

Fuzzy Inference System Driven Hybrid Energy Storage for Sustainable Power Management

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Abstract: Vehicle electrification is gaining attention as a long-term option to overcome the effects of high carbon emissions and dependency on fossil fuels. To solve the issues of limited electric range and fluctuating power demands in electric vehicles (EVs), this study investigates the combination of a Hybrid Energy Storage System (HESS) with a Fuzzy Logic Controller. This method is a cutting-edge solution to addressing speed control difficulties in electric vehicles by combining a Fuzzy Logic Controller (FLC) with a Hybrid Energy Storage System (HESS). The combination of Fuzzy Logic, a sophisticated control approach capable of handling complex, nonlinear systems, and a HESS with numerous energy storage elements promises to transform how electric vehicles manage energy, respond to driver input, and maintain speed profiles. The HESS combines sophisticated battery technology and super capacitors to provide a synergistic approach to balancing energy density and fast power response. The fuzzy logic controller is designed to intelligently manage energy flow within the system, optimising the HESS's performance in real time in response to changing driving conditions, power requirements, and battery state. The study's goal is to demonstrate the usefulness of this integrated strategy in improving the overall energy economy, range, and performance of electric vehicles, which has been simulated and confirmed with MATLAB Simulink.

Keywords: Electric Vehicles; Fuzzy Logic Controller; Hybrid Energy; Storage System; Energy Economy; Ice Vehicles; High Energy Efficiency; Battery Technology; Speed Control; Nonlinear Systems.

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1. Introduction

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Electric vehicles offer a cleaner and quieter alternative to the clamorous, pollution-emitting fuel-driven vehicles. Even though BEVs typically have a shorter driving range compared to ICE vehicles, they can effectively serve as city cars, such as for commuters or in rental and public transportation systems. Additionally, BEVs present an opportunity to lower transportation costs due to their high energy efficiency in electric propulsion. However, it's worth noting that, regardless of the lower energy cost per kilometre travelled in EVs, the long-term expenses can be similar to those of ICE vehicles. One significant factor contributing to this similarity is the expense of battery replacement in BEVs, which can deter people from adopting them. Thus, it is crucial to create plans to solve this issue that may extend the life of batteries. Exact management of an electric vehicle's speed is crucial if one wants to fully realise the advantages of electric mobility. Efficient speed control improves the general driving experience and is especially important for maximising energy use and increasing the range of EVs. By including an FLC together with a HESS, this paper investigates a novel method to tackle the difficulties of speed control in electric vehicles. Combining a HESS made up of several energy storage components with Fuzzy Logic, a potent control technique able to handle complicated, nonlinear systems, promises to transform the way electric vehicles govern energy, react to driver input, and keep speed profiles.

The theoretical basis of Fuzzy Logic Control, the benefits of using a Hybrid Energy Storage System, the design and implementation of the controller, and the practical testing of a prototype electric vehicle will all be covered in the next sections as we investigate the main features of this creative system [4]. Synergising these cutting-edge technologies will help us to improve the energy efficiency, performance, and range of electric cars, hence strengthening their role as a sustainable and ecologically beneficial mode of travel. Intending to hasten the transition to a cleaner and greener automotive future, this paper offers a comprehensive solution that bridges the gap between control theory and practical application, addressing the fundamental challenges of electric vehicle speed control. In this research paper, considering the inherent nonlinearity of the entire system, we have implemented and evaluated a power management system [3].

2. Literature Review

Efficient energy storage systems are needed to store that extra energy and release it when needed. HESS is a promising way to balance energy supply and demand because it uses a combination of different energy storage technologies, like batteries, super capacitors, and flywheels [1]. HEV energy management strategies are currently categorised into two types: rule-based and optimisation-based strategies. In HESS, the battery can provide power at light loads, while the super capacitor can meet the energy needs of both acceleration and regenerative braking [2]. When the main control block of the vehicle uses fuzzy logic, the membership functions enable the power flow controller to determine the optimal way for the hybrid drivetrain to distribute power based on available resources. Krithika and Subramani [5] provided a different control strategy for optimisation [5]. The battery state of charge (SOC) was used to switch between power consumption and power maintenance modes during vehicle operation. The threshold value was used to switch between the engine and the motor. This control approach is basic and reliable, but does not account for dynamic changes in the driving process [6]; [7]. A further strategy for increasing a HEV's electric range is to permit continuous battery charging while the vehicle is in motion. Because solar-driven HEVs (PVHEVs) use solar energy to continuously charge their batteries, they use less gasoline, resulting in lower pollution levels in the environment. For hybrid cars, a major obstacle is finding strong and reasonably priced batteries [8]; [9].

Hybrid systems have the benefit of an overall increase in particular power and/or specific energy. High Power (HP) storage often uses electrical double-layer capacitors (EDLCs) or HP batteries, enabling power acceleration or deceleration. On the other hand, High Energy (HE) storage, often achieved with HE Li-ion cells, guarantees a long-term supply [10]; [11]. Supercapacitors can produce high peak current (up to 100A) practically instantly with excellent efficiency due to their large power density (about 5–10 kW/kg). This capability encourages acceleration and regenerative braking, significantly cutting down on charging time [12]. The electric characterisation of two distinct Maxwell Technologies-made supercapacitor modules (165 F and 130 F) is used to define an equivalent supercapacitor model [13]. The hybrid renewable source includes a wind turbine, a solar PV array, and a PEM fuel cell. When power generation experiences an outage, the fuel cell used here is primarily utilised for loads. To meet the demand for increasing loads, a bidirectional converter connected to the battery regulates the voltage supplied to the load. Both charging and discharging are accomplished with the help of the bi-directional converter [14].

