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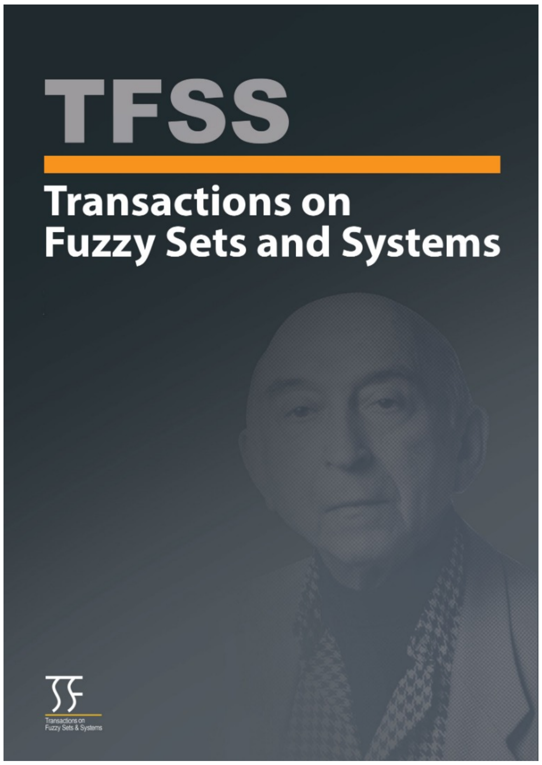

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Power Split Strategy Using Cascaded Fuzzy Control in a Hybrid Electric Vehicle

Eshan Samanta*, **Samarjit Kar**, **Anupam De**

Abstract. In the present scenario, the research outcomes related to hybrid electric vehicles are highly dominating the entire novelty sector. Initially, the long-term operation of electric vehicles was found to be ineffective in the case of electric vehicles (EVs), and then only the hybrid concept was encapsulated. Now, it is a real challenge to control the power split strategy for an ideal run and an economical run as well. Many papers explored and investigated with a few novel initiatives indeed. In this paper, one of the most unique analyses has been discussed by considering rotational inertia and angular displacement of the wheel in the case of running on a battery only. On the other hand, based on the battery state of charge (SOC), battery ampere, as well as power splitting takes place between the battery and the internal combustion engine. The entire concept is described in this paper using a type 1 fuzzy logic controller (FLC) by incorporating Triplets as membership functions (MFs). In this work, the centre of area (COA) method is used for defuzzification. In this work, cascaded fuzzy is introduced as an Artificial Intelligence approach and applied in hybrid electric vehicles for intelligent optimum power splitting strategic planning. The study is theoretically constructed and validated using a few simulation-based results.

AMS Subject Classification 2020: 03B52; 94D05
Keywords and Phrases: Cascaded fuzzy, Battery management, Electric vehicles, Intelligent power split, State of charge.

1 Introduction

In the present scenario, research related to hybrid vehicles is flourishing globally. For a long time many researchers have been working on it by considering fuzzy logic controller as one of the approaches to control specific operations especially the power split of electric vehicles as discussed in [1, 2, 3]. In these articles the authors have discussed considering a series hybrid electric vehicle. Here the fuzzy logic controller takes fuel consumption and fuel emission for constant state of charge (SOC) control. However it is true that the power split mechanism of any Hybrid Electric Vehicle (HEV) actually consists of a planetary gear and thus makes it smoother indeed [4]. The power split control based on battery working state (BWS) is also considered and discussed previously in [5]. In [5], the authors have discussed most of the parameters of the battery cell incorporated for propelling the vehicle. The fuzzy logic management system was tested in real time using an HEV simulation test bench with a real battery in the loop. In order to reduce driving cost a novel energy management system is proposed using a deep learning and discussed [6, 7]. To ensure a good fuel economy battery SOC has been maintained using deep learning approach. To enhance the battery life many proposed techniques are discussed using several optimization theories for introducing an improved

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battery management system (BMS) [8, 9, 10, 11]. In these articles also mostly SOC control has been focused which is very common indeed but restricted to plug-in hybrid vehicles. Many intelligent algorithms have been proposed to control power flow management in electric vehicles [12, 13, 14, 15, 16, 17]. But it is also seen that a few challenges interrupt the battery charging mechanism [18]. This might be an interesting troubleshooting section that could lead to a better optimized electric vehicle in the future era. In [18], the neural network approach's characteristic is that it optimizes two crucial hyper-parameters in order to attain a respectable mean absolute percentage error (MAPE). Two datasets for driving conditions in cities are used to demonstrate the effectiveness of the suggested approach. That means unnecessary charging and discharging are one of the most common scenarios that interrupt optimum performance in terms of SOC for a reliable BMS.

Apart from these the most challenging prospects are the availability of a charging station or the installation cost indeed [19]. In India, implementation of [19] is almost next to impossible as the manuscript ensures a fuzzy based automated queuing system manager to coordinate the entire charging station with an optimum time management. Another serious concern is the size of the battery required to be installed to avoid frequent charging requirements. But this problem was earlier discussed by Jeon et al. in 2021 [20]. Many alternatives have been explored and discussed to resolve the issues related to the battery management system for better reliability of electric vehicles[8, 11]. Rather, it is decided to think of an optimum solution which is independent of charging station and free from complex engineering so that it might ensure a better service and reliable performance under a nominal budget. Prior works lack a systematic framework for co-optimizing SOC stability and fuel economy in HEVs under dynamic driving conditions using cascaded fuzzy logic.

In this paper, a new set of fuzzy inference systems (FIS) has been developed using the cascaded fuzzy technique [21] for hybrid electric vehicles (HEV) to improve battery SOC and fuel efficiency [22] as well. Here, both trapezoidal and triangular membership functions are taken into consideration when designing the output membership function. Two fuzzy inference systems (FIS) were used in the development of this comprehensive design in order to perform various jobs and achieve certain goals. Both the battery management system and the fuel economy section are examined concurrently for the comprehensive analysis.

This paper has two main contributions: 1) A solution is discussed for both fuel optimization and battery management systems in the case of HEV. and, 2) Proposed a novel idea of a multistage cascaded intelligent power split controller.

The rest of the paper presents the same by framing the sections with the proposed method, results and discussions, and subsections framed with cascaded fuzzy, power split controller, fuzzy system rules, membership function, result and discussion as well as future research direction. Finally, the main conclusion and contributions have been discussed in Section 5.

2 Proposed Method

The proposed method consists of the linguistic variable based decision making rules for a Parallel Hybrid Electric Vehicle (PHEV). We have considered an intelligent protection system based on a fuzzy algorithm. But this time a novel approach is considered by introducing a cascaded fuzzy approach. In this work, just two distinctive FISs are considered and designed for the entire power split controller for HEV. Twelve rules in all have been established by taking into account six rules for every FIS. Triplets and Gaussian membership functions are used in the formulation of these rules. Two black boxes are combined in the design of the overall controller system, and one of the engines is then fed to regulate the rate at which the batteries charge. The other one is developed by accessing the battery SOC and battery current rating to control the throttle of the carburetor. The overall work is carried out using the MATLAB 2020 environment for validating the developed intelligent algorithm for a power split control system in modern HEV. The purpose of this work is to introduce the cascaded fuzzy technique to control both fuel efficiency and battery health as well. The key elements of the approach have been covered in the ensuing subsections.

