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Global Optimization of Hysteresis Energy Management Strategies for Fuel Cell Hybrid Electric Vehicles

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Abstract

Fuel Cell Hybrid Electric Vehicles (FCHEVs) represent a new generation of environmentally friendly transportation technologies and have garnered significant global attention due to their potential to reduce emissions and reliance on fossil fuels. One of the critical challenges in FCHEV development lies in the design and optimization of the energy management strategy (EMS), which plays a pivotal role in determining how energy is distributed among the various power sources to maximize vehicle performance, minimize fuel consumption, and prolong system longevity, all while adhering to operational constraints. This study focuses on evaluating and optimizing EMS configurations within two distinct powertrain architectures. The first configuration, referred to as FCB, consists of a Fuel Cell System (FCS) coupled with a high-capacity battery. The second, more advanced configuration—termed FCBUC—integrates an ultracapacitor alongside the FCS and battery to enhance responsiveness and energy efficiency. Both systems were modeled and simulated using a hysteresis-based EMS, which governs the switching logic between power sources based on state-of-charge (SOC) thresholds and power demand fluctuations. To further enhance performance, a global optimization technique was employed to fine-tune key control parameters, ensuring that the system operated near optimal efficiency throughout a realistic urban driving cycle, specifically modeled after conditions in Vietnam. The results demonstrate that the proposed EMSs significantly improve system behavior by efficiently managing power flow and reducing hydrogen fuel consumption. Notably, the FCBUC configuration exhibited superior energy distribution capability and fuel economy by 11.7% reduction in hydrogen consumption and improved efficiency (59.07% avg. for FCBUC) compared to the FCB model. This study highlights the importance of advanced EMS design and powertrain configuration in realizing the full potential of FCHEV technologies in real-world urban environments.

Keywords: Energy efficacy; Energy management system; Fuel cell hybrid electric vehicle; Fuel efficiency; Urban driving cycle

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1. Introduction

In light of mounting pollution, climate change, and energy issues, several nations across Europe, the United States, and several of Asia's developed regions are working together to phase out the use of fossil fuels in automobiles [1]. Hybridization electric vehicles (HEV), fully battery-powered vehicles (BEV), and FCHEV are three examples of the new generation of ecologically friendly automobiles that have been produced as a result. As countries transition towards renewable energy sources and away from fossil fuels, there is a growing demand for the materials and technologies required for the production of BEVs, such as lithium-ion batteries and electric motors [2]. This can create new opportunities for job growth and economic development, particularly in regions that specialize in these technologies. Furthermore, the use of BEVs can also reduce a country's dependence on foreign oil, which can improve energy security and reduce the risk of supply disruptions. However, the success of BEVs will depend on continued investment in battery technology and charging infrastructure, as well as policies that incentivize their adoption.

A hybrid electric vehicle (HEV) that draws power from an engine and an electric motor has been envisioned as a solution to this challenge [3]. However, HEVs still use fossil fuels; therefore, greenhouse gas (GHG) and other pollutants (COx, NOx, SOx, PM2.5, …) would be released into the atmosphere. It is for this reason that we advocate for engine-less FCHEV [4–6]. The EMS is one of the critical considerations among all technologies involved in FCHEV, with the goals of mitigating environmental degradation, improving fuel economy, and enhancing available power performance simultaneously. Even though several challenges remain in the air, numerous massive automobile manufacturers were also engaged in FCHEV research and innovation.

Powertrain hybridization improves vehicles' dynamic and economic performance by mixing diverse renewable technologies but increases flexibility in powertrain and operational complexity. To efficiently coordinate the output of different energy sources, a reliable control approach (or EMS) should then be researched [7,8]. EMSs aim to meet vehicle energy requirements within powerplant operational limits [6]. High costs of manufacturing, infrastructure investment charge and short FCS life limit FCHEV commercialization. To lower FCHEV operating expenses, the EMS control framework must also optimize fuel efficiency and powertrain durability.