3. Hybrid Energy Storage System in EVs

The HESS, which combines batteries and capacitors, is known for its increased flexibility, contributing to prolonged service life and enhanced component efficiency. Moreover, they offer cost and mass reductions compared to storage systems relying solely on batteries or ultracapacitors. In the context of EV battery management, a HESS model typically involves the integration of both batteries and capacitors. This combination allows for a more versatile and efficient management of energy in electric vehicles. The

model operates by strategically utilising batteries and capacitors based on their respective strengths and characteristics. Batteries are generally responsible for providing the main energy storage capacity. They are efficient in storing large amounts of energy over a longer duration. On the other hand, capacitors are employed for their ability to deliver quick bursts of power. This makes them particularly useful in situations that demand rapid acceleration or deceleration. The HESS model optimises the performance of both components by intelligently distributing the workload. During periods of high-power demand, capacitors can handle the immediate needs, preventing strain on the batteries. In contrast, during periods of lower demand, batteries can take over to ensure a sustained and consistent energy supply. Figure 1 depicts hybrid energy storage systems in EV, which is implemented in MATLAB software.

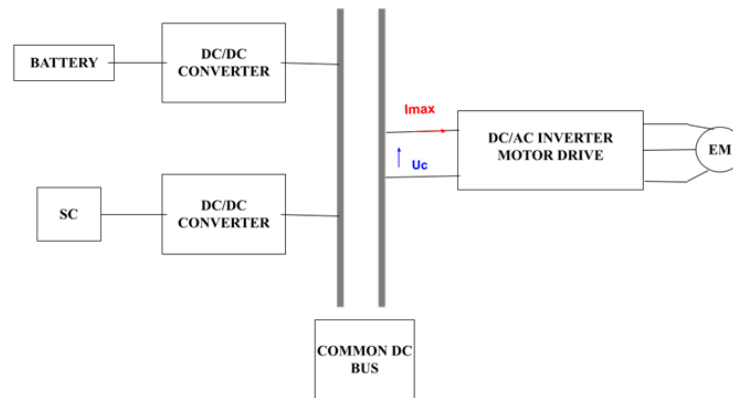


Figure 1: Hybrid energy storage system in EV

However, accurate and timely decision-making is not completely reliable in the conventional HESS system. It does not allow real-time adjustments and optimisation of energy flow between the ultracapacitor stack and the battery based on varying driving conditions. While driving conditions can be unpredictable, the system requires a more nuanced and smarter decision-making, which is particularly beneficial for balancing the compromises between immediate power needs and long-term energy considerations. This paper focuses on providing a more intelligent and adaptive approach to energy management in EVs.

4. HESS Using a Fuzzy Logic Controller

This system provides a HESS for battery management systems in EVs, featuring a fuzzy interfacing system that achieves timely and intelligent decision-making. It offers benefits such as enhanced efficiency, optimised battery life, improved user experience, dynamic energy management, and robustness to variability. The FLC can typically be fed with the Battery State of Charge (SOC), Ultracapacitor State of Charge, Load, Speed information of the EV, voltage and current levels, and environmental conditions. Our system demonstrates the optimisation of the EV performance by feeding the fuzzy logic controller with the outputs of ultra-capacitance, speed profile, battery state of charge, error current, and power load. The FLC for HESS is represented in Figure 2. Fuzzy Logic Controllers (FLCs) are integrated into the HESS model due to their adaptive and decision-making capabilities. The energy storage management combines two or more storage technologies, like supercapacitors or batteries.

Fuzzy Logic provides the handling of uncertainty and precise data. HESS encounters fluctuating load demands, varying states of charge, and diverse storage technologies, resulting in a complex, nonlinear environment. Fuzzy Logic Controller offers solutions to these complexities with real-time adaptive control. Their ability to handle uncertain information enables the system to make optimal decisions based on current conditions, improving its efficiency and adaptability. By enabling immediate reaction to different conditions, Fuzzy Logic ensures that the optimised energy flow among different storage technologies improves the overall performance, reduces losses, and extends the lifespan of storage components. The FLC comprises three processes. First, Fuzzification is used to convert the input data into fuzzy output variables. The three types of fuzzifier used for the fuzzification process are, namely:

- Gaussian Fuzzifier
- Singleton Fuzzifier
- Triangular/Trapezoidal Fuzzifier

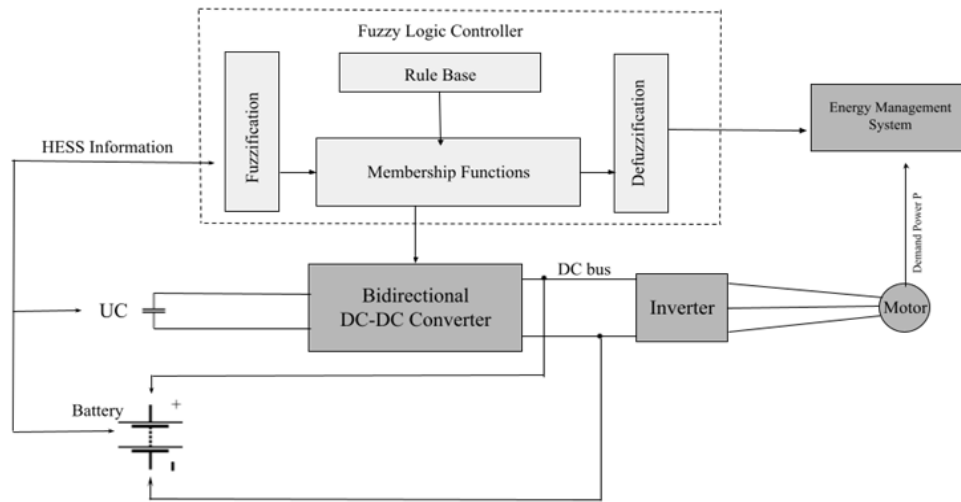


Figure 2: FLC incorporated in HESS

In this paper, the inputs of the fuzzifier are triangular. This fuzzy input is used to build the fuzzy rule inference for the decision-making process. There are two types of fuzzy inference systems (FIS):

- Mamdani
- Sugeno

The fuzzy inference system used in this paper is Sugeno. The last is the defuzzification process, which converts input variables into numerical outputs. There are different types of defuzzification processes. The simulation model implemented in Simulink is illustrated in Figure 3.

