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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 4 | Pages 917-923 | e-ISSN: 2347-470X

Futuristic Energy Management Solution: Fuzzy logic controller-Enhanced Hybrid Storage for Electric Vehicles with Batteries and Super Capacitors

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ABSTRACT- The core focus of this study was directed towards devising an energy management strategy tailored for hybrid storage systems (HSS) within electric vehicles, with the prime objective of enhancing the longevity of the battery cycle. The batteries employed in electric vehicles (EVs) are prone to expedited deterioration resulting from harsh charging/discharging cycles and the substantial power surges experienced during acceleration and deceleration phases. While an excessively large energy storage system (ESS) could cater to the elevated power requisites, it inevitably grapples with augmented dimensions, bulk, and cost implications. In a bid to surmount these challenges, an innovative approach has been explored: integrating battery and supercapacitor (SC) elements within the HSS. This synergy aims not only to curtail the overall ESS footprint but also to elongate the operational lifespan of the battery. The pivotal concern revolves around constructing an adept energy management scheme that orchestrates the interplay between the primary energy storage component and the SC, a resource in demand by EVs. Central to this study is the proposition of an intelligent energy management strategy, grounded in fuzzy logic controller (FLC), seamlessly embedded within the within the HSS of the EV. To translate these concepts into tangible outcomes, a comprehensive assessment was conducted. By leveraging the capabilities of MATLAB/Simulink software, the state of charge for the super capacitor and the power dynamics of the battery were scrutinized across diverse driving scenarios over distinct time intervals. The standout feature of this investigation lies in the employment of an ingenious FLC strategy, meticulously regulating the energy and flow of power and energy between the battery and super capacitor elements within the HSS of the EV. In a comparative analysis against conventional control methodologies, this approach shines vividly, yielding superior outcomes and cementing its efficacy.

Keywords: Electrical Vehicles (EVs), Fuzzy logic controller (FLC), Hybrid storage systems (HSS), Super capacitor (SC)

ARTICLE INFORMATION

Author(s): P Sudhakar, and I Kumaraswamy;
Received: 21/08/2023; **Accepted**: 10/10/2023; **Published**: 30/10/2023;
e-ISSN: 2347-470X;
Paper Id: IJEER 2108-09;
Citation: 10.37391/IJEER.110406
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-11/ijeer-110406.html

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1. INTRODUCTION

Electric vehicles have gained widespread popularity due to their numerous advantages, including easy maintenance, lower operating costs, and positive environmental impact. These vehicles rely on rechargeable batteries to store electrical energy, which powers the electric motors that propel them. The characteristics of an electric vehicle are influenced by factors such as battery size and electric range [1]. Unlike internal combustion engines, electric vehicles produce no tailpipe emissions, reducing greenhouse gas-related concerns. The absence of fixed ratio gearboxes and clutches enhances their reliability and simplicity. Acceleration is determined by motor size and remains consistent, with constant torque [2]. Lithium-ion batteries are the preferred choice for electric vehicles due to their extended lifespan and higher energy density. However, their performance in cold weather is notably reduced compared to other seasons [3]. Designing electric vehicles requires considering various environmental factors to optimize their performance. Hybrid electric vehicles combine the benefits of gasoline engines and electric motors [4]. To address energy storage challenges, technologies like flywheel energy storage and supercapacitors are utilized. Additionally, solar energy through photovoltaic cells contributes to electric vehicle functionality [5]. Ultra-capacitors, composed of electrodes and electrolytes, store energy between these layers. Their storage capacity depends on electrolyte behavior, electrode properties, ion size, and decomposition voltage rates [6]. Electrochemical capacitors exhibit energy and power density ranges between traditional capacitors and batteries [7]. Ultracapacitors experience diminished capacitance during discharge and cycle life [8].