Recent decades have seen a shift from rule-based to optimization-based EMS. Investments of hundreds of millions of dollars have been made by Hyundai, Volkswagen, Daimler, and BMW over the past three decades to advance the technology [9]. The Hydrogen Council observed the number of FCHEV will increase to 10÷15 million units in 2030 and explore 400 million units in 2050. Rule-based techniques are low-computing [10]. They rely heavily on experts' experiences, and it's impossible to ensure global optimal solutions by following present guidelines. Optimization-based methodologies [2,11–13] have been developed to solve these objections. The earliest optimization techniques, such as Dynamic Programming (DP) [14,15], Particle Swarm Optimization (PSO), and Pontryagin's Minimum Principle (PMP), are global techniques that offers optimal control solutions but often suffers from significant computational burden, especially in real-time applications, thereby motivating the development of hysteresis-based approaches that offer reduced complexity while maintaining acceptable performance [16,17]. This particular kind of EMS primarily constructs an optimization problem by using operational parameters of a hybrid electricity system, makes utilization of state variables as a constraint, and optimizes the objectives by employing a feature selection method. ECMS and MPC use less processing [18–20]; however, they can support local desired outcomes. Other research applied and developed Deep Learning and Machine Learning as well as Reinforcement Learning to deal with the real-time model [21–23]; nonetheless, the fundamental data are investigated by the optimization-base results [24,25]. Recent EMS approaches have demonstrated significant advancements in optimization and hybrid control strategies; however, they often overlook the unique charge-discharge dynamics of ultracapacitors, leading to suboptimal energy recovery and power delivery under frequent start-stop conditions typical of urban driving cycles [26–28].

Following this article, the FCHEV was constructed using coupled models of the fuel cell system and hybrid energy storage system (battery and ultracapacitor), and the DP technique was applied to optimize power distribution for maximum fuel efficiency under urban conditions. Building upon this foundation, the present study introduces three key contributions: (1) it represents the first application of a DP-optimized hysteresis-based EMS specifically tailored for FCHEV equipped with ultracapacitors; (2) it validates the proposed EMS under a realistic and highly dynamic urban driving profile, captured from Hanoi's aggressive stop–start traffic conditions; and (3) it systematically quantifies the trade-offs between fuel economy and the degradation of both the battery and ultracapacitor, providing critical insight into the long-term implications of EMS design choices.

This context is organized as follows. Section 2 introduces the mathematics and explains energy sources in FCHEV. Section 3 illustrates the EMS proposal system, Section 4 the evaluation results by MATLAB/Simulink, and the discussion. Section 5, finally, presents the conclusion.

2. Vehicle modeling

2.1. System mathematic

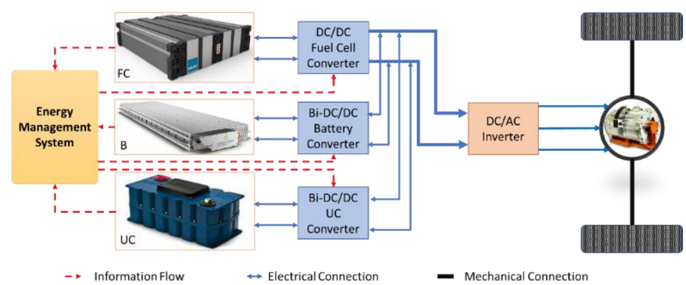

Figure 1. Configuration powertrain in FCHEV

Figure 1 displays the hybrid system's topology. This system is indicated by FCS, battery, and UC. A DC/DC boost converter increases and maintains the FCS output voltage. Two DC/DC bidirectional converters, one increases the constant voltage of the battery, and the other transfers the power of UC from variables. Eq. (1) defines for load power requirement of the vehicle.

$$P_{load} = (\frac{1}{2}\rho_{air} DAv^2 + MgC_r + M\frac{dv}{dt})v \quad (1)$$

2.2. Traction motor modeling

A heat map is used in this context to visually represent the intensity and distribution of key performance metrics—such as power demand, energy flow, or component usage—over time and operating conditions, enabling easier identification of critical patterns [29]. The characteristics of the traction motor are represented by an efficiency map in Figure 2, in which the efficiency and the power demand of the motor can be attained through motor torque and rotation speed (2).