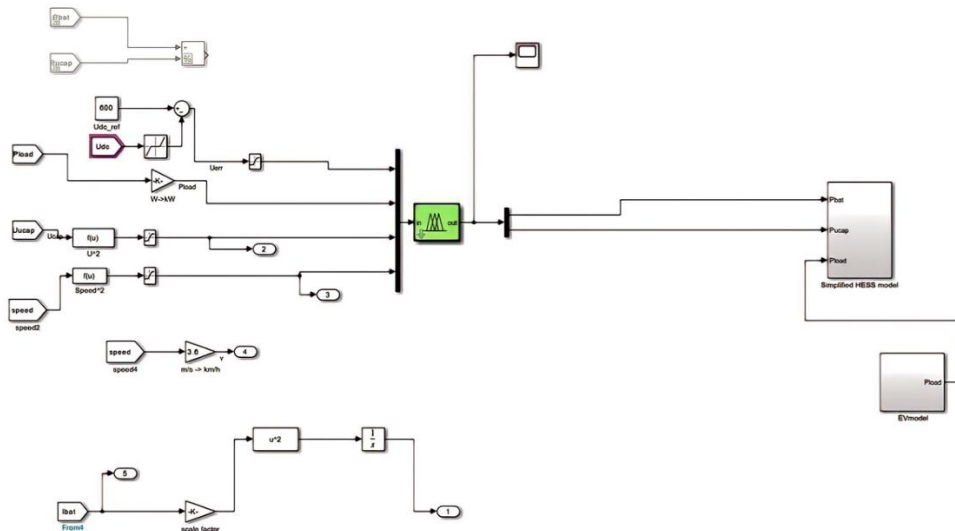


Figure 3: Simulink model of FLC integrated with HESS

In the proposed FLC, the defuzzification method is used, which is given as,

$$y = \frac{\sum_{i=1}^n (w_i * y_i)}{\sum_{i=1}^n w_i}$$

- w_i represents the membership strength or weight of each discrete output.
- y represents the crisp output.
- y_i denotes the discrete outputs.

The four inputs given to the FLC are:

- Error Current
- Speed of the vehicle
- Ultra Capacitor
- Power Load

Based on the given inputs, the signals and membership functions are produced using FLC, employing the Sugeno rule-based system.

4.1. EV Model

The Electric Vehicle (EV) subsystem described above operates based on a fundamental principle of optimising power distribution and efficiency for enhanced vehicle performance, as illustrated in Figure 4. The acceleration speed profile changes over time and is used to calculate the vehicle's velocity. The incorporation of resistive forces, such as aerodynamic and rolling resistance, involves subtracting these forces from the velocity to determine the net force available for propulsion. Then it combines the acceleration and resistive forces to determine the overall force influencing the vehicle's motion.

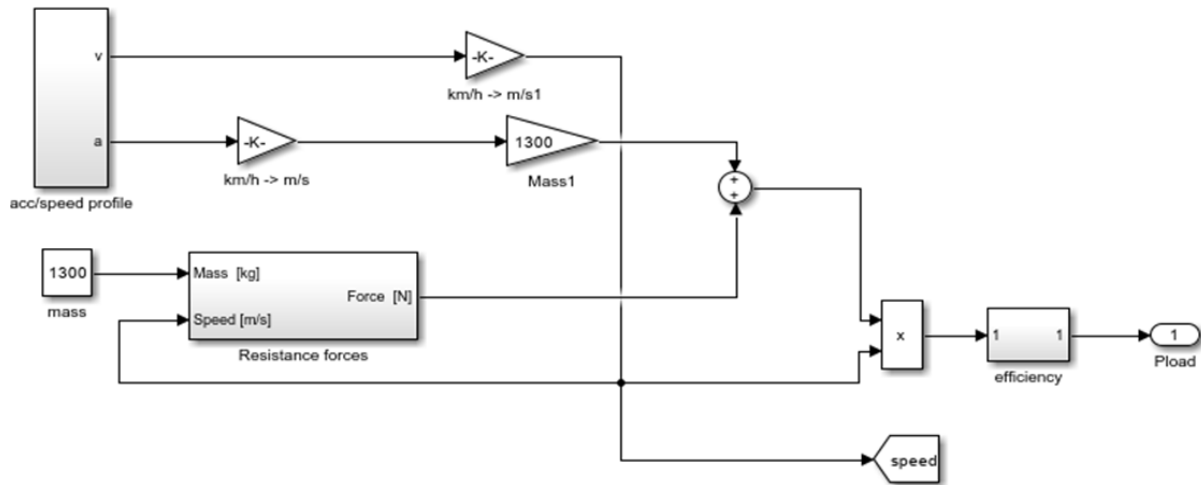


Figure 4: EV model

The efficiency converts the available force into usable power effectively. The final output is the power load, which encapsulates the culmination of these processes and represents the amount of power required or generated by the EV's propulsion system. This EV model with HESS integrates dynamic variables, such as acceleration and resistive forces, with a focus on optimising efficiency and power distribution for superior electric vehicle performance.

4.2. Resistive Forces

This subsystem helps optimise the use of energy in an EV by calculating the force required to overcome resistive forces based on mass and speed inputs. The energy management system can then allocate power from the HESS by combining, for instance, batteries

and capacitors to efficiently meet these force demands. The inputs given to this system are mass and speed. The mass of the vehicle is crucial because it requires force to move. Heavier vehicles require more force to overcome resistive forces. The velocity or speed affects the vehicle's resistance to aerodynamic and rolling forces. As speed increases, these resistive forces also increase. Aerodynamic drag is a force influenced by the vehicle's shape, speed, and air density. As the vehicle moves through the air, aerodynamic drag opposes its motion, demanding more energy to overcome this resistance. Having the speed as an input for calculating Aerodynamic Drag enables the system to adjust and vary the resistance encountered by the vehicle at different velocities. The formula below uses the speed input to calculate the aerodynamic drag force.

$$\text{Aerodynamic Drag} = 0.5 \cdot C_d \cdot A \cdot \rho \cdot v^2$$

Where:

- C_d - coefficient of drag
- A - reference area (frontal area)
- ρ - air density
- v - velocity (speed)

This calculated force is factored into the overall force output of the resistive force subsystem, influencing the energy required to overcome the resistive forces acting on the vehicle. The relationship between mass and rolling resistance can be integrated into the Rolling Resistance formula as:

$$\text{Rolling Resistance} = C_r \times F_{\text{gravity}}$$

Where:

- C_r - coefficient of rolling resistance.
- F_{gravity} - force due to gravity, influenced by the mass (weight) of the vehicle.

