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DEVELOPMENT OF A RULE-BASED ENERGY MANAGEMENT STRATEGY FOR HYBRID ELECTRIC VEHICLES WITH INTEGRATED HYBRID ENERGY STORAGE SYSTEM

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ABSTRACT

Electric vehicles present a compelling alternative to conventional gasoline-powered vehicles, leveraging efficient energy management techniques and showcasing promising prospects for the continued expansion of Hybrid Electric Vehicles (HEVs). The energy management system (EMS) holds a crucial role in HEVs, serving to extend the vehicle's driving range while concurrently lowering costs. This paper introduces an energy management strategy and optimization approach for HEVs equipped with a hybrid energy storage system comprising with Li-ion battery pack and ultracapacitor (UC) pack, implemented through a Fuzzy Logic Controller (FLC). The primary objectives include enhancing battery performance metrics such as state of charge, driving range, and battery lifespan. A parametric comparison is provided with PID controller. Electric vehicle (EV) powered by Batteries offer high energy density, low environmental impact, and durable performance. The integration of both batteries and ultracapacitors is employed to enhance power characteristics. Batteries are used like a primary energy source because these are having high energy density and Ultra capacitors are used for high power density. Simulink serves as a tool for simulating the proposed system's performance, aiding in the determination of the most suitable intelligent system for achieving power efficient operation of the HEV. A comparative analysis of the results from both control techniques is conducted, ultimately recommending the Fuzzy controller for effective energy management in electric vehicles.

Keywords: *Energy storage systems (ESS), Fuzzy logic controller (FLC), Hybrid Electric Vehicle (HEV), Integrated system, Ultracapacitor (UC).*

1. INTRODUCTION

A major downside of fossil fuel consumption is environmental pollution, which can be releases to emissions by the transportation industry [1]. To overcome these problems, we used Energy retention-based EV, these can be categorized different types mainly, Battery electric vehicle, Hybrid electric vehicle (HEV) and Plug-in hybrid electric vehicle. Enhanced efficiency of power electronics and efficiency-focused motor drives are the main characteristics behind the usage of HEV. The efficiency of HEVs primarily relies on the effectiveness of motor drives. Due to the significant enhancement in the performance of diverse power electronics devices like converters, switches, and motor drives, the demand for HEVs is increasing day by day [2]. A vehicle manufacturer is emphasizing HEVs due to their environmental safety benefits. The primary advantage of hybrid electric vehicles, in addition to enhanced fuel economy, lies in the reduction of carbon dioxide emissions.

An ultracapacitor, referred to as a super capacitor or electric double layer capacitor, is a durable energy storage device capable of rapidly storing and discharging electrical energy, outpacing batteries. Unlike batteries that rely on chemical reactions for energy storage, standard capacitors store energy within an electric field situated between two electrodes. Nonetheless, capacitors exhibit limited storage capacity due to their

reliance on electron storage, which results in electron repulsion.

The authors in [3], have proposed that different control strategies with different Energy storage systems, whereas the proposed control strategy is used to improve SOC of the Battery with the combination of Ultracapacitor. Thus, the driving range increased by using Fuzzy controller. This paper brings forth a Simulink model encompassing the entire energy network of the powertrain in an integrated electric vehicle, which is fuelled by both a Battery and Ultra capacitor. The lithium-ion battery serves as a power source for energy storage with rapid response capability, minimal self-discharge, extended lifespan, and substantial energy density.

The concept of EV originated with various energy storage devices, including batteries, supercapacitors (SCs), ultracapacitors (UCs), and fuel cells (FCs). Modifications to electric vehicles (EVs) led to the development of hybrid electric vehicles (HEVs), combining the energy sources to enhance efficiency and provide sufficient support for uninterrupted power supply in vehicles [4,5].

Solar and Wind generation systems are thus moving to the forefront as the primary sources of electricity generation [6]. The biggest challenge of HEV is an efficient energy management system. Currently HEVs are limited in distance, so that we need to increase the driving range of the electric vehicle. This can be achieved by enhancing the state of charge (SOC) of the battery, it related to the capacity of the Battery. It is advantageous to have higher Battery State of Charge (SOC) levels at any given moment. For effective transfer of energy advanced controllers are advised to improve the SOC.

