochemical stress within the PEM membrane.

3.3 Battery and Supercapacitor Modelling

Battery Unit

A 48 V, 40 Ah lithium-ion battery is used to handle medium-duration power variations. The battery is connected to the DC-link through a bidirectional buck–boost converter, enabling:

- Discharging mode (boost operation) to supply power to the DC-link,
- Charging mode (buck operation) during surplus power conditions or regenerative braking.

This bidirectional capability allows effective SoC regulation and prolongs battery life. Fig. 3 bidirectional lithium-ion storage.

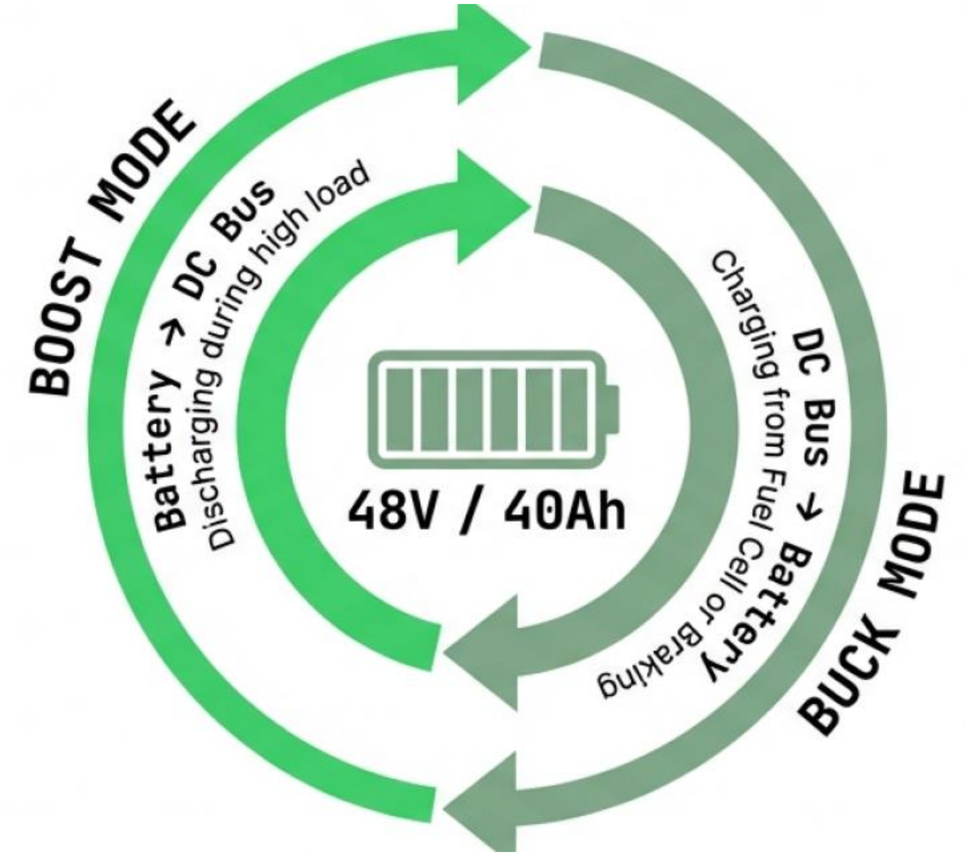
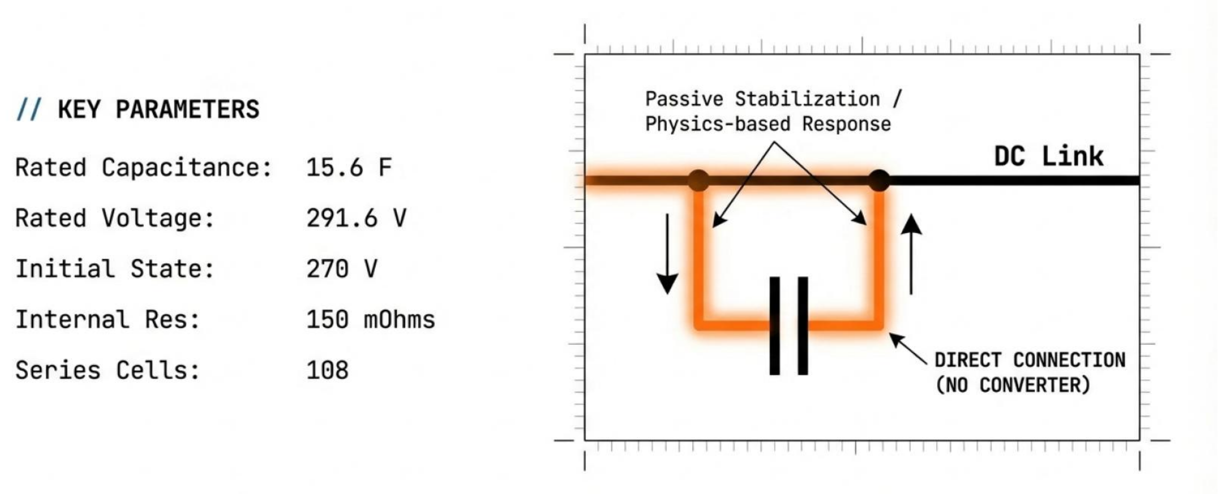