Charging and discharging processes are similar for both capacitors and batteries, making this approach versatile for different energy storage devices within their operating ranges. Super capacitors generally outperform regular batteries in various aspects [9-13], suggesting their potential as battery replacements. While battery-powered cars encounter energy management challenges, hybrid electric vehicles mitigate these issues [14]. Compensator systems exhibit constant output range in hybrid energy storage setups [15]. Rechargeable batteries are integrated into car designs, providing essential lighting and system functionality. Regulators are installed to minimize

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energy consumption [16]. In series hybrid connections, both the motor and engine contribute power to the wheels [17]. Conversely, in other setups, the motor drives the wheels, while the engine recharges the battery and supports motor operation. Advanced electric vehicles can positively impact urban areas [18], with conceptual improvements in electric vehicle assessment. Charge-managing modes involve the motor and electric engine jointly controlling the vehicle. The electric engine, functioning as a generator powered by the motor, maintains the battery's state of charge (SOC) near its minimum level [19]. Power and energy management encompass more than just maintaining energy levels [20-23], involving harmonizing energy systems, power flows, and multiple energy storage systems, all while ensuring efficiency and stability. During acceleration, high power demands arise, which can strain energy sources.

Battery internal properties limit rapid charging or discharging without temperature concerns, potentially reducing battery lifespan. Super capacitors are emerging as an alternative due to their high-power characteristics. The challenge lies in integrating batteries and super capacitors in electric vehicle power systems, necessitating sophisticated power electronics and supervisory control [24, 25]. Research on effective power system management involving synergistic battery and super capacitor operation remains ongoing. In the context of this paper focus on, the proposition of an intelligent energy management strategy, grounded in fuzzy logic controller (FLC), seamlessly embedded within the within the HSS of the EV. The hybrid storage system design that incorporates both super capacitors and batteries encompass various aspects:

- Determining power flow between batteries and super capacitors.
- Establishing a peak power blending infrastructure for the super capacitor system.
- Analyzing energy flow within the vehicle propulsion system.
- Evaluating regenerative energy utilization in vehicles.
- The SC-battery enhances power density during acceleration.

2. BATTERY-SUPER CAPACITOR BASED HYBRID STORAGE SYSTEM (BSBHSS)

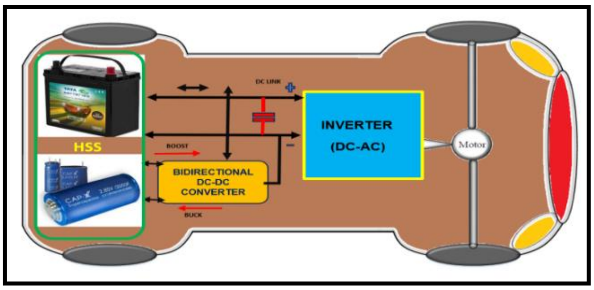

Figure 1: Battery-Super capacitor-based hybrid storage system (BSBHSS)

At the core of every electric vehicle (EV) lies the Energy Storage System (ESS), often referred to as the vehicle's beating heart. Batteries stand as the fundamental choice for fulfilling this crucial role. The energy storage system constitutes the pivotal essence of an electric vehicle, and it's within this system that batteries play their primary role, effectively forming the backbone of the ESS. The integration of a Super capacitor (SC) into this battery framework ushers in a hybridized form of the ESS, giving birth to what can be aptly termed a Hybrid Energy Storage System (HSS). This symbiotic relationship between the SC and the battery serves to enhance power density, particularly during acceleration phases. Illustrated in *figure 1* is the schematic depiction of the electric drive system within the HSS for the EV. SC possesses limited storage capacity, yet delivers a substantial surge of power. While the battery serves as an energy reservoir, the SC meets peak power demands. Integrating both the battery and SC fulfils energy storage and power flow needs, resulting in an efficient energy storage system. Such a system would prove highly advantageous for the automotive and transportation sectors.

Upon dissecting the drive system's block diagram, it becomes evident that a semi-active parallel configuration is employed to facilitate the harmonious interaction between the battery and SC. This configuration designates the battery as the primary energy source, while the SC operates in a supporting role. The primary energy source maintains a direct connection to the DC link, ensuring the constancy of the DC link voltage. Concurrently, the auxiliary source, represented by the SC, establishes its connection through a power electronic interface. An integral component within this drive system architecture is the bidirectional DC-DC converter, which seamlessly interfaces between the distinct energy sources. This converter's prowess lies in its exceptional efficiency, rendering it optimally suited for this intricate energy management task.