$$\begin{cases} \eta_{motor} = (T_{motor}, \omega_{motor}) \\ P_{load} = T_{motor}\omega_{motor}\eta_{motor} \end{cases} \quad (2)$$

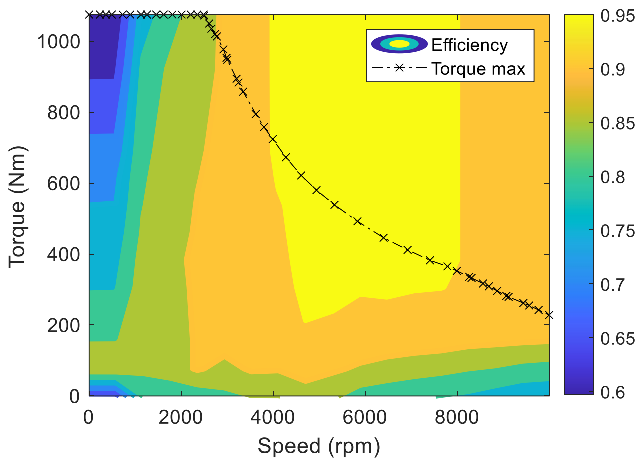

Figure 2. Efficiency map of traction motor

2.3. Power sources

Without using heat or mechanical processes, FCS transforms chemical energy in hydrogen fuel into electrical energy [30–32], especially PEMFCs are frequently employed in vehicles. In accordance with the investigated phenomena, each fuel cell model has its own particularities and economic advantages. Simple and accurate is the best model. This article proposes an electrochemical model to forecast static and dynamic fuel cell behaviour. The FCS model employed in this research relates the fuel cell output voltage to hydrogen, water, and oxygen in the surrounding environment.

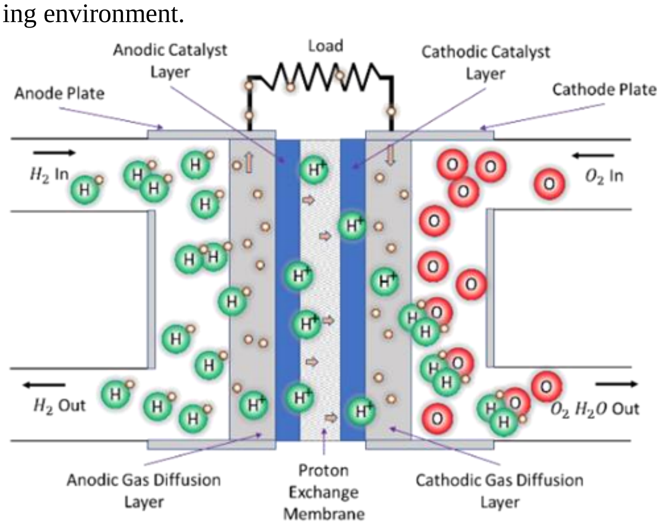

Figure 3. Schematic of FCS power unit

Figure 3 illustrates the working process inside FCS. The voltage produced by FCS is affected by the relative pressures of hydrogen and oxygen, the temperature at which the membrane is hydrated, and the amount of current being generated. It is defined as below.

$$\begin{aligned} &\text{Anode} &:\quad & 2H_2 \rightarrow 4H^+ + 4e^- \\ &\text{Cathode} &:\quad & O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \\ &\text{Exhaust} &:\quad & 2H_2 + O_2 \rightarrow 2H_2O \end{aligned} \tag{3}$$

As long as oxygen and fuel are present, fuel cells provide continuous power. High energy density and low operating temperature are why PEMFCs are used in FCHEV. Chemical interactions restrict load response; consequently, this source is coupled with a hybrid battery-supercapacitor storage system (ESS).