Fig. 3 Bidirectional Lithium-Ion Storage

Supercapacitor Unit

A 291.6 V, 15.6 F supercapacitor with an internal resistance of 150 mΩ is directly connected to the DC-link. Unlike the battery and fuel cell, the supercapacitor does not require a converter, allowing instantaneous current response. Fig. 4 shows passive supercapacitor bank.



// KEY PARAMETERS

Rated Capacitance:	15.6 F
Rated Voltage:	291.6 V
Initial State:	270 V
Internal Res:	150 mOhms
Series Cells:	108

Fig. 4 Passive Supercapacitor Bank

Load Drive

The EV load is represented by a PMSM powered through a Voltage Source Inverter (VSI). The PMSM introduces highly dynamic power demands, accurately reflecting real-world EV operation.

III. Control Strategy / Algorithm Description

4.1 State Machine Control Philosophy

The Energy Management System is implemented using State Machine Control (SMC) due to its simplicity, robustness, and ease of implementation. The SMC monitors the battery SoC and load power to determine the operating mode. Fig. 5 shows the state machine logic.

SoC thresholds:

- Minimum SoC: 60%
- Nominal SoC range: 60% – 85%
- Maximum SoC: 90%

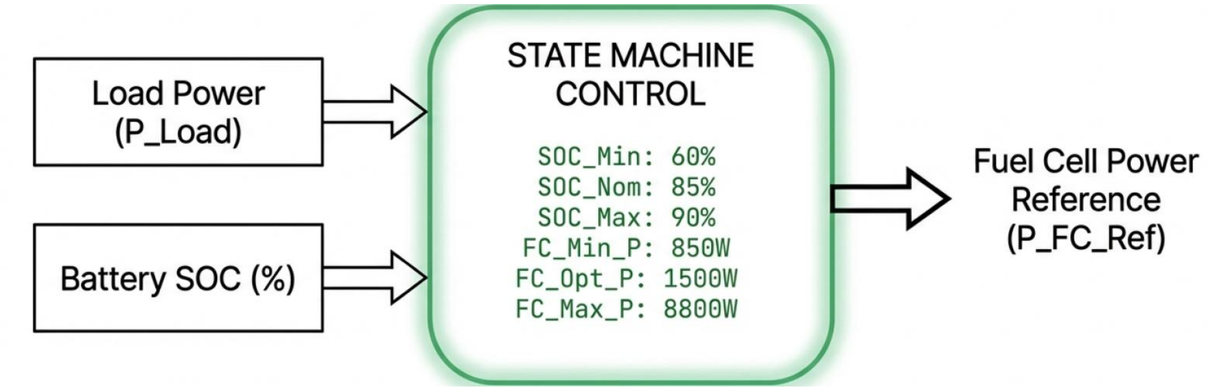
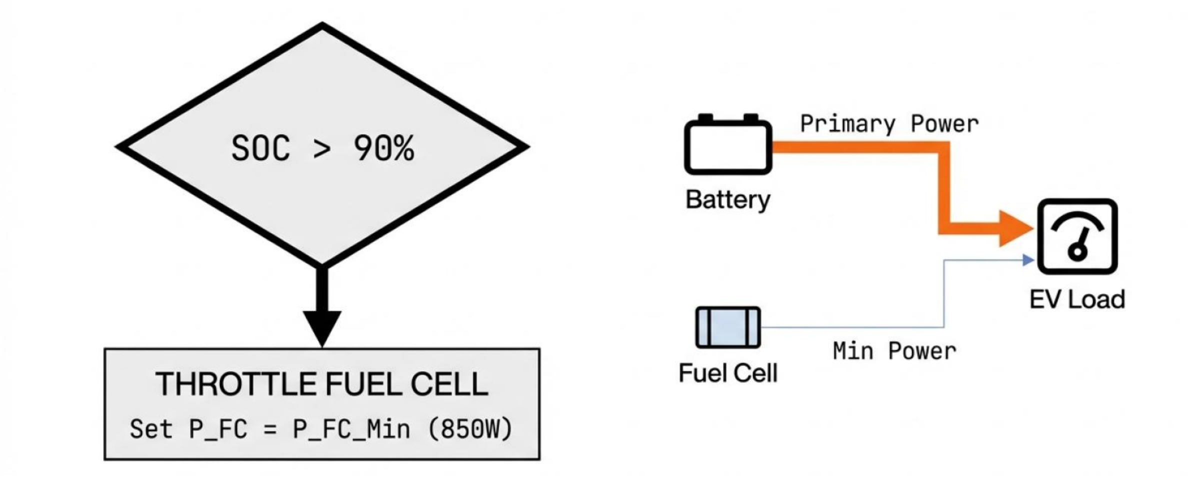