3. HYBRID STORAGE SYSTEM INTEGRATING BATTERIES AND SUPER CAPACITORS

In the configuration of the Battery-Super capacitor Hybrid Storage System (Battery-SC HSS), a multi-input converter (MIC) was employed. This multi-input converter comprised four distinct switches: S1, S2, T0, and Q0. These switches were complemented by two power diodes, D1 and D2, along with a pair of inductors denoted as L1 and L2. Completing the ensemble was an output capacitor, C_{out}. The operational dynamics of the MIC were categorized into three distinctive modes, graphically depicted in *figure 2*.

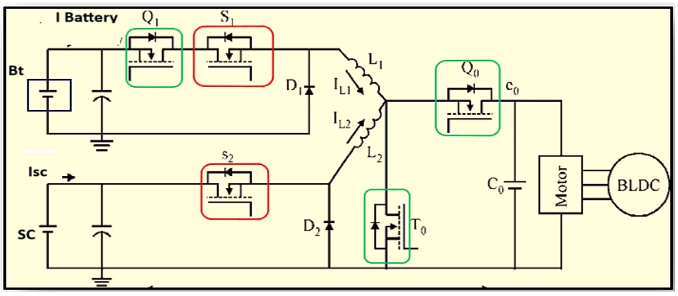

Figure 2: Multi Input Converter Enabling Integration of Battery and Ultra Capacitor within a Hybrid Energy Storage System

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This intricate MIC delved into its operational intricacies through three core modes, each aptly illustrated in figure 3: discharging mode, regenerative mode, and charging /discharging mode. Each of these modes played a crucial role in orchestrating the energy flow within the system, ensuring its optimal functionality and efficiency.

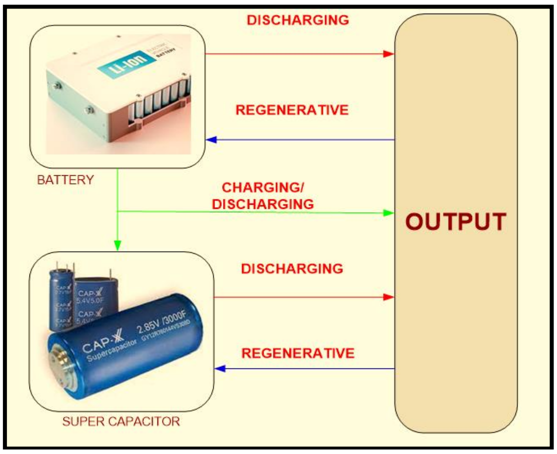

Figure 3: Distinctive functional modes

In the Discharging Mode, the output is modulated by input sources based on the configurations of S1, S2, and T0. Power diodes D1 and D2 operate in a complementary manner with switches S1 and S2 respectively, ensuring balance. Within this mode, a switching cycle comprises four distinct subintervals, each orchestrated precisely. Shifting to the regenerative mode of operation, the MIC enters a state where regenerative braking energy actively replenishes the Energy Storage Systems (ESSs), all under the discerning control of Q0. The voltage levels of the converter intricately influence the operation of Q0, shaping the flow of regenerative power.

Notably, in this regenerative setting, D1 and D2 remain inactive, and Q0 stays switched off. The mantle of carrying the inductor's current is taken up by the inherent body diode of T0. Transitioning further, the third operational mode of the MIC emerges: the charging/discharging mode. This mode comes into play when the power from one input source surpasses the output power, prompting an elegant redistribution of excess energy to an alternative input source. The finesse of this mode lies in its ability to harness residual power and allocate it judiciously.

Synchronized orchestration of S1, S2, and T0 is adeptly executed to maintain the input current in harmony with its designated reference value. Meanwhile, the pivotal switch T0 is meticulously maneuvered to regulate the direct current bus.