An overall analysis is conducted to differentiate between different angular velocities and rpm in terms of charging ability and fuel optimization with the cascaded fuzzy system, respectively, taking into account the simulation model as displayed in Fig. 4. The SOC expression can be found in equation (1). The current data collected in the first step is accumulated as per Table 3 and then added to the SOC calculated in the previous step, thereby calculating the SOC1. The calculation is carried out by integrating the current over time. A calculated result is divided by a whole capacity, and then the rest capacity is expressed as a percentage. This is expressed as in equation (3). In equation (2) SOC% is evaluated for calculating the state of charge due to battery ampere. In the SOC measuring method as shown in equation (1), since the current is detected every second, the equation (2) may be expressed in equation (4). The calculation of SOCi in a step k is performed by accumulating the current flowed in the step k to the SOC in a step k-1 with respect to a reference time of 1 second since the current flowed in the step k is divided by the whole capacity. A method of measuring the SOC of a battery in a battery management system is shown in equation (5).

$$SOC(t) = SOC(t-1) + \int_0^t (\frac{I}{C_{Batt}})dt \tag{1}$$

$$SOC\% = \frac{RemainingCapacityAh}{NominalCapacityAh} \times 100 \tag{2}$$

$$SOC_i = \int (\frac{I}{Ah_{Nominal}})dt \times 100 \tag{3}$$

$$SOC_iK = SOC(K-1) + (\frac{1}{Q_{max}}) \cdot Ik \cdot t \tag{4}$$

$$SOC(t) = SOC(t-1) + \delta SOC_i + gain \times \delta SOC \tag{5}$$

Where,

$$\begin{aligned} SOC(t) &= SOC\,of\,the\,battery\,at\,the\,present\,time; \\ SOC(t-1) &= SOC\,of\,the\,battery\,at\,the\,previous\,time; \\ \delta SOC_i &= I \cdot (t) \times (\frac{T_s}{Capa}) \times 100 \\ T_s &= Current\,Sampling\,Period; \\ Capa &= Rated\,capacity\,of\,the\,battery; \end{aligned}$$

The battery current usually depends on how fast the DC motor shaft is rotating and charging the same via a back to back DC-DC converter. The differential itself rotates the motor shaft as the wheels will be rolling on the floor. That is why entire work is carried out by controlling the speed of the wheel which is actually monitoring the battery current and on the other hand the same current and concerned SOC is considered for controlling the throttle of the carburetor of the specific connected IC engine. The entire concept is developed considering PHEV only and the concerned key parameters and driving cycles are given in Tables 1 & 2.

2.1 Cascaded Fuzzy - An Overview

The concept of cascaded was first proposed in the year 2020 by samonto et al. [21]. The process of differentiating any complex decision into multiple numbers of FIS is finally termed as cascaded fuzzy. When constructing any intelligent system with a fuzzy logic controller, the system is referred to as a cascaded fuzzy system if the FIS calling theory is applied. Since the system is designed with many FIS, the first FIS is considered to be Stage I, and the remaining cascaded FIS are designated as Stages II, III, and so on, up to the *n-th stage*. As a result, another name for this specific design is a multistage cascaded fuzzy system. The

Table 1: Key system parameters for PHEV

Component	Specification
Internal Combustion Engine (ICE)	4-cylinder SI engine, 1.8L, max power 90 kW @ 6000 rpm
Electric Motor	Permanent Magnet Synchronous Motor (PMSM), 60 kW, max torque 180 Nm
Battery Pack	Li-ion, 288 V nominal, capacity = 1.5 kWh
Battery Model	Equivalent circuit model with SOC estimation
Transmission	e-CVT or fixed gear ratio
Final Drive Ratio	4.1
Vehicle Mass	1450 kg (including passengers and fuel)
Regenerative Braking	Enabled, 70% efficiency
Rolling Resistance Coeff.	0.012
Frontal Area	2.3 m
Drag Coefficient	0.28
Wheel Radius	0.3 m

Table 2: Driving cycle used

Driving Cycle	Details
UDDS (Urban Dynamometer Driving Schedule)	Avg speed ∼31.5 km/h; stop-and-go city cycle; 1369 s
HWFET (Highway Fuel Economy Test)	Avg speed ∼77.7 km/h; smooth acceleration; 765 s

entire concept is shown in Fig. 1. In Fig. 1, the overall working of the cascaded fuzzy system is explained by considering [21] as a reference for a better understanding of the entire work flow. The First stage (Stage I) accepts sensor data from both angular displacement and RPM. In the meantime, it processes the data within the black box to ensure a quality battery current for a reliable battery mode operation. In the second stage this battery current along with battery SOC is fed to the stage II black box for a premium fuel mileage by controlling the throttle valve of the carburetor. This unique feature of the cascaded approach has not yet been explored in the era of HEV so far.

The application of the cascaded concept in the proposed approach of this present work is much reliable and novel. Most of the article is considering Battery Management System (BMS) as the most unique parameter to enhance the EVs efficiency for the long run and charge restoring plan for both petrol [5, 6, 7, 8], and diesel engines [22]. But here, dual integration of the fuzzy engine is introduced for controlling the throttle valve of the engine and the battery charging mechanism. An engine valve ensures better fuel management and a charge controller confirms the optimum SOC of a battery in an intelligent hybrid electric vehicle technology. The entire concept is shown in Fig. 2.

In Fig. 2, RPM and angular displacement are considered as input to FIS I and finally it is developed to control the charging mechanism of the battery by controlling battery current. On the other side, FIS II is designed to control the fuel injection for optimum balance between petrol and battery drainage. Here, in Fig. 2, the dark line indicates the final controlling output, whereas, the rest of the lines are the links between the individual components of an intelligent power splitter incorporated into Hybrid Electric Vehicle (HEV). Here, FIS I ensures battery current which in turn feeds to FIS II for quality fuel optimization by controlling the throttle valve. This in turn ensures a reliable transmission system to drive wheels and again the same is fed back to stage I. Likewise here FIS I receives the input from the sensor connected to the wheels for continuous monitoring.

In the case of a typical single stage fuzzy logic control (FLC) system it is rare and almost impossible to implement in controlling any system that is run by any dynamic and varying parameters. Here, let us discuss in brief. Suppose in the case of this proposed work, RPM and angular displacement have been considered

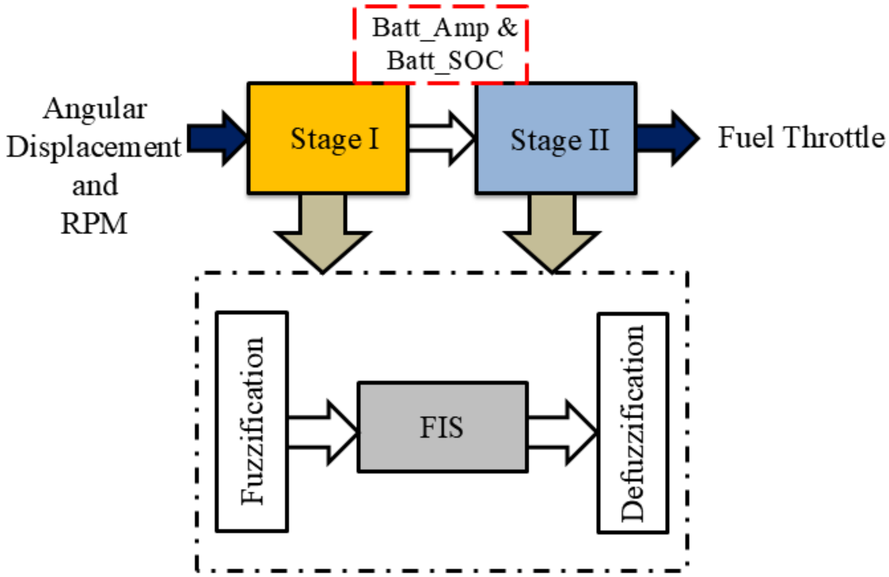


Figure 1: Block diagram of cascaded intelligent power split control mechanism showing internal operation of Stage I and Stage II with a dotted border as provided in [21]