Finally, we are subjected to forces that the HESS needs to overcome to keep the vehicle in motion. This total force accounts for both resistive forces acting on the EV and guides the management of energy and power distribution within the hybrid system to effectively address them. This, in turn, ensures efficient operation and energy utilisation in the EV model.

4.3. Efficiency

The efficiency subsystem receives inputs from resistive forces and the acceleration speed profile. This system works by monitoring these inputs and adjusting the power distribution between various energy storage systems. The saturating component in the Efficiency controls the output by limiting the power flow or electrical signals passing through it. The upper limit mentioned in the system is infinity, and the lower limit is zero. When the inputs exceed a certain level, these elements maintain a maximum value. This prevents further increase in input to avoid power surges or overload and ensures the system operates within safe power levels. The gain refers to the amplification of the magnitude of a signal in terms of power load. Once the input signals have been processed through the elements, the system will integrate them to calculate the power load output. By managing and balancing power flow, the efficiency is enhanced by increasing its range and efficiency.

4.4. Acceleration/Speed Profile

A repeating sequence interpolated block that provides a signal as input to the multiport block. The signal is then passed to the function block, which processes it to produce an output. This output is then taken into the integrator block, which produces the velocity of the signal. The output from the function block can also produce acceleration directly, without the need for the integrator block. This is because acceleration is the rate of change of velocity with respect to time, and the function block output already contains information about the signal's velocity. Thus, the model gives two outputs, such as v-velocity and a-acceleration. These outputs are then fed into the efficiency block via gain blocks and a sum block. The resultant Pload is the output power of the proposed system. This Pload value is then fed into the simplified HESS (Hybrid Energy Storage System) model for further processing. In a simplified HESS model, the Pload value is used to govern the optimal balance of energy storage technologies in the system.

4.5. Simplified HESS Block

HESS might help to control and store electrical energy. The simplified HESS block is illustrated in Figure 5.

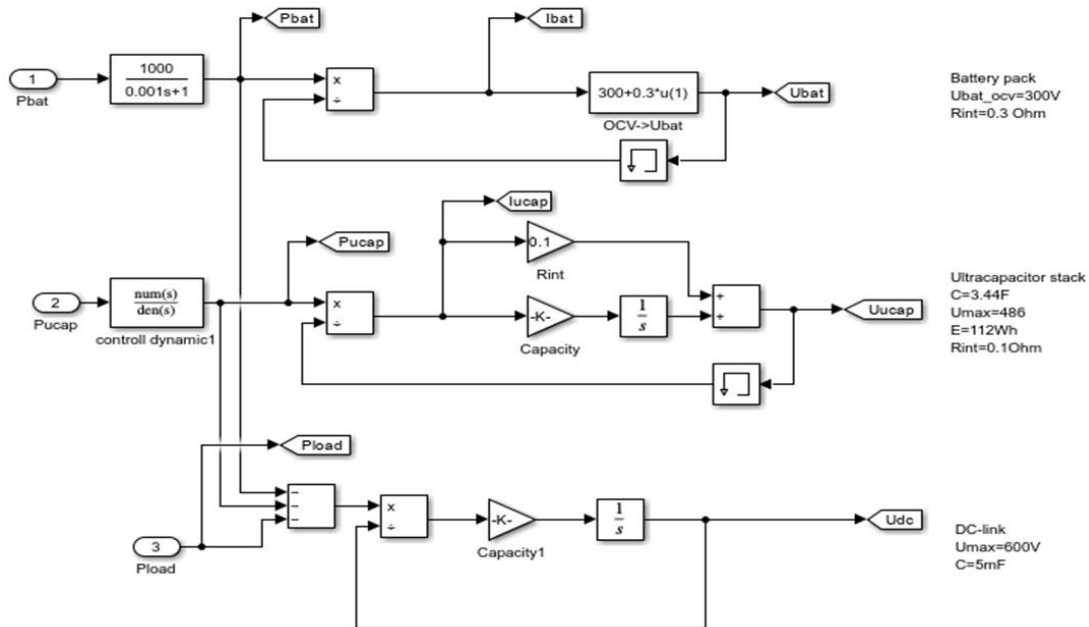


Figure 1: HESS model depicting the ultra-capacitor stack and DC-link voltage

It combines several energy storage technologies, including batteries, capacitors, flywheels, and supercapacitors. HESS can offer a more flexible and efficient energy storage solution by including these technologies. HESS can improve the performance and dependability of systems for energy storage. HESS can offer backup and redundancy features by combining several technologies. This implies that if one part fails, the other parts can continue managing and storing power. By means of various technologies and by minimising the need for further infrastructure, HESS may lower the total cost of energy storage. Often in the area of energy storage systems, the paper Simplified HESS Model is applied. Comprising three sub-models—the Battery Pack Model, Ultracapacitor Stack (Ucap) Model, and DC Link Model—the general operation of the HESS model is significantly influenced by these models, as shown in Figure 6.

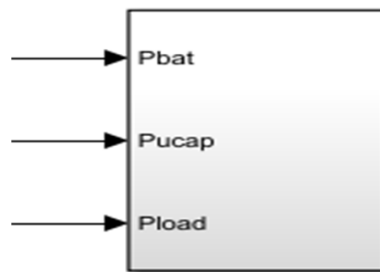


Figure 6: Simplified HESS model

The battery pack model stores energy as chemical energy. As needed, this energy can be converted subsequently to electrical energy. The Ultracapacitor Stack Model stores energy in the form of an electric field. Its ability to deliver quick power makes it appropriate for short-term high-power uses. The DC Link Model finally links the battery and capacitor stacks, controlling the voltage and

current. The blocks in the Simplified HESS model are called Pload, Pucap, and Pbat, which specify the power of the capacitor and battery. While Udc controls the voltage, the parameters Ibat and Iucap specify the battery and capacitor current, respectively. The most often used blocks in the HESS model are the Ibat, Pload, and Ucap blocks. The simplified HESS model contributes to the optimisation process by offering faster convergence, improved accuracy, enhanced exploration and exploitation, robustness to parameter variations, and adaptive learning rates.