4. FLC BASED CONTROL STARTEGY

The converter completion analysis necessitates a well-suited control strategy for design, one that adeptly achieves energy management within the proposed BSBHSS framework. The devised converter and control strategy were rigorously tested in line with *figure 4.*

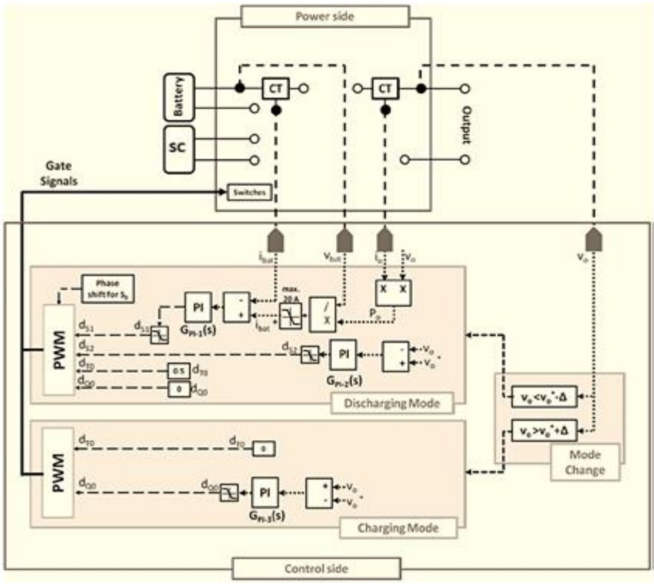

Figure 4: The devised converter and control strategy

The figure distinctly portrays the power aspect, showcasing the converter, and the control aspect, delineating the region for sensed voltage, current, and control strategy. The pivotal Fuzzy Logic Energy Management Strategy efficiently discerns operation modes through output voltage evaluation. These modes are prominently illustrated in *figure 5*. In response, the FLC (Fuzzy Logic Controller) calculates the battery power reference, considering output voltage and SC's SOC (State of Charge). The FLC decisively steers battery power to regulate SC's SOC to a specified level. This calibration ensures SC caters to load demands while adeptly harnessing all accessible regenerative energy. A rate limiter, thoughtfully introduced, fine-tunes battery power reference's rate of change for a smoother profile.

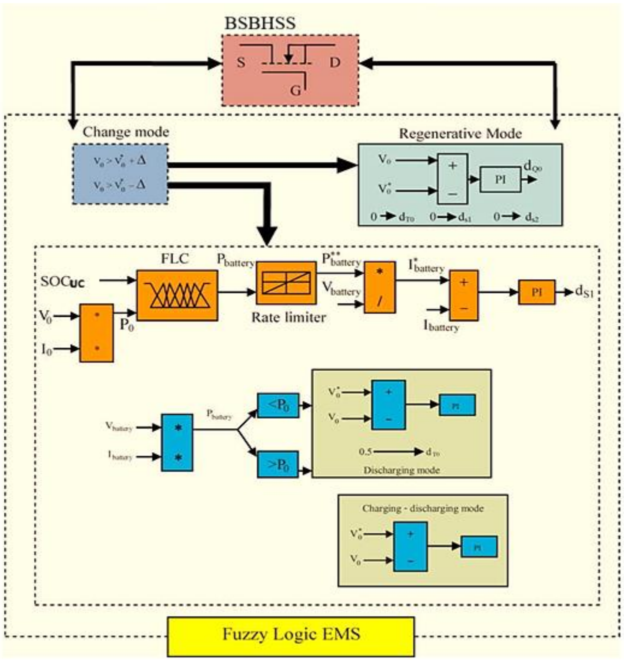

Figure 5: FLC based EMS

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Simultaneously, a PI controller meticulously adjusts battery current to achieve the targeted battery power, orchestrating a seamless performance. The central objective of the energy management strategy is the seamless distribution of active power between the battery and UC. This delicate equilibrium is ingeniously achieved through the implementation of a PI (proportional-integral) controller. This controller plays a dual role: it fine-tunes the duty cycle of S1 to precisely modulate battery power, while concurrently managing the duty cycle of S2 to regulate the DC bus effectively. In this harmonious interplay, the power attributed to UC is precisely controlled, culminating in a balanced allocation of output power demand between the battery and UC. Preserving the battery's efficiency remains paramount, and to this end, the value of dT0 is maintained constant at 0.5 during the discharging mode of the Energy Storage System (ESS). On the contrary, during the charging mode, a distinct modus operandi prevails. Here, a PI controller exerts its influence by carefully regulating the duty cycle of Q0, ensuring that the output voltage aligns steadfastly with its designated reference value. In this charging mode, T0 remains perpetually off, contributing to the intricate orchestration of the operation.