The objective of this paper is to enhance the SOC to enable HEV to travel longer distances. The operation of HEV is simple with Fuzzy controller and effective method [7]. It provides real time supervisory control method. So, the results can be compared with PID controller to prove that FLC is used to improve the SOC of the Battery [8].

The paper is organized as follows: Section 1 introduction of the research topic. Section 2 details the Different energy stored devices for EV. Section 3 presents system description. The Fuzzy logic controller for hybrid system is described in Section 4. Comparative results and discussions are presented in Section 5, and the paper concludes in Section 6. This structured approach ensures a comprehensive understanding of the development and implementation of Fuzzy logic controller for HEV system, addressing key challenges and highlighting the advancements over traditional control methods.

2. MOTIVATION FOR THE WORK

Efficient battery management is essential for the performance and longevity of energy storage systems, especially in renewable energy and electric vehicle applications. Traditional PID controllers, though widely used, often fall short when handling nonlinearities and uncertainties in battery dynamics. FLC offer potential advantages due to their rule-based adaptability and robustness. However, a direct comparative analysis under realistic operating conditions remains limited. This motivates the present study, which aims to evaluate and compare the performance of FLC and PID controllers to identify a more effective control strategy for battery management.

3. PROBLEM STATEMENT

Despite the widespread use of PID controllers in battery management systems, their performance often degrades under nonlinear and uncertain operating conditions. FLC, known for their adaptability and robustness, may offer a more efficient alternative. However, a direct performance comparison under controlled scenarios is lacking in the literature. This research aims to fill that gap by evaluating and comparing the performance of batteries controlled by PID and FLC strategies, focusing on efficiency, stability, and response time

4. DIFFERENT ENERGY STORED DEVICES FOR EV

Fuel Cells (FC), Batteries, and UC are the most used energy storage devices for EV. These devices can function as primary energy sources in EVs or, in certain cases, serve as Indirect energy sources when operating in Integrated mode.

4.1. Fuel Cell

The Fuel Cell (FC) plays a crucial role in converting chemical energy into electrical energy, serving as the primary power source in HEV. Comprising an anode, cathode, and an electrolytic membrane, the FC functions by supplying hydrogen to the anode and oxygen to the cathode. Protons move through the electrolytic membrane, while electrons pass through the load. Notably, Fuel Cells stands out as an efficient energy source,

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contributing to a clean and emission-free power generation process [9]. Different kinds of Fuel Cells find application in EV. In a hydrogen fuel cell, a catalyst at the anode aids in splitting hydrogen molecules into protons and electrons. These components then proceed along separate routes to the cathode. Electrons traverse through an external circuit, producing an electric current or flow of electricity. This process highlights the fundamental electrochemical principles that underlie the operation of hydrogen fuel cells in electric vehicles.

Fuel cells boast several advantages, including high-power density and low weight. Operating at around 80ºC, they facilitate quick start-ups with minimal warm-up time, making them well-suited for applications with demanding power requirements [10].

4.2. Battery

The battery stands out as an excellent and extensively utilized energy source, prevalent in virtually every electronic device [11]. It serves as a crucial power source within the HEV system. The SOC represents the current level of energy stored in the battery as a percentage of its total capacity [12]. The battery, much like Ultra capacitors, plays a crucial role in providing rapid response for peak power demands during acceleration and recovering energy during deceleration [13].