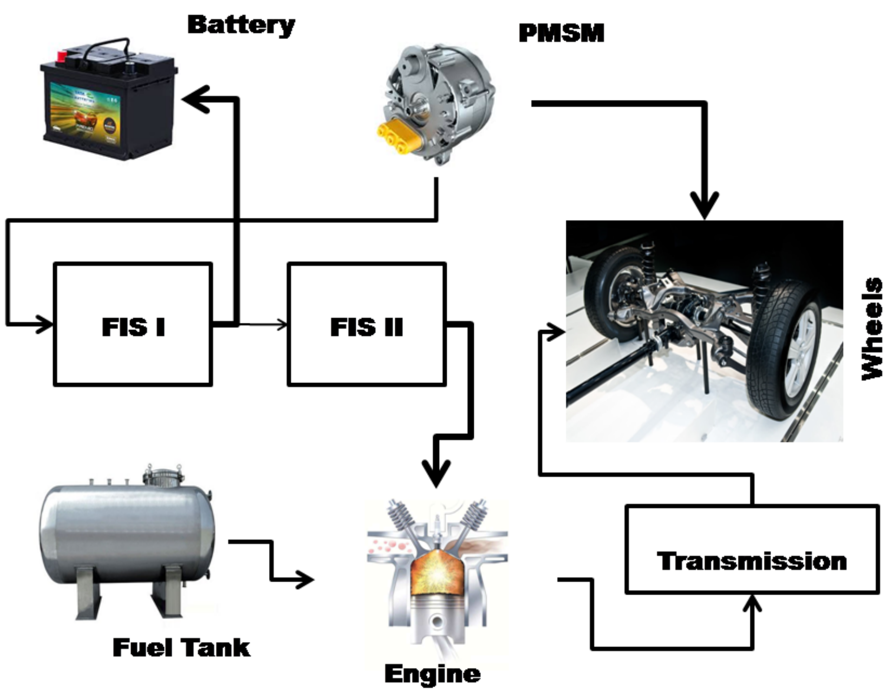


Figure 2: Schematic diagram of cascaded intelligent power split control mechanism

as input. On the other side, Fuel injecting throttle and Battery SOC are the two back to back simultaneous output fetched from black box after defuzzification of the entire crisp set of values. This is actually impossible in case of single stage FLC network. But, if we consider other applications like ANFIS, NN then compared to those approaches cascaded fuzzy is more simpler and less expensive as well. Considering this framework and simplicity, the rest of the control strategies are incapable of balancing SOC and fuel efficiency simultaneously.

2.2 Power Split Controller

The previous models of power split fuzzy controllers are designed to monitor the battery SOC and other parameters to split the desired power between the engine/generator set and the batteries instantaneously [23, 24]. Yavasoglu et al. proposed a novel power train mechanism using two propulsion machines by introducing a hybrid energy storage system [25]. PI controller has been introduced by cipek et al. for designing a low-level electric generator speed control loop [26]. Liu et al. proposed two control algorithms are introduced: one based on the stochastic dynamic programming method, and the other based on the equivalent consumption minimization strategy [27]. Engine operation optimization is done by considering the overall vehicle efficiency and considerable engine power as well. Analysis of the validation of the concerned algorithm designed for the intelligent power split controller is done by implementing the cascaded fuzzy technique, as shown in Fig. 4. An artificial fuzzy based controller is introduced in this work. Many researchers have explored fuzzy in power split controlling scheme [16, 28], but, in this paper a novel concept using cascaded fuzzy technique is introduced and discussed. It is very important to consider SOC of batteries firstly because SOC is related

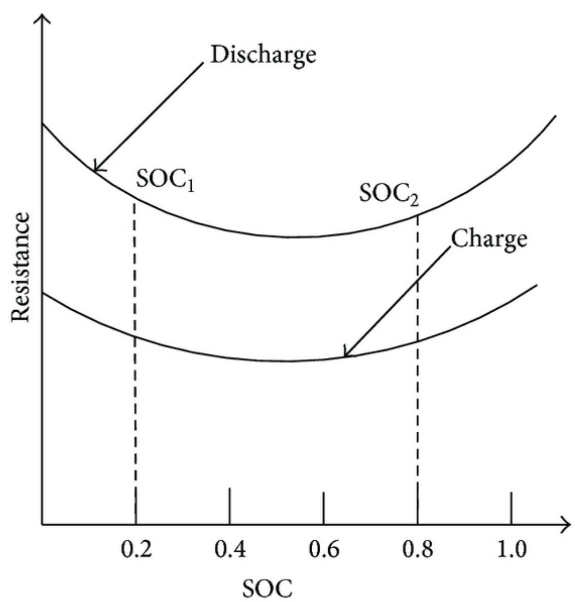


Figure 3: Resistance curve corresponding to SOC [24]

to the ICE output torque. The resistance curves and the voltage curve corresponding to SOC of the single NI-MH battery used in this study are shown in Fig. 3. To ensure the batteries charging/discharging efficiency, we define that, when SOC is over 0.8, the ICE must be stopped to avoid the overcharging the batteries. When SOC is lower than 0.2, the ICE must be started to avoid the over-discharge of batteries.

$$k1T_{isg} = T_{elec} = T^{req}{}_{ice} - T^{act}{}_{ice} \tag{6}$$
$$k1T_{isg} + k2T_{emg} = T_{elec} = T^{req}{}_{ice} - T^{act}{}_{ice} \tag{7}$$
$$k1T_{isg} + k2T_{emg} = T_{elec} = T^{req}{}_{ice} - T^{opt}{}_{ice} \tag{8}$$
$$\omega_{isg} = k1\omega_{ice}, \omega_{emg} = k2\omega_{ice}, T^{opt}{}_{ice} \neq 0 \tag{9}$$
$$k2\omega_{isg} = k1\omega_{emg}, T^{opt}{}_{ice} = 0 \tag{10}$$

where, $\beta = 15.9155$, $\gamma = 10^{-6}$, $\delta = 10^{-3}$.

Where,

$$\begin{aligned}
T_{isg} &= Output\,torque\,from\,the\,ISG;\\
T_{elec} &= Output\,torque\,of\,the\,electrical\,system;\\
T_{ice}^{req} &= Torque\,demand\,on\,the\,ICE;\\
T_{ice}^{opt} &= Optimum\,output\,torque\,of\,the\,ICE\\
T_{ice}^{opt} &= 0;\\
T_{emg} &= Output\,torque\,from\,the\,EMG;\\
\omega_{isg} &= Speed\,demand\,on\,the\,ISG;\\
\omega_{ise} &= Actual\,speed\,of\,the\,ICE,\\
\omega_{emg} &= speed\,demand\,on\,the\,EMG.
\end{aligned}$$

When the internal combustion engine (ICE) is stopped, the optimum output torque of the ICE should be zero. The actual speed of the ICE depends on the power-split HEV speed and the gear ratios. k1 and k2 are the gear ratios. In this work, all these conditions are incorporated and discussed using a fuzzy black box and presented in the rest of the sections.