5. SIMULATION FINDINGS AND DISCUSSIONS

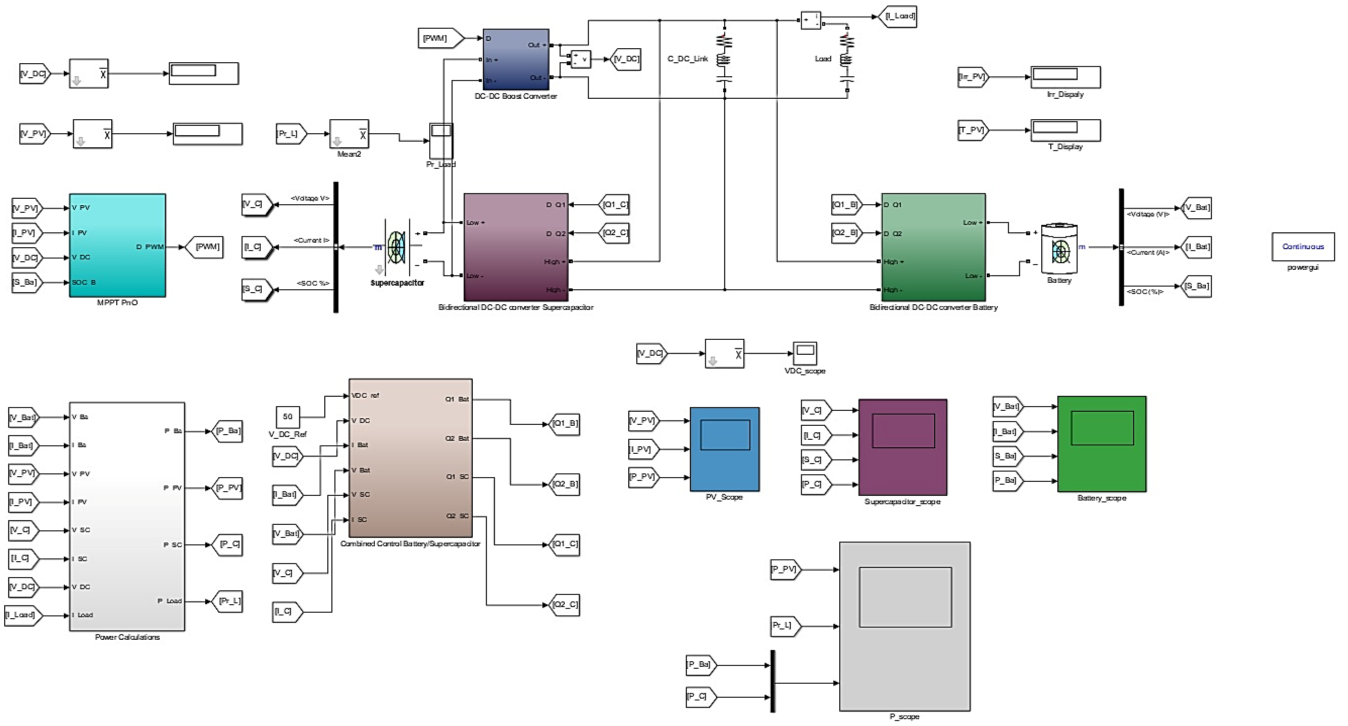
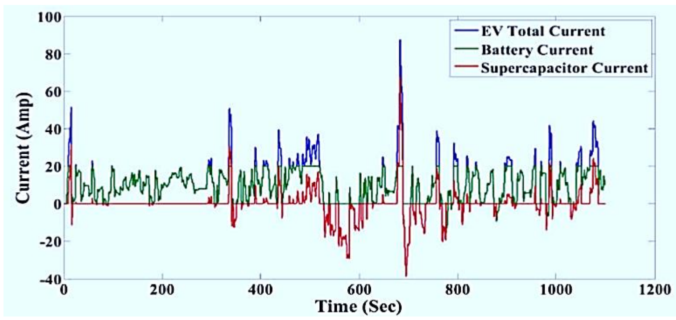