The function block comprises two main components - OCV (open circuit voltage) and Ubat. OCV is the voltage measured by the battery when no load is connected to it. Ubat, on the other hand, is the battery voltage when it is connected to a load (obtained from feedback). The function block uses these two parameters to produce the final output of the battery pack model. The Ultracapacitor stack model uses a power ultracapacitor as input. This capacitor passes through a control dynamic and product block, and the output is given to a sum block, which adds the two inputs. The control dynamic and product block likely serve to regulate the flow of energy through the circuit, ensuring that the ultracapacitor is charged and discharged efficiently and safely. The sum block adds the two inputs, likely to provide a more stable and consistent flow of energy. This circuit also includes a capacitor connected to an integrator and an internal resistor, likely designed to smooth out the flow of energy and prevent sudden spikes or drops. In contrast, the ultracapacitor current flows through the circuit. The feedback signal is provided to the product block through a memory block, which likely helps fine-tune the circuit and ensure it operates at maximum efficiency.

The use of an ultracapacitor offers many advantages over traditional batteries, including high charge and discharge rates, longer lifespan, and higher efficiency. The integration of the capacitor with the control dynamics and product block allows for more precise control of the energy flow in the circuit. The sum block then combines this energy with another input, potentially providing a more stable and reliable source of power. The DC link model consists of a sum block that uses input parameters such as Pbat and Pucap, with another input being Pload. The output of this sum block is then fed into a product block, which passes through a capacitor and integrator, producing Udc as the final output. Additionally, some of the output signal is sent back as feedback to the product block as the other input. This circuit is commonly used in power supply applications, where the input power is first regulated and converted to a desired output voltage or current. The sum block considers the battery input power (Pbat) and the power used to charge the capacitor (Pucap), with the difference representing the power consumed by the load (Pload). The product block then multiplies this power value by the feedback signal to adjust the output voltage or current accordingly. Finally, the capacitor and integrator filter out any high-frequency noise or ripple in the output, producing a smooth and stable DC output signal.

5. Results and Discussion

The proposed system was simulated using MATLAB Simulink as shown in Figure 7.

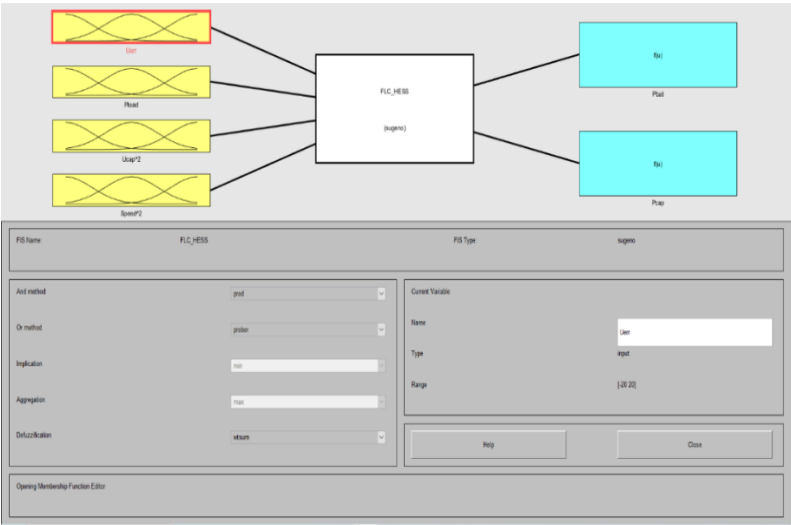


Figure 7: Fuzzy inference system

The Error current input consists of five membership functions (MFs), If the error current is between the range -45 to -15, it denotes 'Negative Large', 'Negative Small' ranges from -30 to -0.6, 'Zero' membership function ranges from -15 to 15, 'Positive Small' ranges

from 0.6 to 30, Finally, 'Positive Large' covers the range from 15 to 45. The speed and power load input have five member functions. The 'Pload' variable within a fuzzy logic system is segmented into four distinct membership functions, each operating within the range of 0 to 50. If the Power load is between 4 and 9, it denotes 'neg_zero'. The 'large' function ranges from 9 to 75 and forms a trapezoidal function. 'Small' triangular function, ranges from 9.084 to 53.08. 'Large2', represented by a trapezoidal function, ranges from 0 to 90. The provided code establishes the 'U^2' variable in a fuzzy logic system, partitioning it into eight distinct MFs within the range of 0.25 to 1.