The battery outperforms the UC in energy density; in contrast, the UC outperforms the battery in power density. UCs have high capacitance and semipermanent lifespan. Because ions are transported between the electrodes, UCs may be charged and discharged quickly while maintaining high efficiencies. Overcharging and over-discharging have little effect on lifespan, and these indices can be evaluated by SoC, represented by the State of Charge [33]. UC serves as one of the most important parts of the forthcoming generation of ESS; nevertheless, the ideal time and output power for boosting vehicle efficiency have not been clearly stated. Utilizing the equivalent circuit equations depicted in (8)

$$SoC_{uc} = \frac{Q_{init} - \int I_{uc}}{Q_{\max}} \tag{4}$$

$$P_{uc} = V_{uc} I_{uc} \tag{5}$$

where Q_{init} is the initial charge [C], Q_{max} the maximum charge [C], C_{uc} the rated capacitance [F], I_{uc} stands for UC current, $V_{uc,oc}$ is open circuit voltage, V_{uc} is terminal voltage, $R_{uc,i}$ is internal resistance, and P_{uc} is the power of the UC.

Battery open circuit voltage, which is simplified and depicted in Figure 4, is calculated by terminal voltage with an internal resistance as (9)

$$V_{b,oc} = V_b - I_b R_{b,i} \tag{6}$$

$$P_b = V_{b,oc} I_b - R_{b,i} I_b^2 \tag{7}$$

$$I_b = \frac{V_{b,oc} \pm \sqrt{V_{b,oc}^2 - 4P_b R_{b,i}}}{2R_{b,i}} \tag{8}$$

$$SoC_b = SoC_{b,init} - \frac{\int I_b}{3600 \times C_b} a \tag{9}$$

through these formulations, $V_{b,oc}$ represents the open circuit voltage, V_b is terminal voltage, I_b shorts for current, $R_{b,i}$ is internal resistance, P_b is the power, $SoC_{b,init}$ the initial SoC, and C_b is the rated capacity of the battery.

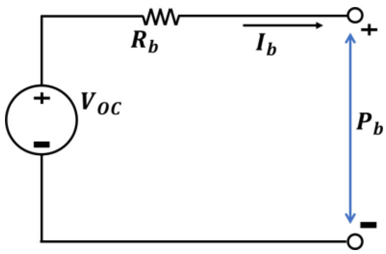

Figure 4. Schematic of the battery model

When ESS is charged, the energy should be first stored in the UC, which is more efficient than the battery. Whenever both battery and UC exceed the minimal SOC, the UC is not used; using it during this period can cause power supply failure because of the energy density. DC/DC converters are used to manage ESS terminal voltages/current with 95% efficiency.

3. Energy management strategy

Assuming the velocity of the vehicle is measured in advance from the experimental project, see Figure 6. Thus, subsequent studies have endeavoured to consider the optimum approach for EMS across the reverse FCHEV simulation environment so that FCHEV can ensure the restrictions of reference driving conditions. While it can be challenging to predict the vehicle's speed in advance, other research has advised updating the control parameters.

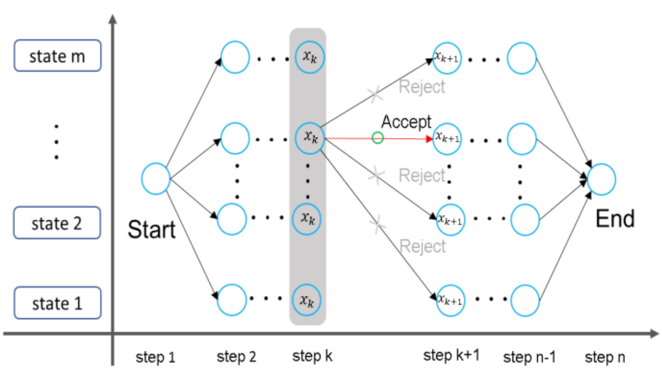

Figure 5. Diagram of DP process

The goal of the following solutions was to discover the problem's optimal path. DP gives a vital trajectory to verify calculation accuracy according to the Bellman principle [34]. Throughout this paper, DP is used as the backward simulating model's electricity structured approach. The recommended technique can be utilized with various control systems that get feedback signals through backward simulation. By eliminating subpar control options at each time step, DP creates a powerful trajectory in boundaries. It takes a multi-stage toward the rear perspective to maximize; the discretized state is based on the optimal choice made in the previous step to solve a problem. This iterative procedure is repeated whenever a perfect answer has been discovered. The ideal cost to go between sample step k and next step $k+1$ in the simulation cycle is written as formula (13).