Figure 6. Simulink Model of proposed system

This section outlines the comprehensive dynamic model created in MATLAB/Simulink for simulating the BSBHSS within an electric vehicle (EV) presented in *figure 6*. The model is tailored to an urban driving scenario and encompasses various case studies designed to showcase the application of the proposed FLC-based EMS for the BSBHSS system. These case studies encompass diverse conditions representative of city ride driving. Within these conditions, the focus is on estimating the State of Charge (SOC) for both the battery and SC, which serves as a key metric for evaluating the effectiveness of the proposed methodology, particularly in terms of battery life enhancement. The BSBHSS is examined across a spectrum of working scenarios, spanning load variations from low to high values. The validation of the proposed system's efficacy involves the integration of recorded data and mathematical models of distinct energy sources into MATLAB/Simulink. The simulation captures the behaviour of battery and SC energy sources under various constraints, reflecting real-world conditions. The simulation journey emulates a distance of approximately 15,000 meters, encompassing a range of urban routes marked by differing road heights, curves, slopes, high and low traffic conditions. The following are simulation parameters: Nominal Capacity 110-Ah, Nominal Voltage 100 V, Weight 132 kg, Maximum Charge Voltage 117 V, Discharge Cut-Off Voltage 82 V, Rated capacitance 65F.



(a)

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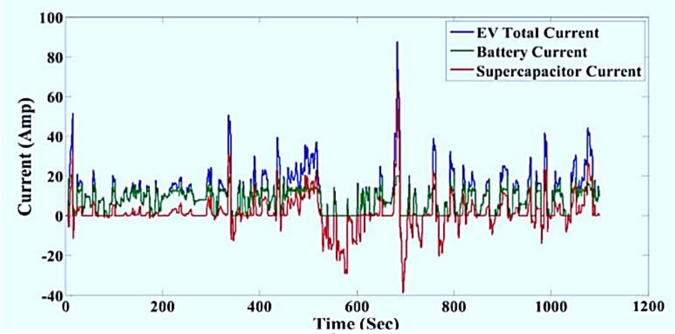
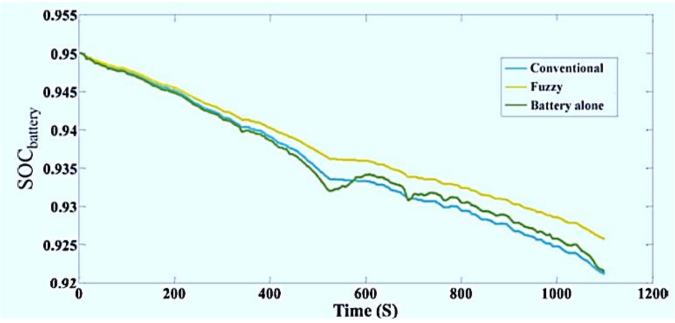


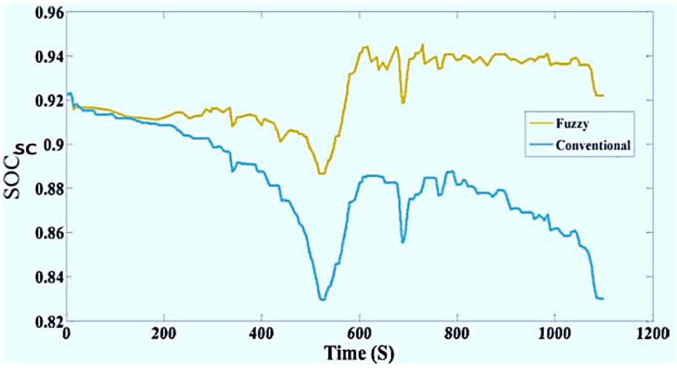
(b)

Figure 7: BSBHSS current dynamics within the context of EVs during city tour driving scenarios unveils two distinct regulatory approaches: (a) Conventional Controller and (b) Fuzzy Controller

Figure 7 presents a comparative visualization of observations obtained from two distinct control paradigms: (a) Conventional Controller and (b) Proposed Fuzzy Controller. The outcomes unequivocally support the premise behind adopting a fuzzy logic controller. The application of the fuzzy controller, as opposed to the conventional counterpart, brings about significant enhancements in the battery's state of charge profile. Moreover, the power regulation facilitated by the fuzzy controller exhibits a remarkable level of smoothness, thanks to its adept incorporation of rate control mechanisms. The results presented in this study underscore the impressive performance of the fuzzy-based control strategy. Notably, the utilization of the fuzzy controller leads to a discernible extension in battery life, showcasing its superiority over the conventional control approach.