Fig. 5 State Machine Logic

4.2 Operational States

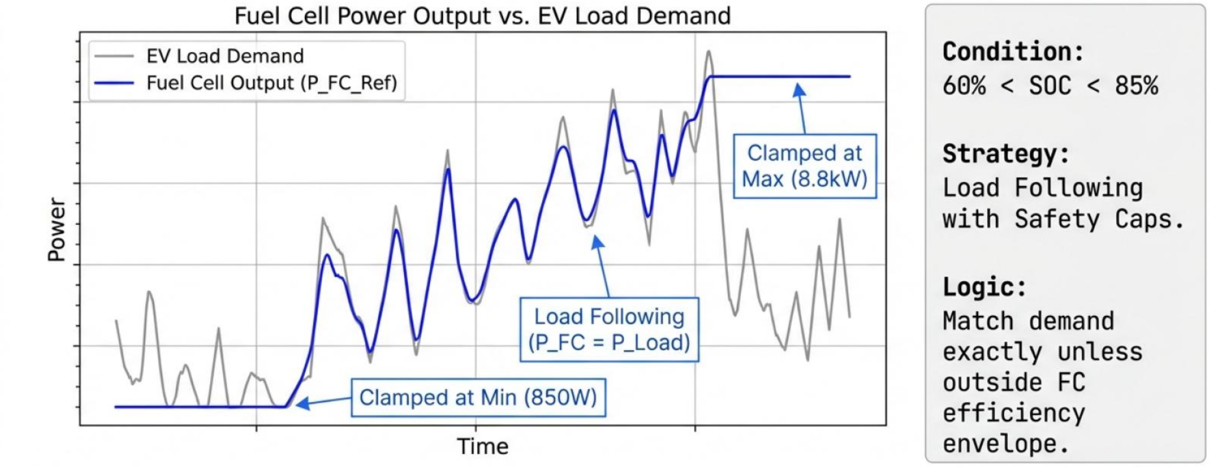
- **State 1 (SoC > 90%)**

  Battery charging is restricted to prevent overcharging. Excess power is absorbed by the supercapacitor or curtailed at the fuel cell level.



- **State 2 (60% ≤ SoC ≤ 85%)**

  Normal operation mode. Power is shared among fuel cell, battery, and supercapacitor according to load demand.