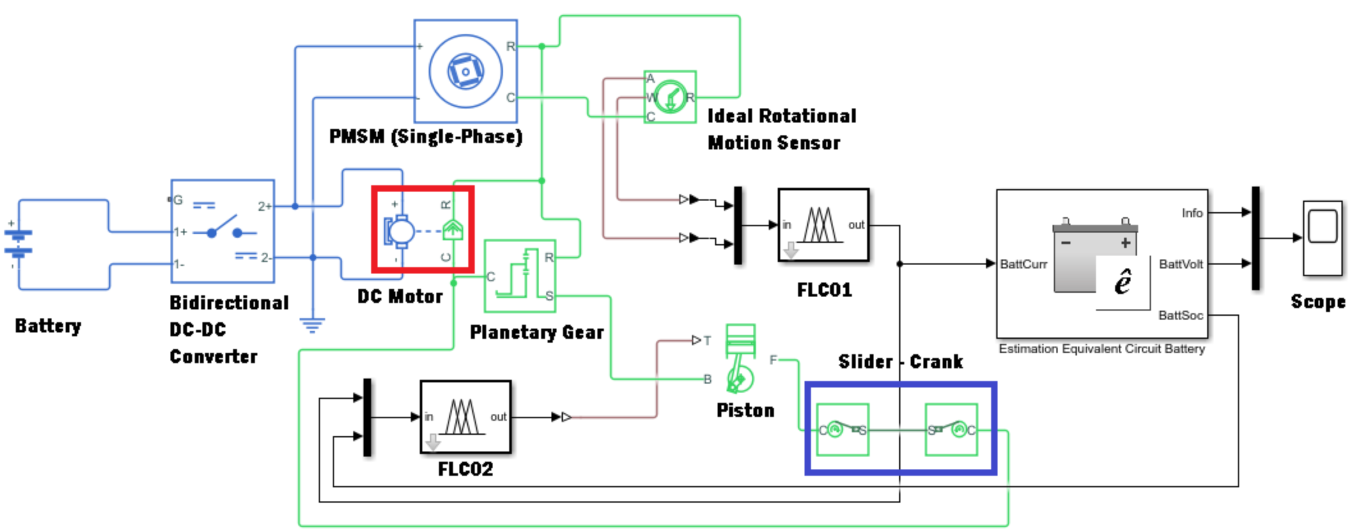


Figure 4: Simulation model of proposed power split controller

Table 3: Battery parameter values for the proposed HEV system

Parameter	Symbol / Unit	Value	Justification
Nominal Capacity	$Ah_{Nominal}$	**5.2 Ah**	Matches typical hybrid packs (not EV); designed for power assist, not long range.
Battery Energy	E_{Batt}	**1.5 kWh**	Sufficient for regenerative braking and low-speed electric drive.
Internal Resistance	R_{int} (Ohm)	**0.05 Ohm (per cell)**	Impacts heat generation and voltage drop; low value ensures better efficiency.
Number of Cells	-	**240 (1.2 V per cell)**	Based on voltage and chemistry (e.g., NiMH or Li-ion).
Cell Capacity	C_{cell}	**5.2 Ah**	Cells selected to match pack capacity and current draw requirements.
SOC Operating Range	-	**4080%**	Prevents over-discharge/charge; increases battery life.

2.3 Fuzzy System Rules

The cascaded fuzzy algorithm is basically not a singular mode of rules set. Overall, 12 rules have been introduced. These rules are separately designed for two different fuzzy logic black box. Among these rules, effective target is to control both the battery current and carburetor throttle as well. These controls required a separate set of rules implemented in two different fuzzy logic controllers. The complete regulations are explained in Table 5. The learning rules in this suggested system are designed using if-then logic only.

Table 4: Indication of the allotted membership functions designed for the proposed HEV system

Membership Functions	Indications
Very Low	VL
Moderate Low	ML
Moderate High	MH
Very High	VH
Positive Displacement	positive
Negative Displacement	negative
Low RPM	Low
Moderate RPM	Moderate
High RPM	High
Low Batt SOC	Low
Medium Batt SOC	Medium
High Batt SOC	High
Carburettor Throttle Open	Open
Carburettor Throttle Close	Close

The complete list of rule abbreviations used in the design of the relevant intelligent power split controller is explained in Table 4. These rules are developed for FLC01 to achieve the next input to FLC02 of the cascaded intelligent electric hybrid vehicles. The rules are designed in the following manner like, for example,"if RPM is Moderate and Angular Displacement is Positive then the command for the next stage battery current i.e. FLC02 is Moderate High", again "if the Battery current is Very High and battery SOC is Medium then the command to the throttle is close the system".

Let us take one example for better clarity. In case during the initial stage when the vehicle is at standstill condition. Just at the beginning the vehicle will start using fuel only and once it reaches to a certain momentum right then just focus on the rules that have been declared just few lines earlier. When the momentum is just gained and at that time RPM is Moderate, again in the same way vehicle is running forward and Angular Displacement is Positive. Now just move towards the output side. The battery current has to be moderately high as the vehicle is not at its full speed. This ensures the rules like battery current i.e. FLC02 are Moderate High. This in turn keeps SOC medium and due to this, the throttle is close. This is how the system will work logically in case of real world interfacing.

2.4 Membership Function & Surface View

In this section, a detailed analysis of the membership functions (MF) is carried out for FLC01 of cascaded power split controller. In Fig. 5, the MF of RPM is designed by considering triplets only. This specific selection is made for some certain reason to introduce proper switching of algorithm during real world system interaction. This is because as the vehicle is under continuous monitoring scenario in that RPM varies in a fast manner and the same has to be considered by the black box itself. This is way the triplets are deputed

Table 5: Rules configuration set for optimized fuel efficiency of proposed EHV model

Throttle		**Battery SOC**		
		Low	**Medium**	**High**
B Current	VH	Open	Close	Close
	MH	Open	No Change	Close
	ML	Open	Open	Close
	VL	Open	Close	Close

Table 6: Rules configuration set for optimized battery performance of proposed EHV model

Speed		**A Displacement**		
		Negative	**None**	**Positive**
RPM	High	VL	VL	VH
	Okay	MH	No Change	ML
	Low	VL	No Change	VL

so as to perform membership functions for RPM indeed. It is true that for any instant decision triangular function is considered to be the best choice [23]. The 'Low' membership function is taken as a narrow because only 20% are to be considered for slow speed as in this case battery current is directly associated with the speed of the vehicle. This is perfectly allied with the condition in case when the HEV is running using battery only.