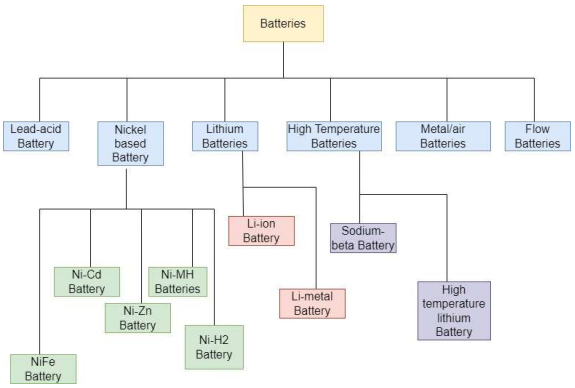


Figure 1: Types of Batteries

Figure 1 displays various types of batteries utilized in HEVs. Among these, the Li-ion battery stands out due to its numerous applications distinguished by superior specific energy, heightened energy density, enhanced energy efficiency, and prolonged cycle life.

4.3. Ultracapacitors/Supercapacitors

Super capacitors and ultracapacitors are acknowledged energy reservoirs in HEV systems, notable for their distinctions in electrode length and storage capacity [14]. Super capacitors operate by storing electrical energy between two electrostatic double layers, which form through the establishment of thin charge layers at the interface of the electrolyte and electrodes [15]. In contrast, ultracapacitors diverge from traditional batteries in that they do not store electrons directly. Instead, they store positively and negatively charged ions, employing a liquid electrolyte to facilitate energy flow. Unlike batteries, ultracapacitors do not rely on chemical reactions [16]. This feature makes ultracapacitors well-suited for automotive applications requiring rapid bursts of power or quick energy storage, such as during regenerative braking.

Additionally, ultracapacitors have a significantly longer lifespan than batteries because they lack the physical and chemical changes that accelerate degradation [17]. While a typical battery may last for 2,000 to 3,000 charge cycles, an ultracapacitor can endure over 1 million cycles. They also offer greater stability than batteries, do not contain heavy metals, and operate effectively within a temperature range of -40°C to 65°C.

5. SYSTEM DESCRIPTION

This Integrated system comprises a Battery-ultracapacitor connected to loads, including an electric vehicle. The key energy sources in this hybrid setup are the Battery and UC to facilitate the integration of these sources, dc–dc converters are employed. This arrangement allows for efficient conversion and management of electrical power between the Battery-UC hybrid source and Electric vehicle, contributing to a comprehensive and well-integrated hybrid energy system [18].

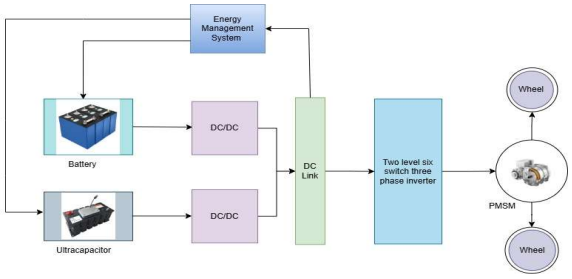


Figure 2: Electric Vehicle Connected Hybrid System

From Figure 2 the Buck/Boost converter linked to the Battery array serves as an optimal power tracking controller. Ultracapacitor is connected to the Buck/Boost converter and these two systems commonly connected to DC link. DC link is

connected to the Two level six switch three phase inverter which is connected to the PMSM and connected to the wheels of an electric vehicle. At the condition of starting of vehicle it requires full acceleration then both Battery and Ultracapacitor will work, after reaching to accelerated point for smooth operation battery will works and ultracapacitor will charge [19]. At the condition of regenerative braking three phase converter will work like a rectifier and battery charges.

Energy management system plays a key role in maintaining SOC of the battery. By maintaining Duty ratio of the DC link voltage, we can improve the SOC of vehicle battery. This can be done by using FLC which is used to control the battery state of charge. Where PID controller also used in electric vehicle for maintaining SOC and to improve battery range but extension of this system is called Fuzzy logic controller which will be compared in the results section.

6. FUZZY LOGIC CONTROLLER FOR HYBRID SYSTEM

The battery charge controller block serves to regulate battery charging and discharging while the vehicle is in motion. It takes inputs of error in DC link voltage and changes in error of DC link voltage are based on a predefined set of rules, output is Duty ratio. By monitoring the dc link voltage and change in error of dc link voltage, the HEV can be optimized for intelligent operation [20], by maintaining these values SOC can be improved with PWM technique, the controller adjusts the SOC to maintain it, thereby increasing the driving range of the vehicle.