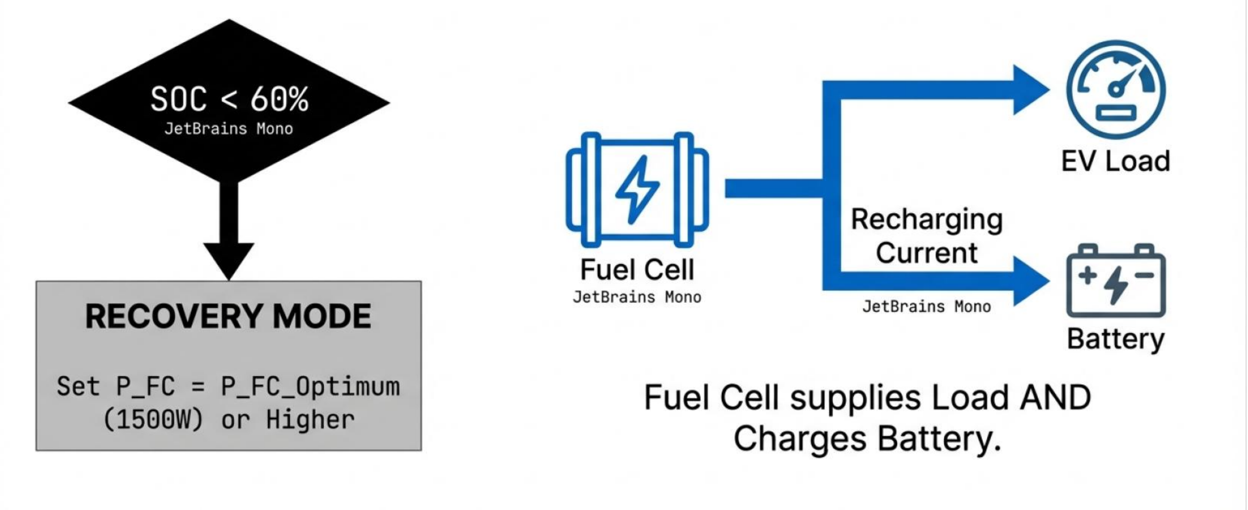
Condition:
60% < SOC < 85%

Strategy:
Load Following
with Safety Caps.

Logic:
Match demand
exactly unless
outside FC
efficiency
envelope.

- **State 3 (SoC < 60%)**

  Battery recovery mode. A fixed charging power of 1,500 W is enforced to restore battery SoC.



Fuel Cell supplies Load AND Charges Battery.

4.3 Power Reference Generation

Fuel cell power limits:

- $P_{fc\_min} = 850\,\text{W}$
- $P_{fc\_opt} = 1{,}500\,\text{W}$
- $P_{fc\_max} = 8{,}800\,\text{W}$

The SMC ensures the fuel cell operates within these bounds. PI controllers regulate converter duty cycles to maintain the DC-link voltage at 270 V, with an allowable variation between 265V and 285V. Fig. 6 shows the voltage regulation & loop control.