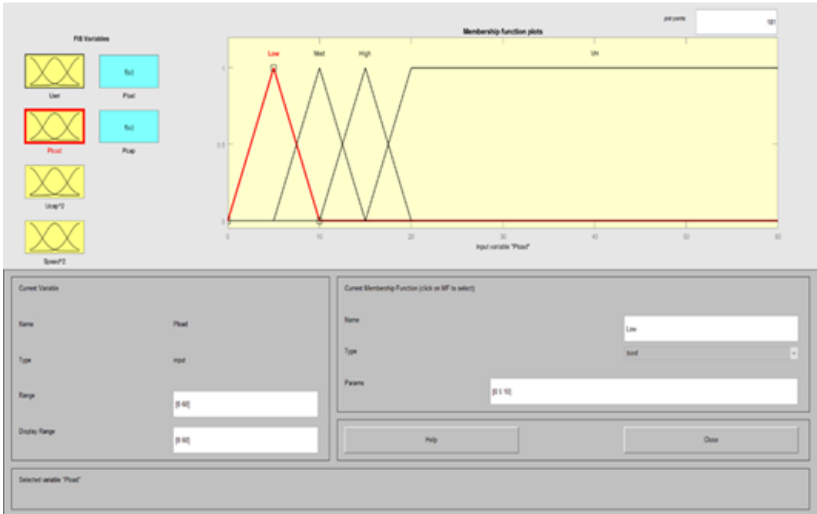


Figure 8: Membership functions of power load

The ultracapacitor has eight-member functions. If the capacitor is between 0.2969 and 0.5781, it denotes that 'zero' is represented by a triangular function. 'Low' is another triangular function spanning from 0.25 to 0.625. 'Mid' covers the range from 0.4375 to 0.9. 'High' is represented by a triangular function from 0.625 to 1. 'Max' ranges from 0.9 to 1.188. 'Z+L' is defined as a trapezoidal function from -0.0875 to 0.625, indicating the 'Zero to Low'. 'Z+L+M' spans from -0.2875 to 0.9, signifying 'Zero to Low to Mid'. 'Z+L+M+H' ranges from -0.6625 to 1, characterising the 'Zero to Low to Mid to High'. The membership functions of the power load are described in Figure 8.

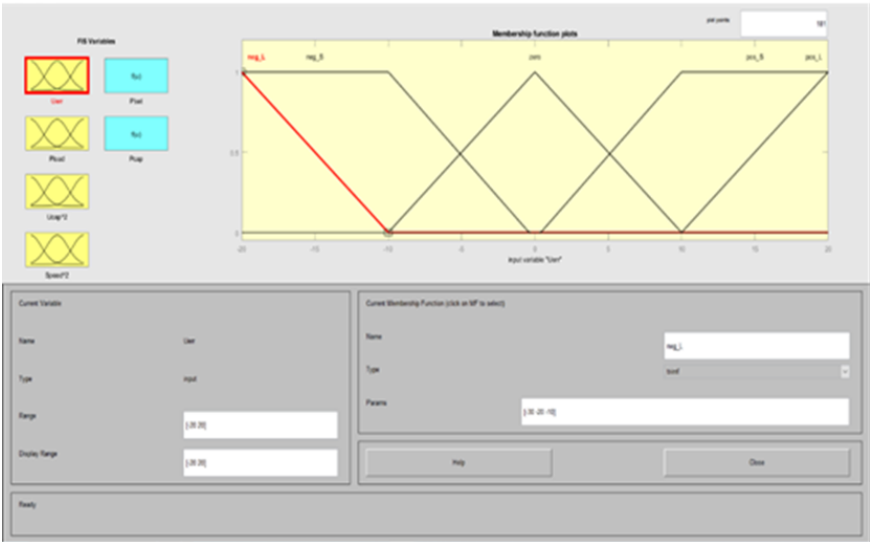


Figure 9: Membership functions of error current

The speed input has four distinct membership functions, operating within the range of 0 to 1. 'Zero' is represented by a triangular function, spanning from -0.33 to 0.33. 'Low' is characterised by a triangular function, ranging from 0 to 0.6667. 'High' encompasses the range from 0.33 to 1. 'max' is another triangular function spanning from 0.6667 to 1.333. These membership functions are designed to categorise specific linguistic terms and segments in the fuzzy logic-based analysis and classification of various conditions related to speed considerations in the system (Table 1).

Table 1: Rules given to the FLC

Error Current	P _{load}	U _{cap} ²	Speed ²	P _{bat}	P _{cap}
Neg_L	Low	VL	Zero	Line	Line
Neg_S	Med	Low	Low	Char	Char
Pos_S	High	Mid	High	Disch	Disch
Pos_L	VH	High	Max	Zero	Zero
Zero	None	VH	None	None	Line
None		Under			None
		Over			

Similarly, the membership functions were given for the ultracapacitor, speed, and power battery. The rules have been made for these inputs, which are named as very low, low, medium, high, Negative Large, Negative small, Positive large, Positive small, and very high. Figure 9 represents the membership functions of the error current, showing variations at different times (Figure 10).

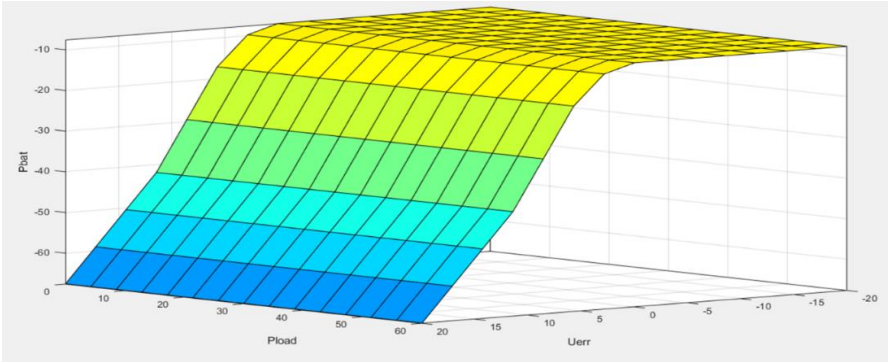


Figure 10: 3D output of FLC with power load and error current as inputs

The surface rises sharply and remains flat when the error reaches a constant value. The smooth transition on the surface reflects the fuzzy inference mechanism — no sharp jumps. A fuzzy controller provides a smooth transition from one state to another.

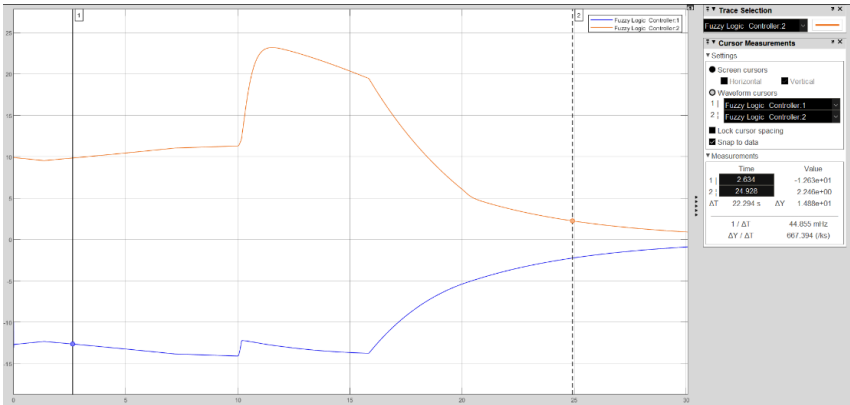


Figure 11: Simulation output of fuzzy logic controller

The scope block tool in MATLAB Simulink provides us with the results of a simulation. In this paper, the system displays the signals from Fuzzy Controller 1 and Fuzzy Controller 2. The simulated output of the fuzzy controller is described in Figure 11. The fuzzy controller-1(Orange) shows a faster initial response, rising sharply around $t = 15$. An Overshoot is observed before stabilising, which is typical of a high-gain or more dynamic controller.