$$
\begin{aligned}
J_k(x^k_{Batt/UC}) = \min\{&\text{Hydrogen Consumption}(x^k_{Batt/UC}, u^k_{Batt/UC}) \\
&+ J_{k+1}(\text{Temporal State}(x^k_{Batt/UC}, u^{k+1}_{Batt/UC}))\}
\end{aligned}
$$
$$
\text{subject to } x^{k+1}_{Batt/UC} = \text{Temporal State}(x^k_{Batt/UC}, u^{k+1}_{Batt/UC}) \qquad (10)
$$

where the cost function of the problem is the minimum fuel consumption of transitioning from step k to step $k+1$, state variable $x^k_{Batt/UC}$ presents for the battery's, UC's SoC at the step k, $u^k_{Batt/UC}$ is the UC and battery controllable voltage values, the Temporal State represent the temporary SoC values of UC and battery in (4) and (12). In order to effectively implement DP, the splitting energy problem is discretized utilizing Euler discretization, at which point the dimension of the optimization plant becomes a $n \times m$ matric, where n and m in Figure 5 can be expressed by

$$
n = \frac{t_f}{\Delta t} \qquad (11)
$$

$$
m = \frac{SoC_{\max} - SoC_{\min}}{\Delta SoC} \qquad (12)
$$

where SoC_{max}, SoC_{min}, and ΔSoC are the maximum, minimum, and gap between the battery SoCs, respectively. In order to prevent unnecessary fuel costs caused by an uneven SoC, it is recognized that the final SoC point is equivalent to the beginning SoC set.

4. Simulation results

A thorough comparison is made between the FCB and the FCBUC in terms of EMSs for the Hanoi driving cycle. For each system, data simulations are gathered for various boundaries of battery SOC ranging from 48% to 52% (referred to as 50%), while the UC SoC in FCBUC is referred fully charged after simulation [28]. Because the suggested management is a global plan, each test displays the referred starting SOC at the end of the simulation. As a result, for the presented models, the hydrogen energy utilized is assessed as a cost function of the requested energy.

Table 1. Statistical Characteristics of the Hanoi driving cycle.

Metric	Time [s]	Speed [m/s]	Description
Maximum	3935	12.22	Total duration / peak vehicle speed
Mean	1968	4.655	Average time point / average vehicle speed
Median	1968	5.00	Midpoint in time / typical cruising speed
Standard Deviation	1136	2.934	Variability in time and speed over the cycle
Range	3935	12.22	Full time span and speed variation across the cycle