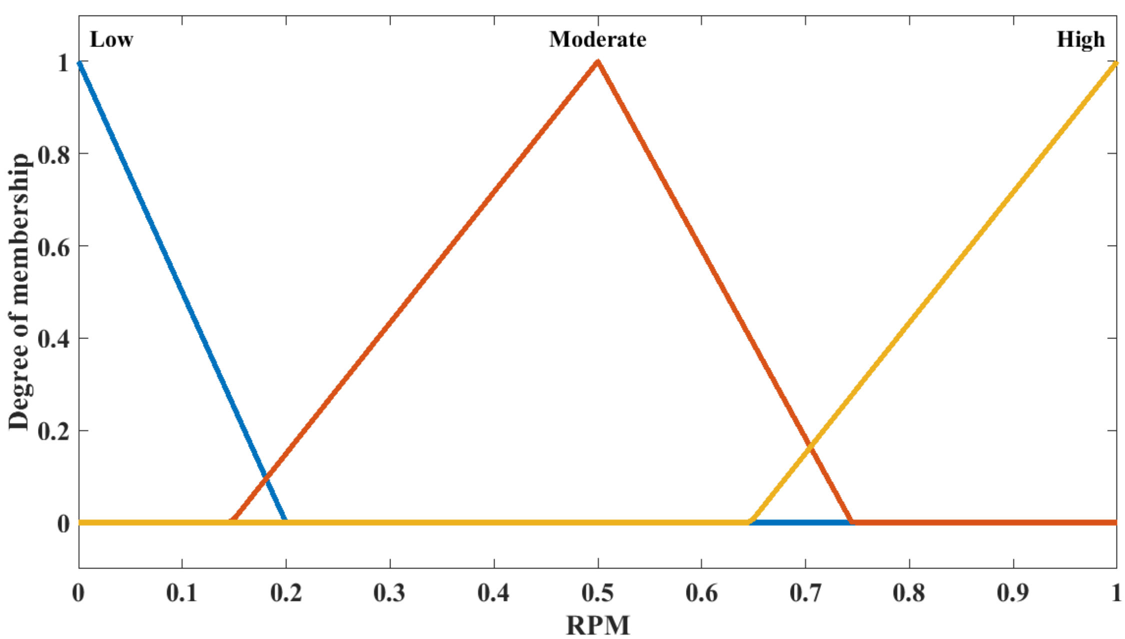


Figure 5: First input membership function of FLC01

The 'Moderate' MF is considered from 15% to 75%. The final 25% is taken into account as 'High' MF to design the concerned RPM MFs. The objective of designing the same is to check the speed of HEV in case when the driving mechanism is following the source from battery only. Similarly, in Fig. 6 it is observed that the MFs for angular displacement of the wheel is taken as 'negative' for counter clockwise rotation ad 'positive' for clockwise rotation only. The 'no change' MF is introduced just to make aware of the fact in case if the wheel is static somehow in any case. The range of all potential input values for a fuzzy system is known as the Universe of Discourse. Any set that permits its members to have varying membership grades within the interval [0,1] is referred to as a fuzzy set. In this case, it is essential to implement a Gaussian function during displacement analysis as the concerned angular displacement is too dynamic and uncertain in nature as it reflects the speed of the vehicle as well . Since the analysis has to be sensitive and will be predicted if the error comes in negative or might be positive based on clockwise and counterclockwise direction and thus, the interval [-0.1,0.1] is referred to as a fuzzy set in this case only. The output section of the FLC01 is

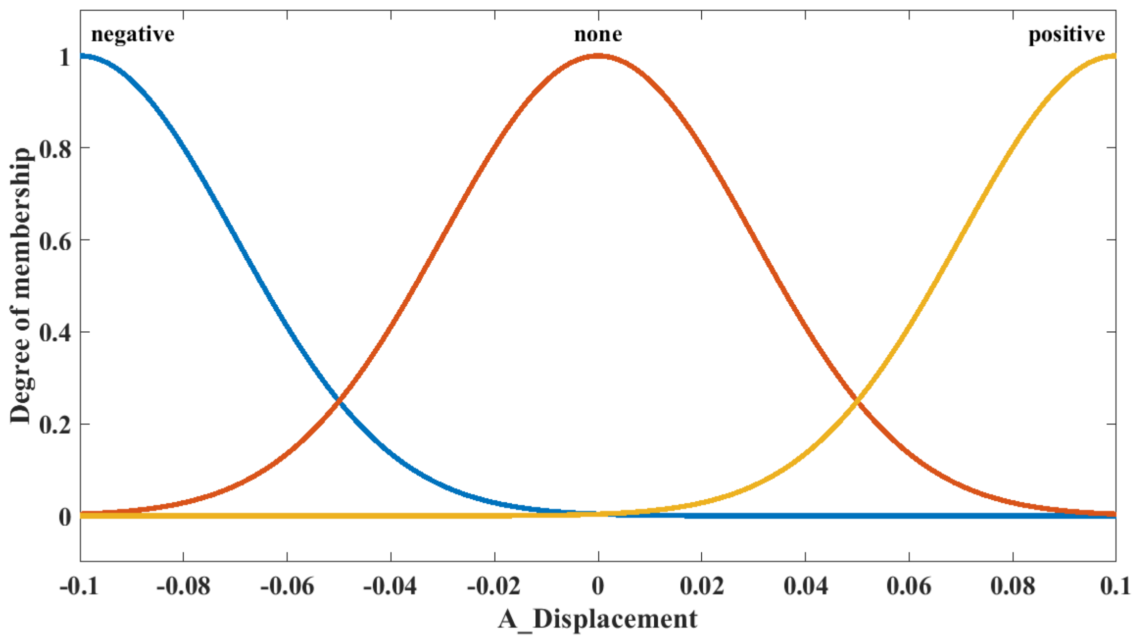


Figure 6: Second input membership function of FLC01

given in Fig. 7. Here, the universe of discourse is considered same as that of input sections. MFs are taken steeper just to trigger the switching mechanism to draw battery current. This has to be instant for better transient response and to prevent switching loss as well. Since, the output of the FLC01 feeds the output to the FLC02 for controlling throttle of the carburetor to optimize the fuel efficiency. Thus, the first input MF incorporated for FLC02 is same as FLC01 output section, the only difference is the elimination of 'No Change' MF as shown in Fig. 8. The second input to the FLC02 is considered battery SOC and the same is designed by introducing trapezoidal MF to promote sustainability and to predict the specific SOC. Here, overlapping is considered based on certain points like firstly, the threshold percentage has been adopted to set 50% in this case. The degree of interaction is considered to be just 5% to 10% only. This concerned SOC is highly dependent on battery current as discussed in eq. 1. The same set of MFs are discussed earlier is presented in Fig. 9. A clear picture of output section of FLC02 is given in Fig. 10. In Fig. 11, it is clearly presented that if RPM is high then battery current is also very high. This is very natural as to propel the entire vehicle in case of battery driven mode maximum ampere is naturally required to generate torque for a certain amount of angular displacement indeed. On the other hand, Fig. 12 ensures that if battery current is minimum battery SOC is maximum or sometimes viceversa as well. Likewise, in this section the concerned MFs are designed in such a way that they will control the throttle only if fuel is required to be injected as like FI technology. In some cases to maintain an optimum fuel consumption and to achieve better efficiency as well the entire throttle might not effectively change its state. This is introduced by incorporating 'No Change' MF.