The primary application of the fuzzy logic controller lies in managing various converters, with its utility now extending to regulating the state of charge (SOC) in hybrid electric vehicles' batteries. Numerous system variables influence the controller's overall efficacy. It is essential for the controller to adeptly regulate all parameters in tandem with shifts in battery status. In such scenarios, the fuzzy logic controller emerges as the optimal choice, demonstrating its proficiency in effectively managing battery SOC [21].

The primary role of Fuzzy Logic Control (FLC) lies in the selection of input and output variables, as well as membership functions [22]. These functions are diverse and are then employed in max-min composition, combined with AND/OR rules, to produce the controller's output. This process ensures that the controller's output accurately reflects the system's behavior based on the input variables.

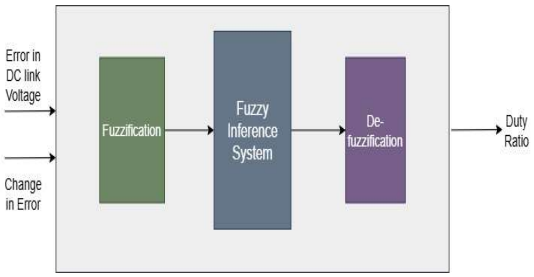


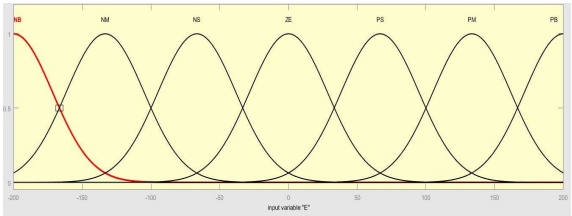
Figure 3: Working of Fuzzy logic controller for HEV

Figure 3 shows the working diagram of FLC. The error in dc link voltage and change in error in dc link voltage are the inputs of the controller. Initially, the process entails fuzzification, where the fuzzifier converts the input into a fuzzy set. Subsequently, the fuzzy inference system employs predefined rules to process the fuzzified input and produce an output. This output is then transmitted to the defuzzification block, which yields the duty ratio as the final output.

6.1. Membership Functions

Figure 4 represents the membership functions for both inputs and outputs which are used to study FLC. From Fig.4(a) that the input is classified into 7 types that are negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB). Error in dc link voltage value in range between -200 to +200.

Similarly, the change in error input function also 7 membership functions for each input. The range is taken -1 to +1 and the duty ratio output function also 7 membership function and range taken between -100 to +100.



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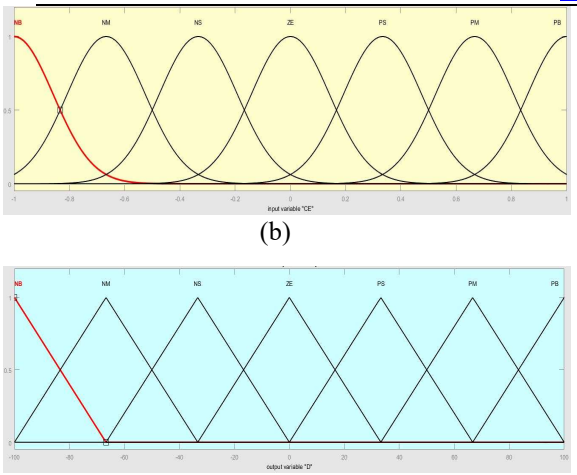

(b)

(c)

Figure 4: Membership functions: (a) Error in dc link voltage input (b) Change in error and (c) Duty ratio output

The key advantage of such systems is their adherence to precise rules, ensuring execution within the specified rule limits. Utilizing the dc link voltage battery state of charge (SOC) can enhance, enabling the hybrid mode for longer-distance travel.

The Simulink model used to simulate PID controller and Fuzzy logic is represented in Figure 5.