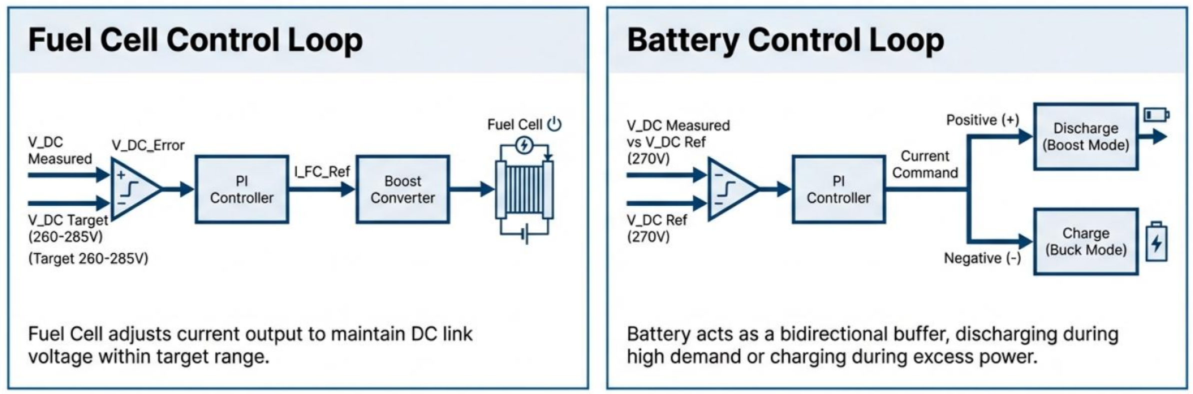


Fig. 6 Voltage Regulation & Loop Control

IV. Simulation Setup and Parameters

To validate the effectiveness of the proposed Hybrid Energy Storage System (HESS) and the associated State Machine Control (SMC)–based Energy Management System, a detailed simulation study was carried out using MATLAB/Simulink. The simulation framework captures the dynamic interaction among the fuel cell system, bidirectional battery converter, supercapacitor, and the PMSM-based traction load. Emphasis was placed on reproducing realistic operating conditions, including power transients, load fluctuations, and energy source constraints.

IV.A System Parameters

The simulation model was configured using parameters that reflect practical EV powertrain specifications. These parameters were carefully selected to ensure that the results remain representative of real-world applications while allowing meaningful evaluation of the proposed control strategy.

The fuel cell system is rated at a nominal power of 10.2875 kW, with a maximum allowable output of 12.544 kW. Correspondingly, the nominal and maximum current limits are set to 250 A and 320 A, respectively. These limits are enforced in the control logic to prevent excessive current stress and to protect the PEM membrane from degradation due to rapid current variations.

The battery unit is modelled as a 48 V, 40 Ah lithium-ion battery, which provides sufficient energy buffering capability to manage medium-duration load variations. A bidirectional DC–DC converter enables both charging and discharging modes, allowing the battery to support the DC-link during high demand and recover its State of Charge (SoC) during low-load or surplus energy conditions.

The supercapacitor is modelled with a capacitance of 15.6 F and an internal resistance of 150 mΩ. This configuration allows the supercapacitor to deliver and absorb large currents over short durations, making it suitable for handling high-frequency power transients. Its relatively low internal resistance ensures minimal energy loss during rapid charge–discharge cycles.

The DC-link voltage is regulated around a reference value of 270 V, with an allowable maintenance range of 265 V to 285 V. This voltage window is selected to ensure stable operation of the inverter-fed PMSM while accommodating transient disturbances. Additionally, a constant battery charging power of 1,500 W is defined for battery recovery operation when the SoC falls below the minimum threshold.

Overall, these parameters establish a balanced system where each energy source operates within its safe and efficient region, enabling effective evaluation of the proposed SMC-based EMS.

IV.B Drive Cycle Implementation

To emulate realistic EV operating conditions, a variable drive cycle is applied as the load input to the system. This drive cycle introduces frequent acceleration and deceleration events, resulting in rapidly changing power demands at the DC-link. Such conditions are critical for testing the robustness of the energy management strategy, as they require continuous real-time power redistribution among the fuel cell, battery, and supercapacitor.

The dynamic nature of the drive cycle ensures that:

- The supercapacitor is repeatedly subjected to high-frequency current demands,
- The battery experiences moderate charging and discharging cycles,
- The fuel cell is forced to operate under smoothly varying power references rather than abrupt changes.

This approach allows verification that the fuel cell avoids rapid power ramping, thereby preventing oxygen starvation and thermal stress, while the DC-link voltage remains stable under all operating conditions.

V. Results and Discussion

The simulation results provide a detailed insight into the dynamic behavior of the proposed HESS and clearly demonstrate the effectiveness of the State Machine Control strategy in managing power flow and maintaining system stability.

V.A Power Distribution and Dynamic Response

At the initial stage of simulation, when there is no immediate load demand, the supercapacitor operates in a charging mode, drawing a small amount of energy to establish its voltage level at the DC-link. As the drive cycle progresses and the load demand increases, a distinct hierarchical power-sharing behaviour emerges.

1. **Supercapacitor Response**

   The supercapacitor responds instantaneously to sudden changes in load power. It delivers sharp bi-directional current spikes that closely follow the derivative of the load power demand. This rapid response prevents sudden voltage dips or overshoots at the DC-link, ensuring voltage stability during transient events.

2. **Battery Contribution**

   The battery supplies the medium-term power deficit that arises when the load demand exceeds the optimal operating range of the fuel cell. Acting as an energy bridge, the battery smooths the transition between transient and steady-state operation, thereby reducing the stress on both the fuel cell and the supercapacitor.