(a)



(b)

Figure 8: State of Charge (SOC) dynamics within a BSBHSS unfolds two distinctive perspectives: (a) Battery and (b) Super capacitor (SC)

Figure 8 shows the investigation into State of Charge (SOC) dynamics within a Hybrid Energy Storage System (HESS) unfolds two distinctive perspectives: (a) Battery and (b) Supercapacitor (SC). This unequivocally demonstrates that the integration of the fuzzy control strategy, as opposed to the conventional approach, leads to a significant enhancement in both battery State of Charge (SOC) and Supercapacitor (SC). Consequently, this augmentation in SOC profiles contributes to a noticeable extension in battery life. The outcomes underscore the proficient efficacy of the suggested fuzzy controller in significantly bolstering the BSBHSS performance within the electric vehicle, across diverse cycles and speeds. Variations in SC voltage, load current, and State of Charge (SOC) levels were meticulously tracked and quantified utilizing a fuzzy controller during the city tour drive conditions, as depicted in *figure 9*. Scrutinizing the undulations within the SC power profile offers valuable insights; it becomes apparent that the SC adeptly handles abrupt shifts in output power demands.

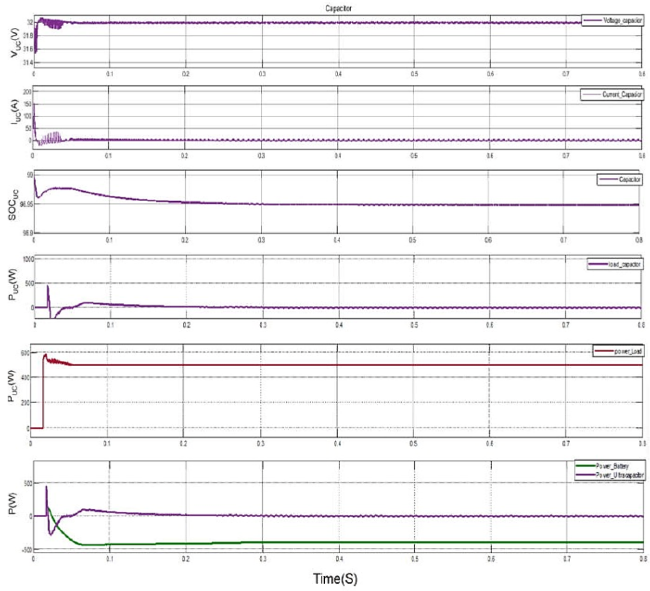


Figure 9: Simulation Results: Investigating SC Voltage, Current Load, and State of Charge (SOC) Levels under City Tour Driving Conditions

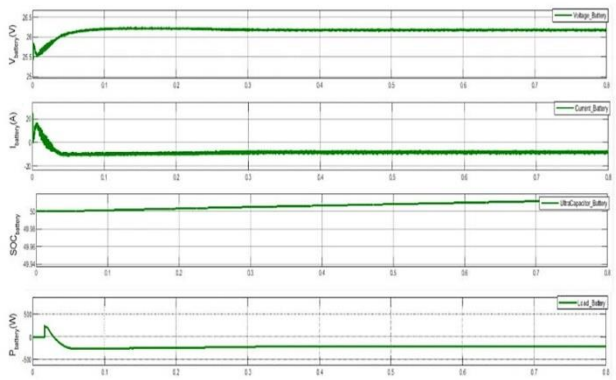


Figure 10: Simulation Outcomes: Analysis of Battery Voltage, Current, Load Dynamics, and State of Charge (SOC) Profiles under Urban Driving Scenarios