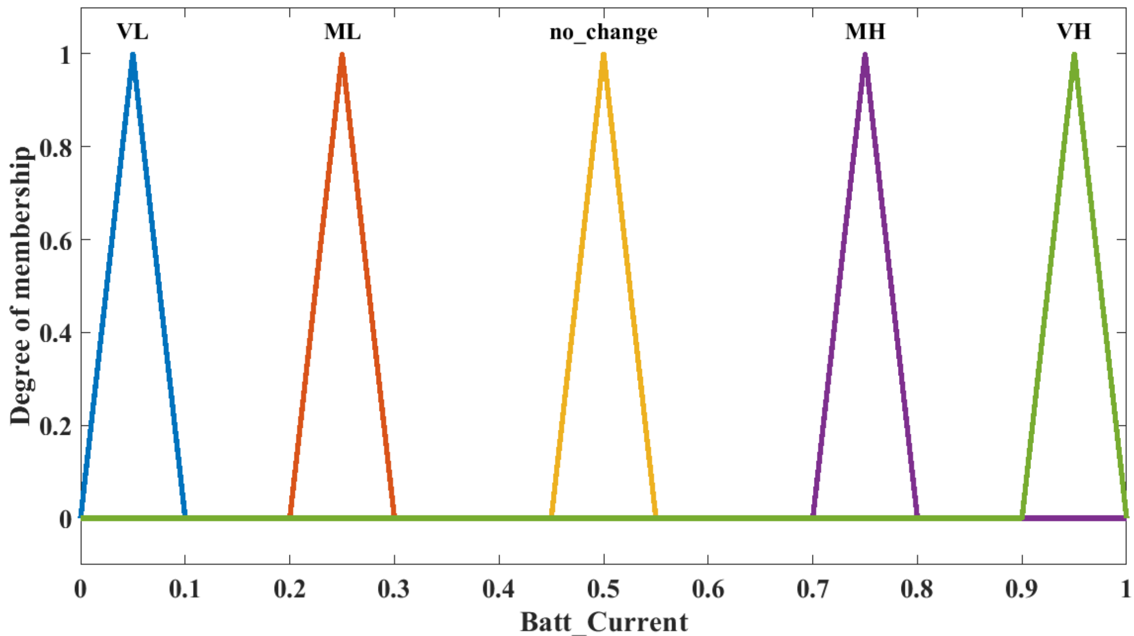


Figure 7: Output membership function of FLC01

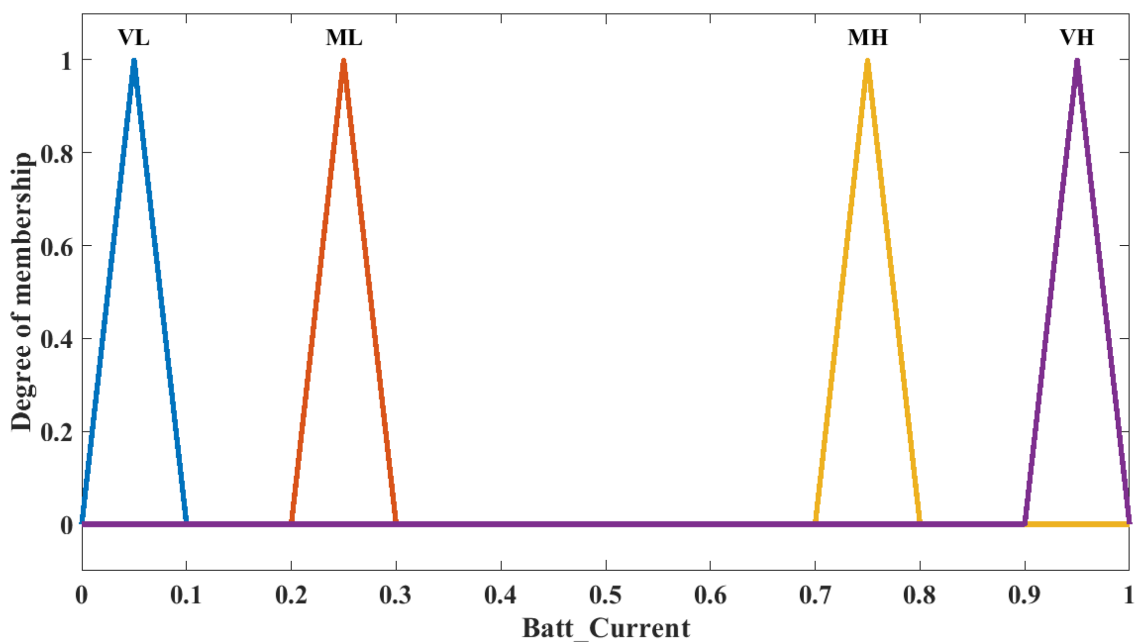


Figure 8: First input membership function of FLC02

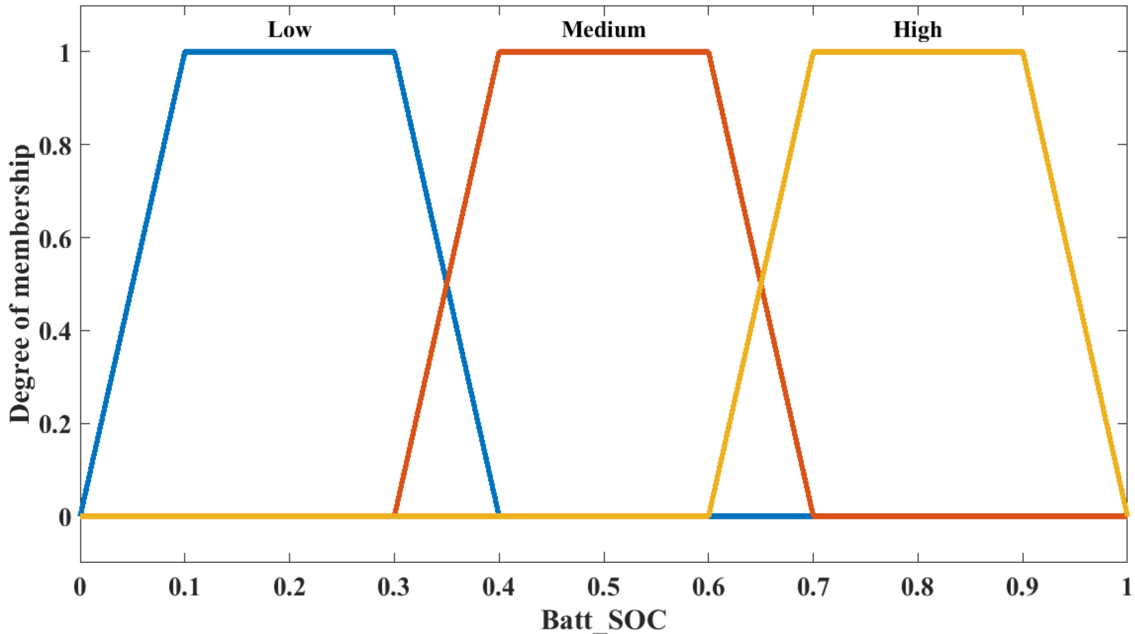


Figure 9: Second input membership function of FLC02

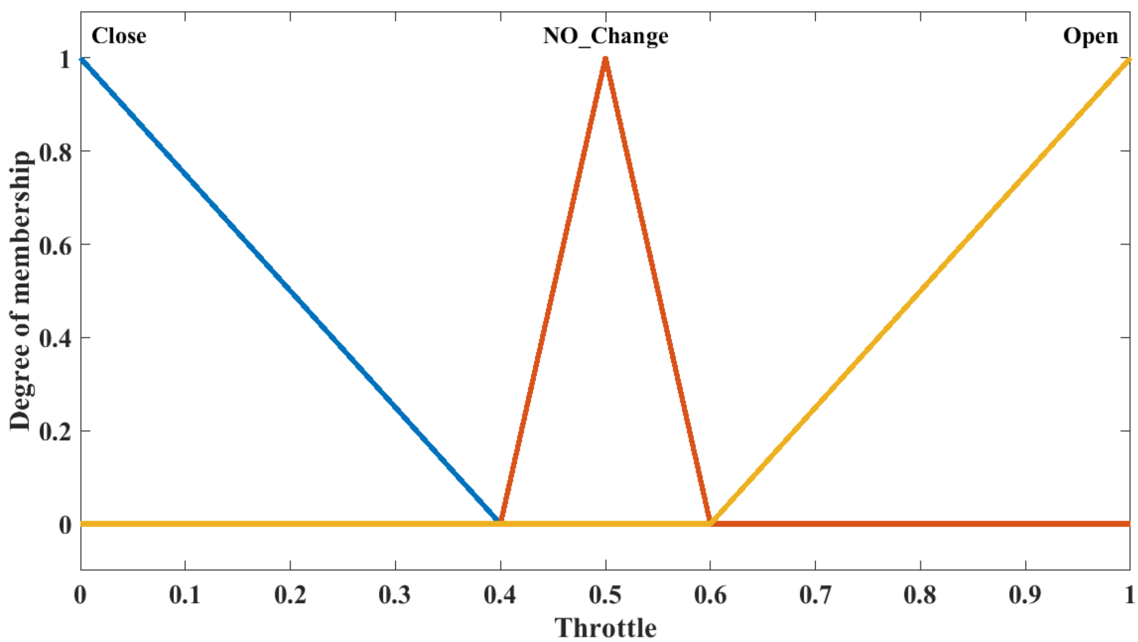


Figure 10: Output membership function of FLC02

3 Results and Discussions

In this section, a detailed analysis of the simulation results is presented. In Fig. 13 it is explained that how the throttle control is lagging the battery current. The distinguished facts are as follows. In the case of battery operated mode throttle is low enough in terms of universe of discourse and thus enough voltage is not generated to operate a solenoidal valve to control fuel injection to the carburetor. In Fig. 13, the difference