3. **Fuel Cell Operation**

   The fuel cell gradually ramps up its output to meet the steady-state power requirement. The SMC enforces strict current and power limits, ensuring that the fuel cell does not experience abrupt changes. This controlled ramping is crucial for preserving fuel cell efficiency and longevity.

This tiered response clearly illustrates the complementary roles of the three energy sources within the HESS.

V.B Voltage and Current Stability

One of the most critical performance indicators of the proposed system is DC-link voltage regulation. Simulation results confirm that the DC-link voltage remains consistently within the predefined range of 265–285 V, even during aggressive load transients introduced by the drive cycle.

Fuel cell consumption analysis, expressed in Liters Per Minute (LPM) and Grams Per Second (GS), shows a direct correlation with the stabilized power output. This indicates that the fuel cell operates efficiently and avoids unnecessary fuel consumption caused by power oscillations.

The battery SoC remains well-regulated throughout the simulation, fluctuating only between 60% and 65%. This behaviour validates the effectiveness of the SMC recovery logic in State 3, where a constant charging power of 1,500 W is applied to restore the battery SoC without overloading the DC-link or stressing the fuel cell.

V.C Role of Peak Shaving by the Supercapacitor

A key outcome of the simulation is the clear demonstration of peak shaving by the supercapacitor. By absorbing and supplying high-frequency power components, the supercapacitor significantly reduces the di/dt stress imposed on the battery.

This effect is evident from the supercapacitor current waveform, which exhibits rapid bi-directional spikes, while the fuel cell current remains smooth and heavily damped. As a result:

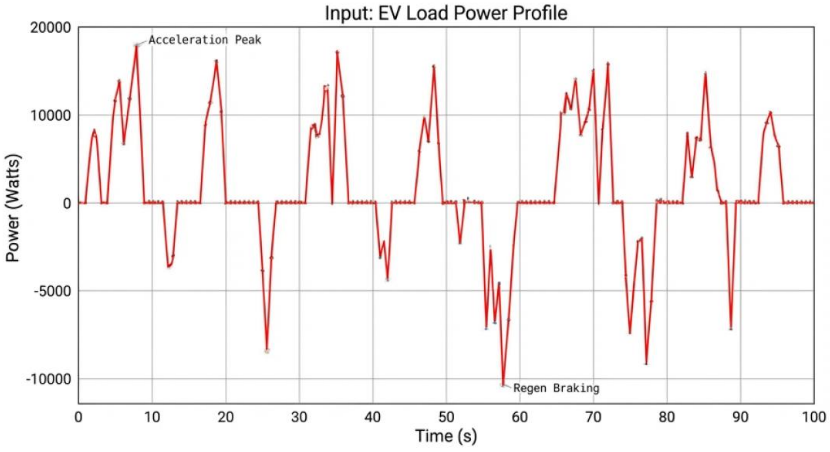
- Battery aging due to high current stress is minimized,
- Fuel cell degradation mechanisms are mitigated,
- Overall system reliability is improved.

V.D Performance Visualizations

The simulation results are further supported by the following visual analyses:

- **Figure 7: Power Sharing Waveforms**

  Illustrates the coordinated power response of the fuel cell, battery, and supercapacitor. The supercapacitor current closely follows the rate of change of load power, while the fuel cell exhibits a controlled ramp.