The Table 1 outlines the rule-based approach for handling various ranges of input values within the fuzzy charge control system.

Table 1: Rule strategy for estimation of current

Duty Ratio		Error						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
Change in Error	**PS**	Z	PS	PM	PB	PB	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	NM	NS	Z	PS	PM	PB	PB
	Z	NB	NM	NS	Z	PS	PM	PB
	NS	NB	NB	NM	NS	Z	PS	PM
	NM	NB	NB	NB	NM	NS	Z	PS
	NB	NB	NB	NB	NB	NM	NS	Z

This system utilizes the Mamdani system to assess the fuzzy output. The parameters used for designing simulation model are represented in Table 2

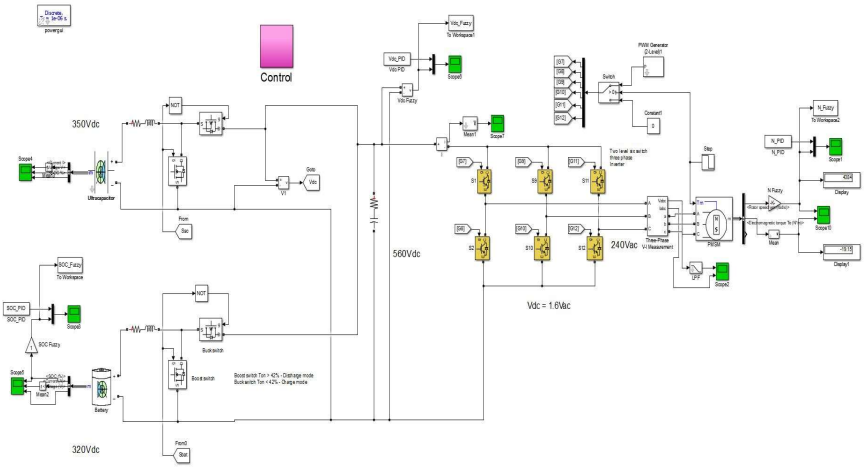

Figure 5: Simulink model of Hybrid System

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Table 2: Simulation model specifications

Parameters	Values	Units
Battery		
Nominal Voltage	320	Volts
Rated capacity	90	Ah
Nominal Discharge current	39.13	Amps
Ultracapacitor		
Rated capacitance	1	mF
Rated voltage	350	Volts
PMSM		
Voltage	560	Volts
Speed	3000	RPM

7. SIMULATION RESULTS

The preceding section's model is simulated and the results are provided in the following two conditions, that are:

- At starting condition and
- At braking condition.

At starting condition both battery and ultracapacitor discharges and three phase converter works as a rectifier which is connected to the PMSM drive. From 0 sec to 4 sec considered as the starting and normal driving of the vehicle. Braking applied at 4 sec then motor works like a generator and three phase converter works as an inverter then battery stores energy by using regenerative braking method.

From Figure 7 the SOC curve of battery with PID controller is initially at 100% and gradually decreases to 99.892% up to braking condition of 4 sec. At the time of braking condition, the motor will work as a generator and charges the battery from 4 sec to 5 sec from 99.892% to 99.896%. With Fuzzy controller the SOC curve of the battery is initially at 100% and gradually decreases to 99.946% up to braking condition of 4 sec. At the time of braking condition, from 4 sec to 5 sec battery charges from 99.946% to 99.952%. we can conclude that by using Fuzzy logic controller battery SOC maintained smoothly and driving range also increases at the end.

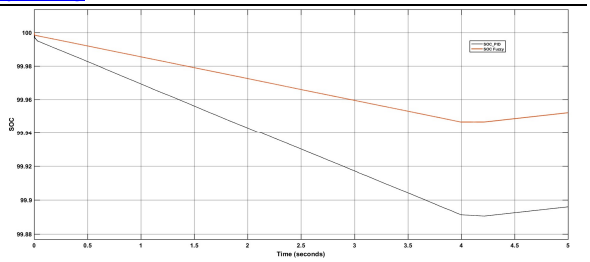


Figure 7: Battery SOC using PID and Fuzzy controller

Figure 8 shows dc link voltage of PID controller and fuzzy controller. Where ripples get reduced using fuzzy controller so that error reduced and SOC improved using fuzzy controller.