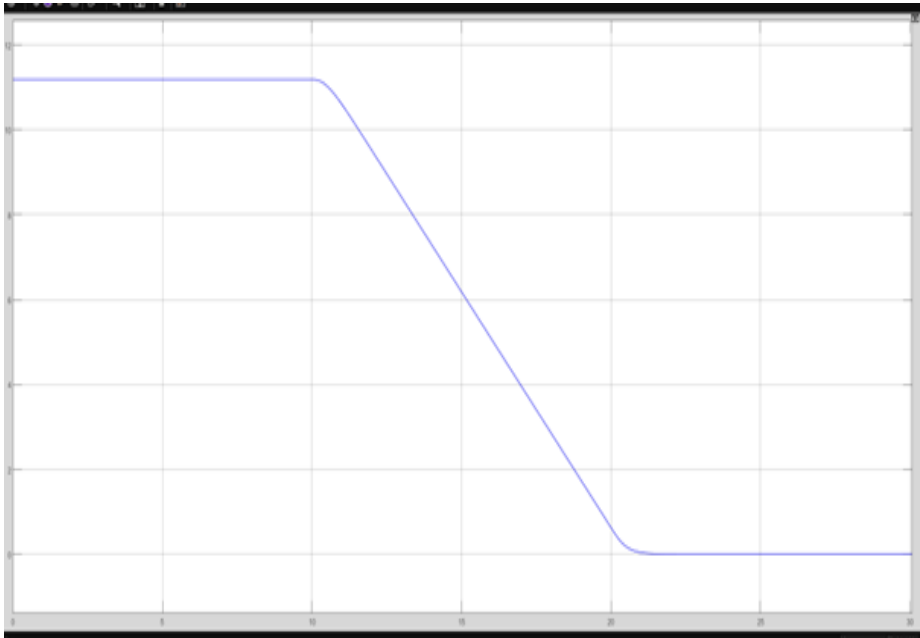


Figure 12: Output of speed profile

The charging speed variation with respect to time is represented in Figure 12. The constant speed of the vehicle starts to decrease at $t=10$ and reaches its lowest limit at $t=20$, after which it remains constant(flat). A smooth transition happens because of the fuzzy logic controller. The power load value is illustrated in Figure 13.

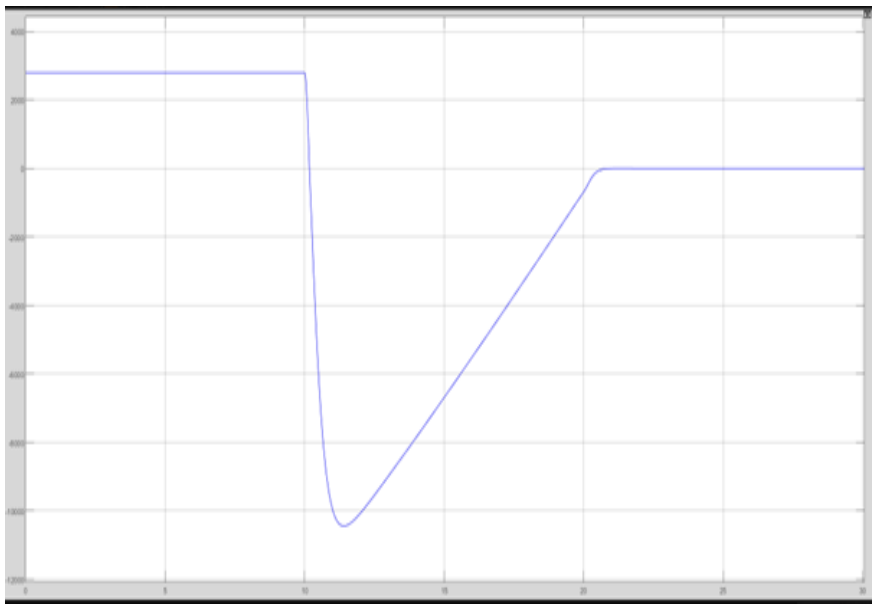


Figure 13: Output of power load

The DC link voltage typically represents the output of the capacitor voltage, connecting the rectifier to the input of the inverter. It is used in electric vehicles as an intermediate energy storage. The variation of the DC link voltage is described in Figure 14. Monitoring of the DC link voltage is essential to protect the system against overvoltage.

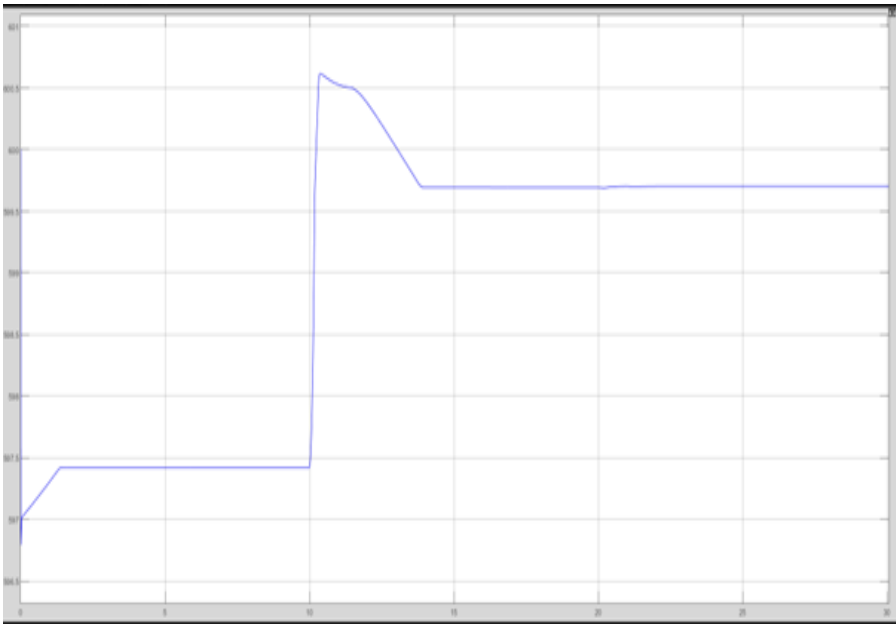


Figure 14: Output of dc-link voltage (U_{dc})