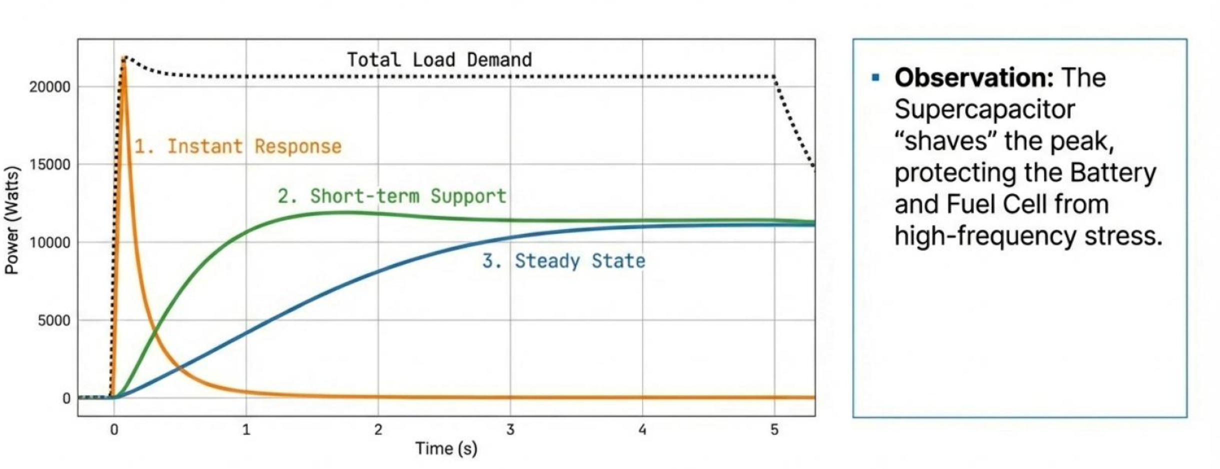


- **Challenge:** The power system must satisfy this erratic demand instantly.
- **Initial Conditions:** Battery SOC @ 65% | Supercapacitor @ 270V

Fig. 7 Power Sharing Waveforms

- **Figure 8: DC-Link Voltage and Battery SoC**

Demonstrates stable DC-link voltage regulation within the 265–285 V window and confirms that the battery SoC remains within the optimal 60–65% range.



- **Observation:** The Supercapacitor "shaves" the peak, protecting the Battery and Fuel Cell from high-frequency stress.

Fig. 8 DC-Link Voltage and Battery SoC

- **Figure 9: Fuel Cell Characteristics**

  Presents the fuel cell voltage–current (V–I) characteristics and fuel consumption trends (LPM and GS), confirming that the fuel cell operates strictly within the defined P_{fc_min} and P_{fc_max} limits. Fig. 10 shows efficiency and resource management.