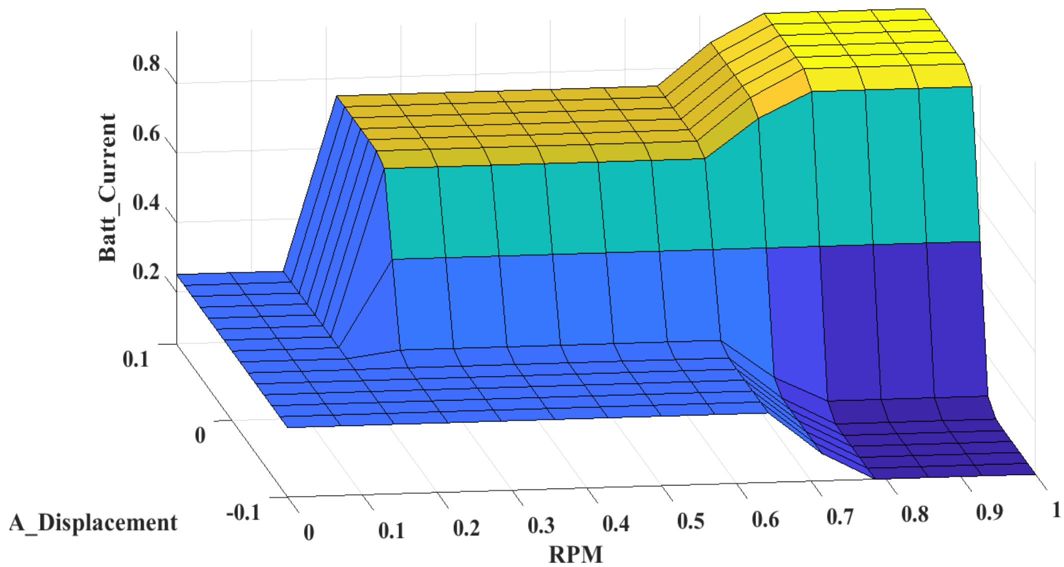


Figure 11: Surface view - battery current monitoring section

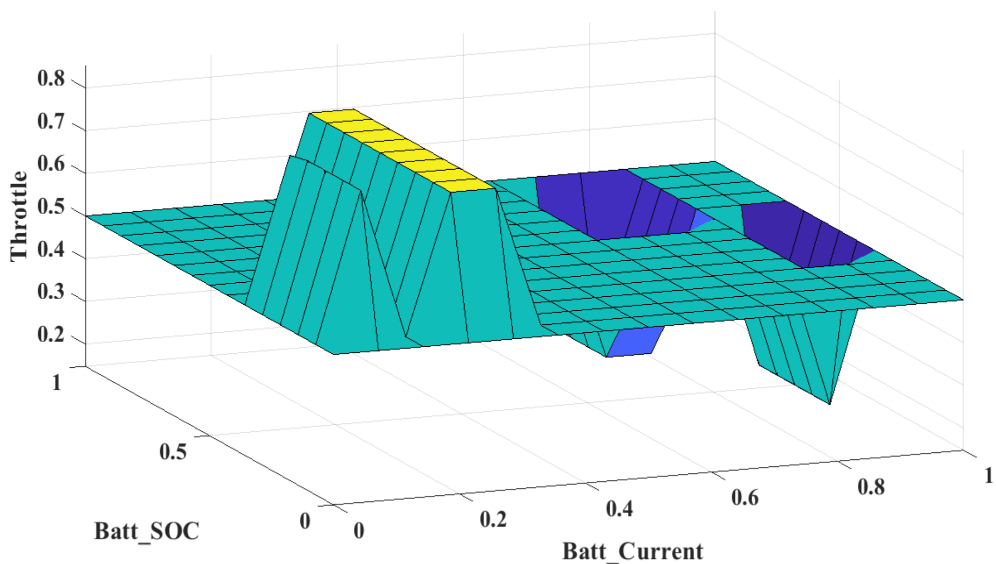


Figure 12: Surface view - throttle control of carburetor

scope is clearly ensuring that when the battery mode propels the vehicle consistently. In that case the throttle is not even operating unnecessarily. This is clearly shown in Fig. 13. From Figs. 14 and 15, it is very clear that the FLC based power splitter enhances the fuel optimization and battery efficiency as well of an HEV as well. In Fig. 15, it is clearly observed that initially battery current is zero as throttle is open for fuel injection to start the vehicle for saving battery fast discharge as in the case of initial state it will draw a huge ampere. After 3 seconds the battery current is gradually decreasing to zero. On the other hand, the throttle is high for battery optimization during gear shift only. Once the gear change is complete power is again shifting back to battery for better performance. Since battery powered propelling is independent of gear box. After 4 seconds