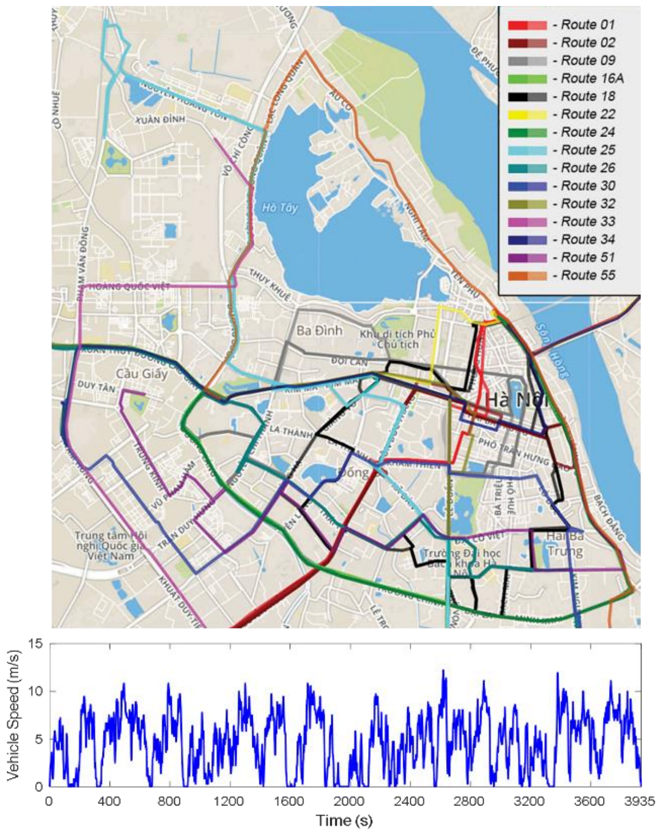

Figure 6. The driving cycle of intra-city bus in Hanoi, Vietnam

The FCS plays a pivotal role in managing power flow within a FCHEV, particularly during dynamic driving conditions. It is designed primarily to either increase or decrease its output power in response to unexpected accelerations or decelerations, thereby stabilizing overall system behavior. This strategic power modulation helps to alleviate the substantial burden that would otherwise be placed on the FCS by compensating for transient demands. Specifically, the FCS addresses part of the low-frequency positive components of the power request—those associated with sustained acceleration or cruising—and simultaneously absorbs portions of the slow-varying negative power components encountered during regenerative braking or coasting. This dual function mitigates frequent cycling stress and prolongs the life of the fuel cell stack by avoiding rapid and extreme power fluctuations.

Furthermore, the system's intelligent integration with the UC subsystem enhances performance under high-frequency power demands. The inherent malleability and slower dynamic response of the FCS are complemented by the UC's capability to handle short bursts of power—either for rapid acceleration or sudden braking events—thanks to its high power density and fast response characteristics. In these instances, the UC efficiently supplies or absorbs energy that the FCS or battery cannot respond to in time, effectively increasing the hybrid system's overall energy responsiveness and buffering capability. As a result, the UC not only meets transient power needs but also contributes to stabilizing the SOC across the ESS, minimizing degradation and ensuring prolonged component longevity.

To ensure sustainable operation over typical driving cycles, it is crucial that the maximum power output of the FCS be greater than the average power demand of the FCHEV. This design consideration prevents the SOC of the battery and UC from depleting too quickly, thereby maintaining system balance and operational efficiency. In the context of the simulation conducted, the FCS power was configured to a constant value of 180 kW throughout a prolonged 3900-second driving profile. This fixed setting was selected to reduce the complexity of the ESS management strategy, while still allowing for realistic and practical evaluation of the energy flow and system interaction between the FCS, battery, and UC, as depicted in Figure 7.

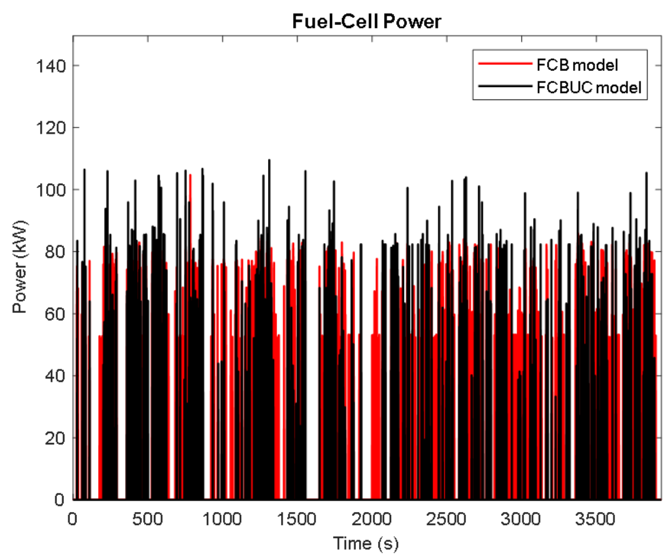

Figure 7. Comparing the FCS power accomplished by DP for FCB and FCBUC

Figure 8 illustrates the dynamic behavior of the battery within the FCHEV system, specifically focusing on voltage, current, and SOC profiles as governed by the proposed EMS. These waveforms reflect the battery's role as a flexible energy buffer in the Energy Storage System (ESS), modulating its output in response to real-time power demands. The battery's output power oscillates around the zero axis, transitioning between charging (negative power) and discharging (positive power) modes depending on the operating conditions of the vehicle. These fluctuations are closely tied to acceleration, deceleration, and regenerative braking events, reflecting the dynamic interplay between the battery, fuel cell, and auxiliary energy storage components.