The output of battery current over a period of time is illustrated in Figure 15. The battery current is sufficient to drive the load under normal operating conditions. The simulation is accomplished using the interactive simulator scope present in MATLAB Simulink.

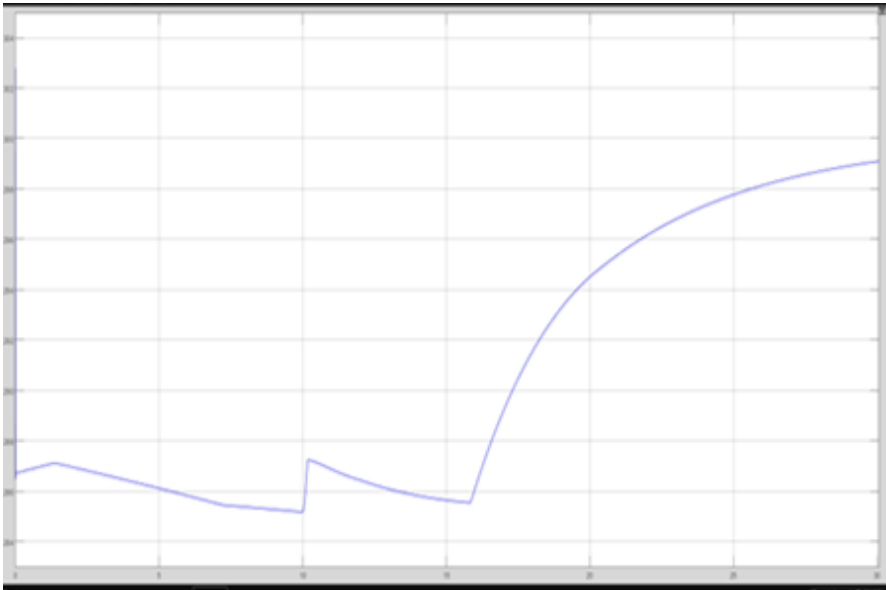


Figure 15: Output of battery current (I_{bat})

Peak-to-peak signal, statistics, median, RMS value, amplitude rise, and edges are the metrics derived from the scope. Examining these factors helps us to get an insightful analysis of the behaviour of the system being mimicked. Using the block scope offers

several main benefits, such as allowing us to see simulation findings in real time and enabling us to quickly identify any problems or anomalies in the system to take corrective action. The acceleration output of the sensor is depicted in Figure 16. The block scope also lets us change the simulation parameters on the fly, which may be quite helpful for testing various situations, maximising the performance of the system, and making sure it satisfies one's needs.

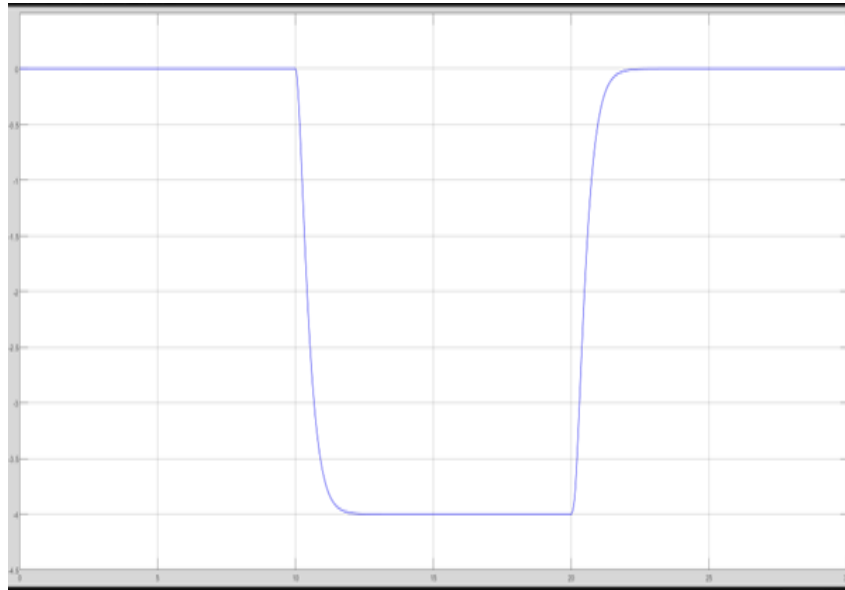


Figure 16: Output of acceleration

6. Conclusion

Thus, a hybrid energy storage system (HESS) is a mix of two or more energy storage systems working in concert to provide improved performance and efficiency. A prominent component of the power management system for HESS is the fuzzy logic controller (FLC). Without sacrificing the car's performance, it has been optimised and simulated to reduce the instantaneous battery current. The optimised FLC meets the main objective of the power management system. Prolonging battery life and reducing the risks of overcharging or overheating depend on reducing battery current. The performance of the car should not suffer at the same time. The FLC intends to strike a balance between these two goals. The outcome of the simulation shows that the optimised FLC can preserve decent vehicle performance while significantly lowering battery current. This is a quick way to help create dependable and effective HESS for several uses. The FLC can be further customised and enhanced to fit the specific needs of various energy storage systems and vehicles.

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Ethics and Consent Statement: The research was carried out in compliance with ethical standards, and informed consent was obtained from all relevant participants prior to data collection.

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