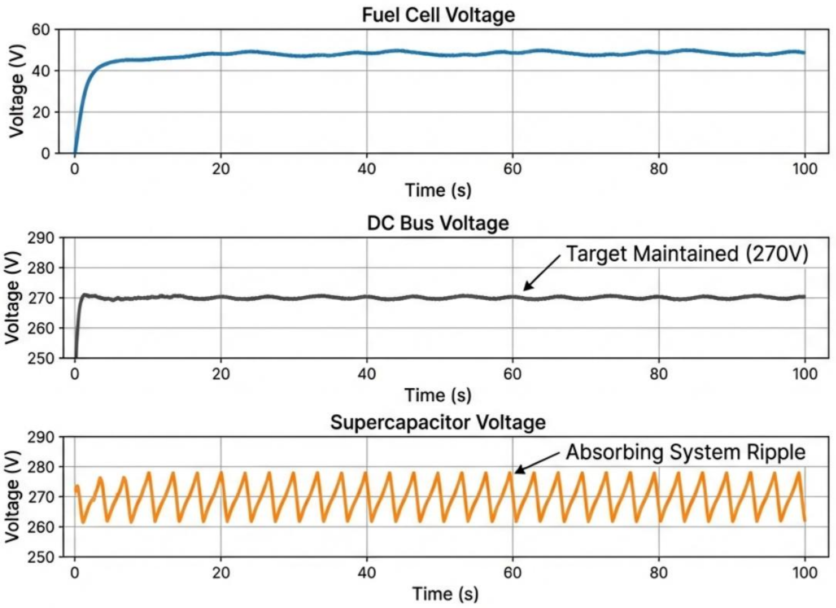


Fig. 9 Fuel Cell Characteristics

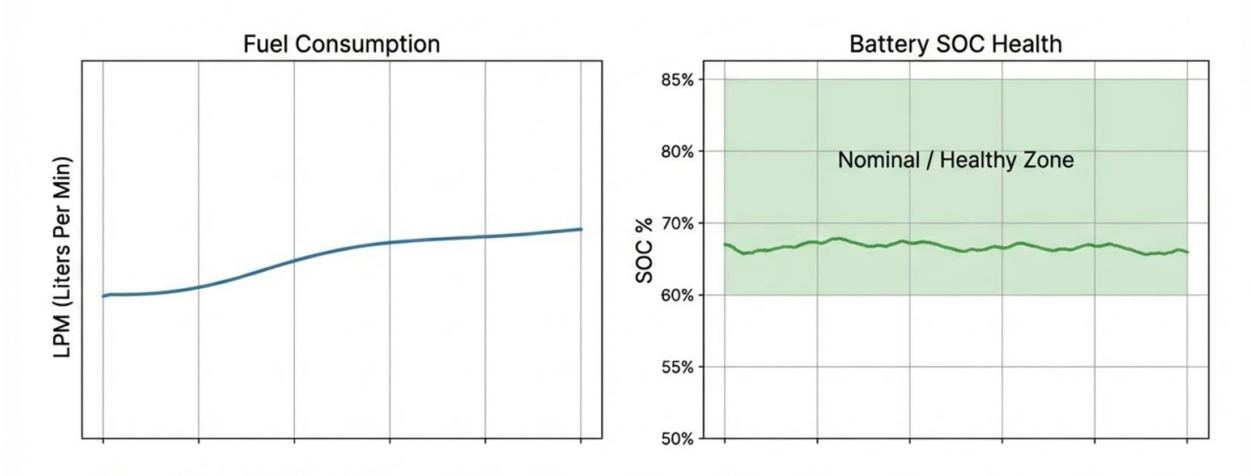


Fig. 10 Efficiency and Resource Management

VI. Conclusion and Future Scope

This study successfully validates a three-source Hybrid Energy Storage System for electric vehicle applications using a State Machine Control–based Energy Management Strategy. By integrating a PEM fuel cell, a lithium-ion battery, and a supercapacitor, the proposed system effectively balances long-term energy supply with high-frequency power responsiveness.

The simulation results confirm that:

- The fuel cell is protected from oxygen starvation and thermal stress,
- The battery operates within a narrow and healthy SoC range,
- The supercapacitor efficiently handles transient power demands,
- The DC-link voltage is maintained within the specified 265–285 V range.

Compared to single-source energy systems, the proposed architecture demonstrates superior fuel economy, enhanced system longevity, and improved dynamic performance, making it highly suitable for next-generation electric vehicles.

Future Scope

Future research should focus on:

- Optimizing regenerative braking energy recovery, particularly in coordinating energy flow between the battery and supercapacitor,

- Investigating advanced EMS techniques such as optimization-based or AI-assisted control strategies,
- Implementing Hardware-in-the-Loop (HIL) testing to validate the real-time feasibility and robustness of the SMC logic on embedded control platforms.

Overall, the proposed HESS presents a practical and scalable solution for achieving durable, efficient, and high-performance zero-emission transportation systems.

Acknowledgment

Nil

References

[1]. Mounica, V.; Obulesu, Y.P. Hybrid power management strategy with fuel cell, battery, and supercapacitor for fuel economy in hybrid electric vehicle application. *Energies* **2022**, *15*, 4185.

[2]. Rahman, A.U.; Ahmad, I.; Malik, A.S. Variable structure-based control of fuel cell–supercapacitor–battery-based hybrid electric vehicle. *J. Energy Storage* **2020**, *29*, 101365.

[3]. Kalaivani, P.; Joice, C.S. Design and modelling of a neural network-based energy management system for solar PV, fuel cell, battery and ultracapacitor-based hybrid electric vehicle. *Electr. Eng.* **2024**, *106*, 689–709.

[4]. Benhammou, A.; Tedjini, H.; Hartani, M.A.; Ghoniem, R.M.; Alahmer, A. Accurate and efficient energy management system of fuel cell/battery/supercapacitor/AC and DC generators hybrid electric vehicles. *Sustainability* **2023**, *15*, 10102.

[5]. Kamel, A.A.; Rezk, H.; Abdelkareem, M.A. Enhancing the operation of fuel cell–photovoltaic–battery–supercapacitor renewable system through a hybrid energy management strategy. *Int. J. Hydrogen Energy* **2021**, *46*, 6061–6075.

[6]. Zhang, Q.; Han, J.; Li, G.; Liu, Y. An adaptive energy management strategy for fuel cell/battery/supercapacitor hybrid energy storage systems of electric vehicles. *Int. J. Electrochem. Sci.* **2020**, *15*, 3410–3433.