A detailed inspection reveals that the battery SOC trajectory in the FCB model shows a substantial decline relative to its initial value, highlighting a more aggressive usage pattern. This indicates that, in the absence of UC support, the battery in the FCB model bears a heavier workload, experiencing frequent high current charging and discharging cycles. Such operational stress not only accelerates battery aging due to thermal and chemical degradation mechanisms but also diminishes its expected service life. The deep cycling seen in the FCB configuration underlines the limitations of relying solely on the battery to manage transient power fluctuations and peak demands. In contrast, the FCBUC model maintains a comparatively stable SOC, with less pronounced deviations from the average level, demonstrating the benefit of incorporating a high-power-density UC into the system architecture.

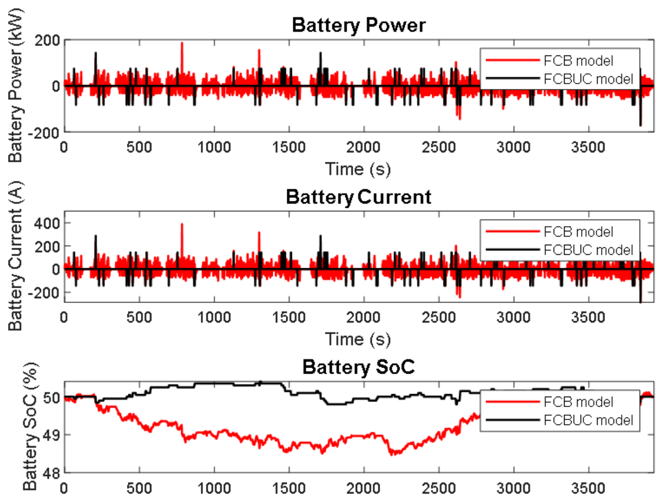

Figure 8. Characteristics of battery in FCB and FCBUC models

This difference between the two configurations is further emphasized by analyzing the hydrogen consumption characteristics. The FCB model, due to its reliance on the fuel cell to meet not only average but also transient power demands, exhibits a higher rate of hydrogen energy usage. It must frequently ramp up the fuel cell output to compensate for battery depletion, especially during repeated acceleration events. On the other hand, the FCBUC model demonstrates greater efficiency in power distribution. By delegating fast, high-frequency energy demands to the UC, the FCS in the FCBUC configuration can operate closer to its optimal efficiency point, resulting in reduced hydrogen consumption, as illustrated in Figure 9. Consequently, the FCBUC model not only preserves battery health and SOC stability but also achieves improved overall system efficiency by optimizing energy flow within the hybrid drivetrain.

Moreover, the voltage and current waveforms across both models reveal notable similarities in overall linearity, which can be attributed to consistent EMS logic governing each system. However, the magnitude and duration of current surges in the FCB model are more severe, reaffirming the stress imposed on its battery system. This further supports the argument that hybrid configurations integrating ultracapacitors can significantly enhance the performance, longevity, and fuel efficiency of FCHEV.