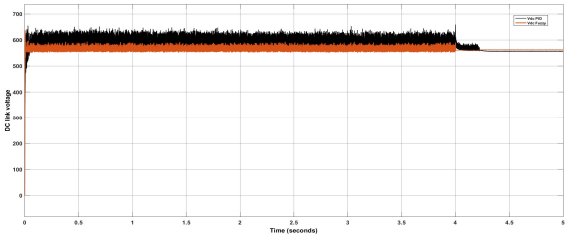
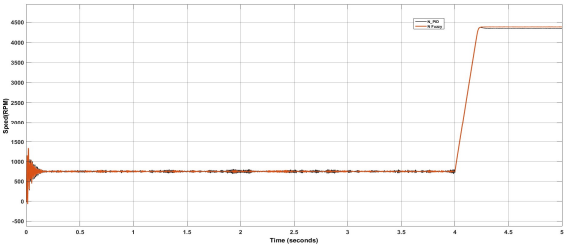


Figure 8: DC link voltage of PID and Fuzzy controller

Figure 9 shows the speed and torque characteristics of PID and fuzzy controller, where the simulation implemented with same speed and torque parameters but there is a smooth operation with fuzzy controller. At the braking condition torque to the negative condition and battery charges using inverter.



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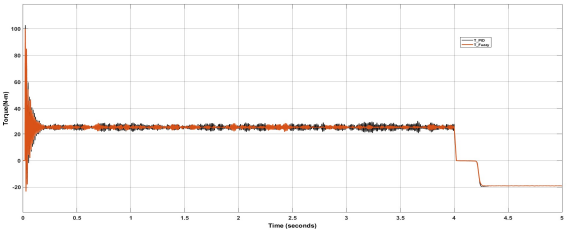

(b)

Figure 9: (a) Speed characteristics of PID and Fuzzy controller and (b) Torque characteristics of PID and Fuzzy controller

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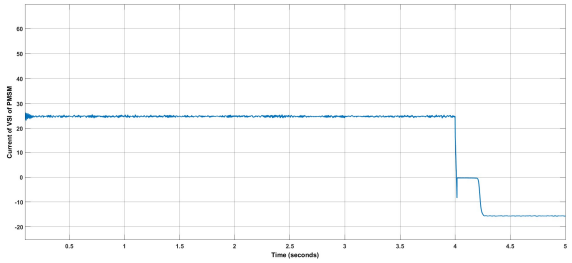
Figure 10 shows the DC link current and Vabc and Iabc of VSI of PMSM. At braking condition current goes to the negative peak.



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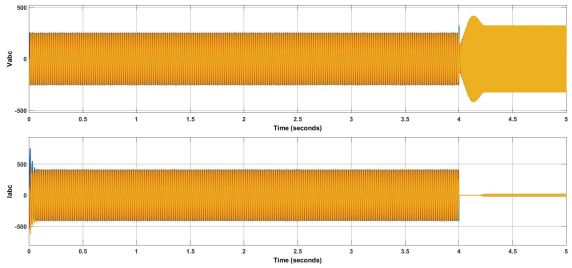


(b)

Figure 10: (a) DC link Current of PMSM and (b) V_{abc} and I_{abc} of VSI of PMSM

Figure 11 shows the SOC curve of ultracapacitor with PID controller. It continuously charges and discharges until brake condition, at braking condition it stops charging and battery charges using regenerative braking method. Ultracapacitor acts like a backup to the battery and it reduces stress on the battery so that we can improve the lifespan of the battery.