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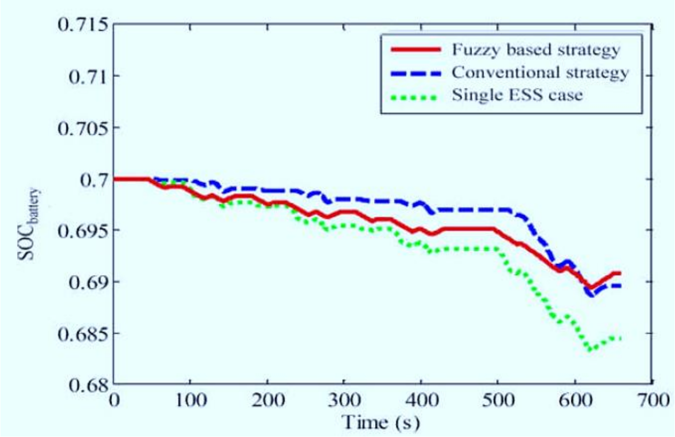

Figure 11: Evaluating State of Charge Trajectories for Battery Using the Proposed Energy Management, Strategy, Conventional Approach, and a Single Energy Storage System within Urban Driving Scenarios

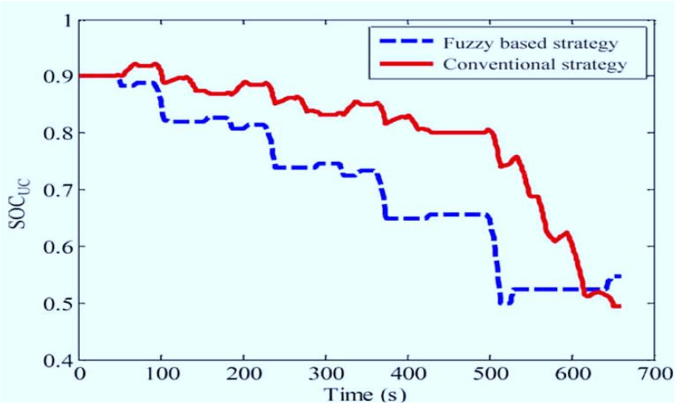

Figure 12: Assessing Supercapacitor State of Charge Trajectories via the Proposed Energy Management Strategy and a Rule-based Approach during Urban Driving Scenarios

These findings emerged within the context of a city driving cycle, characterized by dynamic load fluctuations occurring in response to ever-changing traffic conditions. As vividly illustrated in *figure 10*, the discernible shifts manifest in battery power, voltage, current, and state of charge requisites, attributed to the intricate interplay of traffic dynamics and frequent instances of acceleration and deceleration. In light of these circumstances, the implementation of fuzzy control emerges as a compelling solution, adeptly regulating all facets of battery and SC performance. In *figures 11* and *12*, we observe the analysis of Super capacitor (UC) State of Charge (SOC) trajectories. These trajectories are assessed within the context of the proposed fuzzy-based energy management strategy, juxtaposed with conventional control, under city tour driving conditions. Moreover, this control strategy brings forth a harmonizing effect on the power profile, a feat achieved with the aid of a rate limiter mechanism. This collective orchestration culminates in an overall enhancement of battery health.

CONCLUSIONS

An Energy Management Strategy (EMS) founded on Fuzzy Logic Control (FLC) has been meticulously crafted. This innovative design not only governs the Supercapacitor's (SC) State of Charge (SOC) but also intricately shapes the power trajectory of the battery. In a direct comparison with the conventional approach, centered around Energy Management Strategy, an intriguing discovery emerged. The SC plays a dynamic role akin to a powerhouse, seamlessly channeling power to the battery during acceleration scenarios, thereby alleviating the battery's load. This strategic orchestration contributes to a comprehensive enhancement of battery parameters, notably the State of Charge (SOC) for both the battery and SC. This fortuitous outcome directly correlates with an extended battery lifespan. Through these empirical findings, it becomes resoundingly evident that the adopted EMS operates with remarkable fluidity, amplifying the vehicle's battery life substantially. The SC-battery enhances power density during acceleration, optimizing efficiency by 0.5 in the discharging mode of the Energy Storage System (ESS). Research indicates that the Electro-Mechanical System (EMS) optimization positively impacts all battery parameters, notably the State of Charge (SOC) and Unavailable Capacity State of Charge (UC SOC), resulting in a remarkable 57% extension of battery lifespan while maintaining efficiency during discharge.

Conflicts of Interest: The authors declare that, there is no conflicts of interest regarding to this article.

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