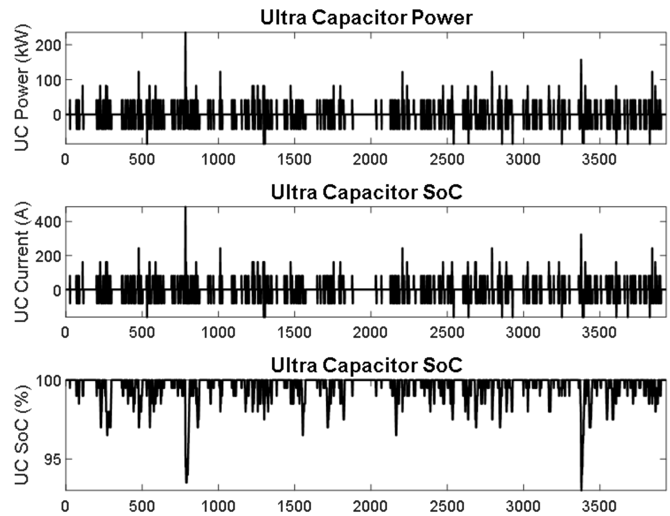

Figure 9. Power of UC in Hanoi driving cycle

The average efficiency of the FCHEV, when evaluated over the real-world Hanoi driving cycle, is recorded at 58.74%. This result reflects the combined performance of the EMS, powertrain configuration, and control strategy under practical operating conditions. Among the tested configurations, the FCBUC model once again demonstrates its superior performance, particularly when paired with the DP control technique. The integration of a high-power-density ultracapacitor into the system architecture allows for more effective management of transient energy demands, contributing to improved energy flow and minimized energy losses.

A key indicator of this enhanced performance is the hydrogen consumption: the FCBUC model consumes only 1438.8 grams of hydrogen over the entire driving cycle, compared to 1630.3 grams consumed by the conventional FCB model. This reflects a 0.67% improvement in hydrogen efficiency for the FCBUC model, which, while modest in percentage, is significant in long-term fuel economy and operational cost when extrapolated over extended use. Moreover, the FCBUC model achieves both higher average and peak FCS efficiencies—59.07% and 59.52%, respectively—surpassing the FCB model's corresponding values of 58.40% and 59.39%. This improvement confirms that the FCBUC system operates the FCS closer to its optimal efficiency range for a larger portion of the driving cycle.

These findings are further substantiated in Table 2, which summarizes the performance comparison between the FCB and FCBUC models. The FCBUC configuration not only enhances hydrogen economy but also contributes to a more balanced load distribution between the ESS components. By enabling the fuel cell to avoid rapid load changes and reducing the battery's peak power demands, the ultracapacitor acts as a critical buffer that smooths out power transients by reduces battery stress (20% fewer deep cycles). This synergy between the three energy sources allows the EMS to allocate power more intelligently, improving system stability, extending component lifespan, and reducing fuel consumption without compromising performance.

As a result, the FCBUC model emerges as a more efficient and sustainable solution for fuel cell vehicle applications in urban traffic scenarios such as those represented by the Hanoi driving cycle.

Table 2. The comparison between FCB and FCBUC.

Model	FCS Efficiency		Fuel Consumption
	Average	*Highest*	
FCB	58.40%	**59.39%**	1630.3 (g)
FCBUC	59.07%	**59.52%**	1438.8 (g)

5. Conclusion

In this study, a power management algorithm was developed for Fuel Cell Battery Ultracapacitor Electric Vehicles (FCBUC-EVs), employing a hybrid energy storage system that integrates a fuel cell stack, a battery pack, and an ultracapacitor bank. The proposed DP-optimized hysteresis control strategy effectively managed power distribution across the components without requiring frequent algorithm switching. Simulation and experimental results under Hanoi's urban driving conditions demonstrated the effectiveness of the approach, achieving a notable energy efficiency of 59.07% and improved fuel economy. These outcomes suggest that the proposed EMS is particularly well-suited for deployment in developing countries, where urban and rural driving patterns typically involve frequent acceleration and deceleration. However, the method's reliance on Dynamic Programming, which operates offline, and the use of fixed hysteresis thresholds present limitations in adaptability and real-time application. Future research will address these constraints by exploring real-time control strategies such as Model Predictive Control (MPC) and incorporating multi-objective optimization to better manage trade-offs between fuel economy, component longevity, and system efficiency. Furthermore, the control framework holds potential for integration with alternative energy sources such as solar, flywheel, or wind systems, offering a flexible foundation for sustainable vehicle technologies.

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Conflict of Interest Statement

The author declares that there is no conflict of interest in the study.

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