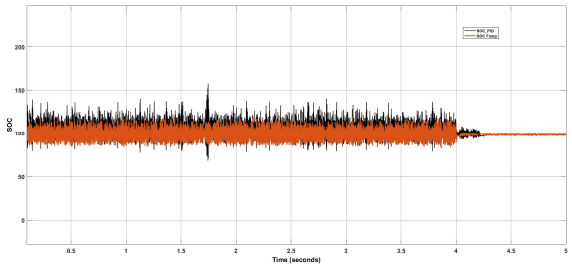
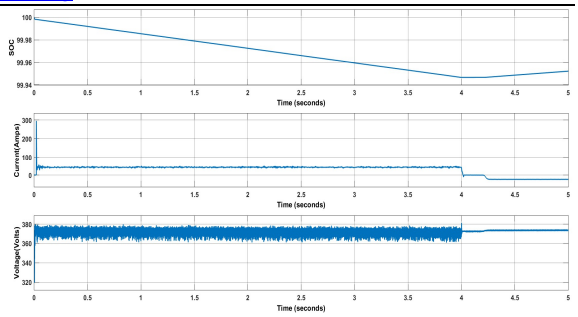


Figure 11: SOC of ultracapacitor with PID and Fuzzy controller

Figure 12 indicates Battery and ultracapacitor SOC, voltage and current waveforms with fuzzy controller.



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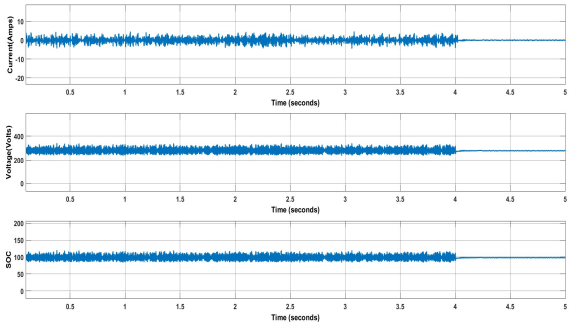

(b)

Figure 12: SOC, current and voltage with Fuzzy controller of (a) Battery (b) Ultracapacitor

Table 3 below presents a comparison of various parameters between the PID controller and the Fuzzy Controller.

Table 3: Comparison of various parameters using different Energy management systems

Parameter	Battery Controller	
	PID	FLC
Time(sec)	5	5
Initial SOC%	100	100
Final SOC%	99.89	99.952
SOC drop	Sharp	Small

The findings indicate that the Fuzzy logic controller is a more advanced and precise system, grounded on the input/output data pairs of the system.

The objectives of the study were fully met, with simulation results confirming the superior performance of FLC in terms of stability and battery management. These outcomes not only validate the potential of FLC for real-world battery control applications but also provide a more

comprehensive benchmark for future controller evaluations.

8. DIFFERENCE FROM PRIOR WORK

Previous studies have widely utilized PID controllers for battery management with different energy storage devices like solar cells and fuel cells due to their simplicity and ease of implementation. Some recent works have explored fuzzy logic controllers (FLCs), highlighting their robustness. But in this study provides a detailed evaluation of battery management with ultracapacitor of PID and Fuzzy controllers.

The limitations of this paper include the use of limited operating conditions and the reliance on manually designed fuzzy logic rules.

9. CONCLUSIONS

The PID approach governs battery SOC, optimizing it for longer journeys, while the FLC system, leveraging input/output data pairs, further refines SOC control. Advanced optimization techniques are applied to both PID and Fuzzy logic controllers, facilitating a comparative analysis of their performances.

The simulation results indicate that the PID controller maintained the battery SOC at 99.89% by the end of the drive cycle, albeit with drops during accelerations. In contrast, the battery SOC remained higher, above 99.952%, at the end of the drive cycle when using the fuzzy controller system with Triangular membership function. This demonstrates the effectiveness of the fuzzy controller in maintaining SOC, achieving approximately 99.952% even after a 5-second drive. We can conclude that by using fuzzy controller we improved the performance of the battery. So that SOC of the battery improved and enabled HEV for longer distances.

HEVs represent the future of transportation, emphasizing the importance of intelligence and power efficiency in their design. This study contributes to the development of controllers that meet both criteria, facilitating a smooth transition towards sustainable transportation.

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