01.png 01.bb

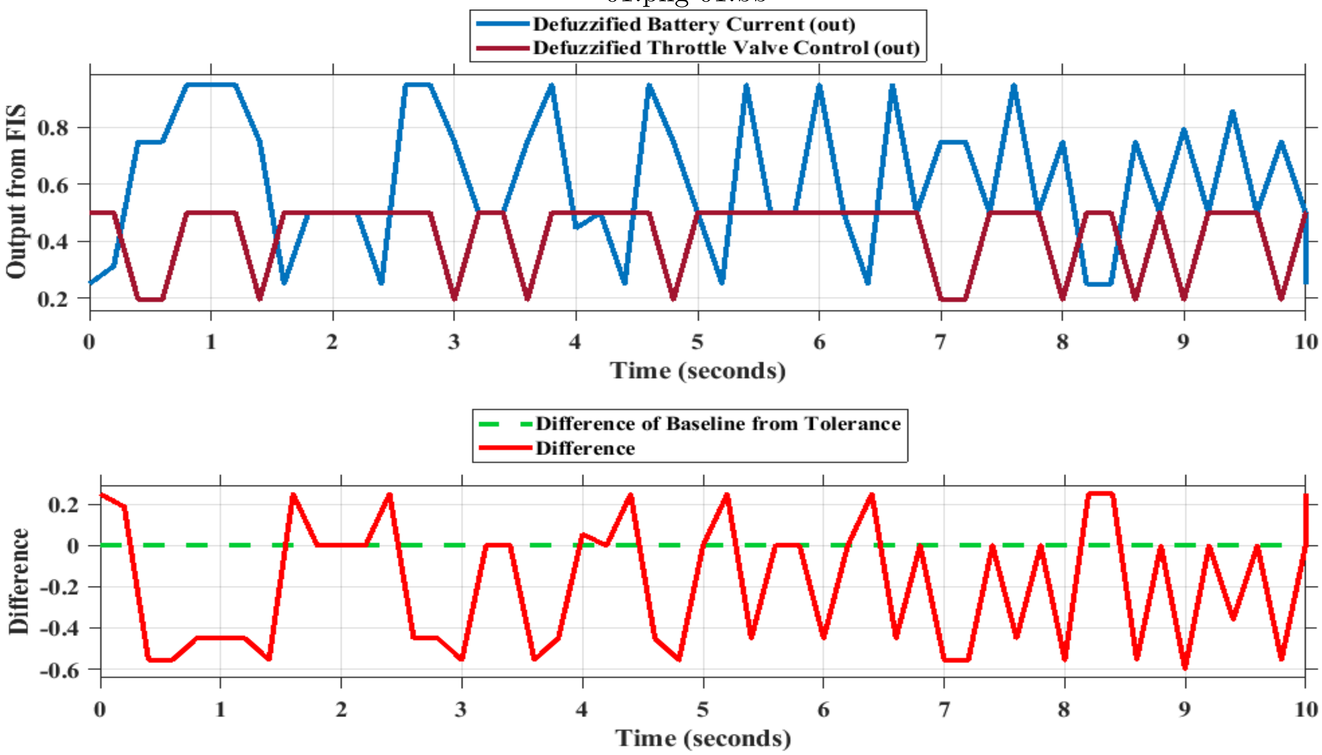
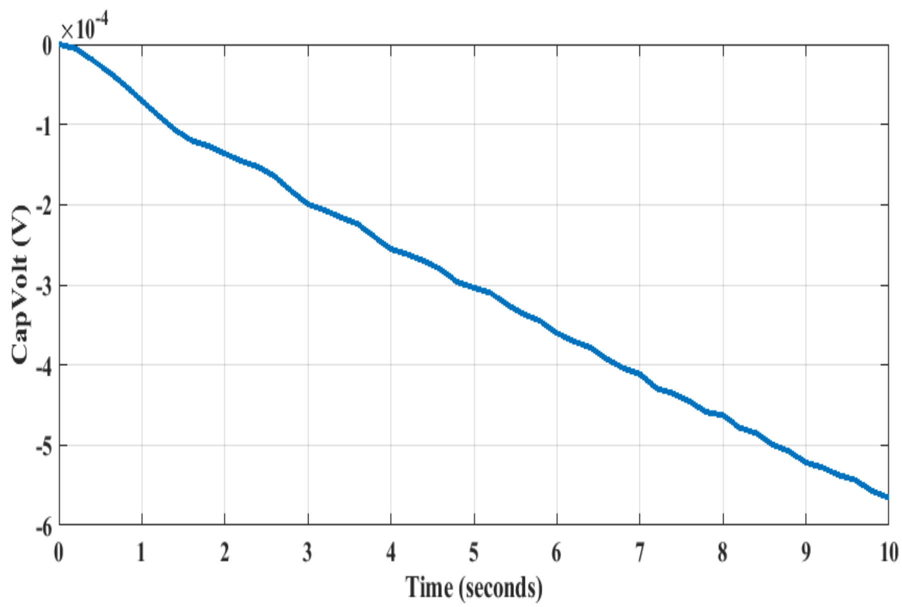


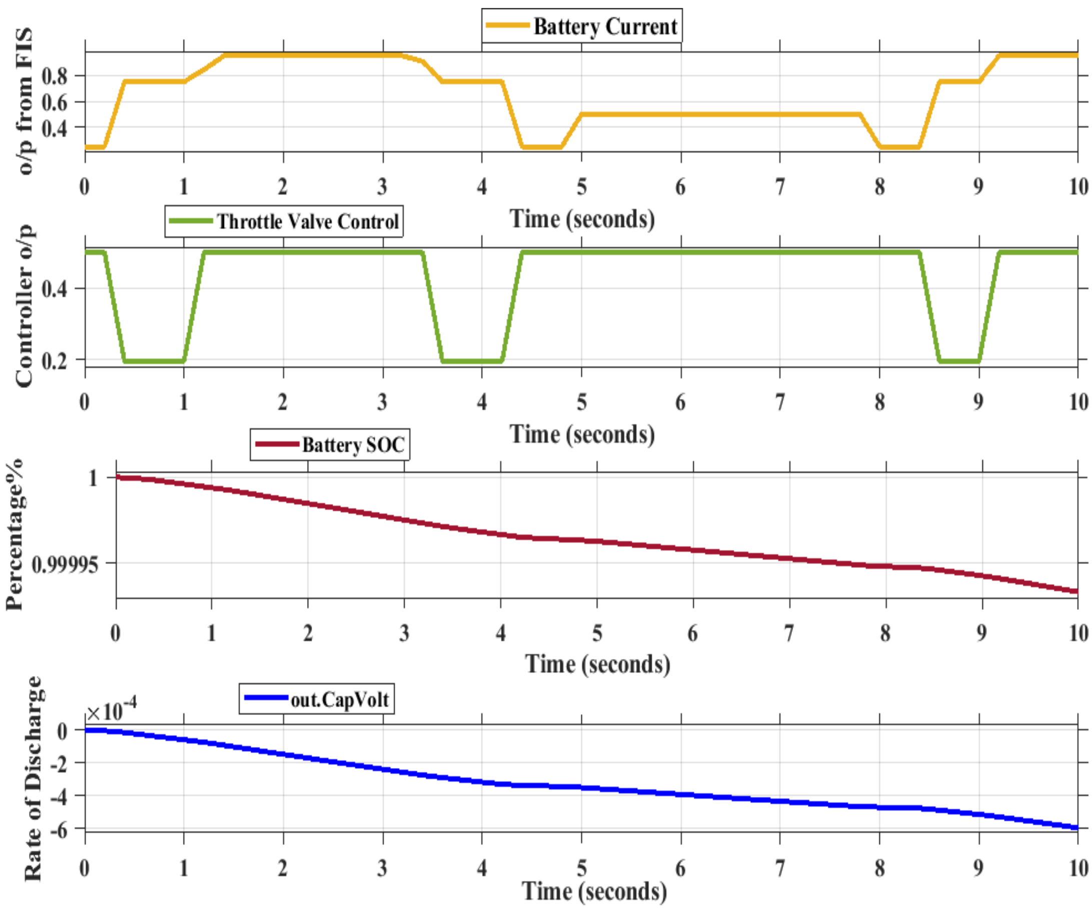
Figure 13: Simulation report - battery current & throttle control for fuel optimization



volt0.png volt0.bb

Figure 14: Capacitor voltage analysis for the proposed HEV model

battery is low enough and same as it shows in case of fuel injection due to the throttle valve opening. In Fig. 15, it is also clear that the battery SOC is somehow changing towards high peak slightly with a positive inclination during fuel injection. This ensures a better battery efficiency as compared to conventional EVs.



5000.png 5000.bb

Figure 15: Brief analysis of proposed HEV model after simulation

Interestingly it is also clear that in Fig. 15, the discharge of capacitor voltage is a bit different as compared to the battery SOC curve but negligible in terms of deviation.

Fig. 16, ensures that the existing EHV is comparatively a slightly unstable as compared to the proposed model. This is very clear after considering Figs. 15 and 16. In Fig. 16, energy efficiency is very unstable as compared to Fig. 15. In Fig. 15, throttle output ensures a consistent performance and this indicates a better response in terms of stable efficiency due to optimized battery backup with a stable SOC%.

Table 7, represents the comparative analysis of Battery SOC and fuel efficiency by considering the Fuzzy Logic Controller (FLC), Machine Learning (ML), Adaptive Neuro Fuzzy Inference System (ANFIS) and proposed cascaded concept of FLC. It is very true that fuel saving is much better in case of ML whereas battery SOC is not up to the mark as compared to the proposed methodology. It is also true that no such articles have discussed regarding the throttle valve control to optimize fuel consumption by reducing fuel engagement to a certain percentage.

Figs. 17 and 18 ensure the output after defuzzification from FIS02. FIS02 actually controls the throttle valve. From Fig. 17, it is clear that the throttle valve is not operated by the proposed controller. Firstly, it is also required to explain that the speed set for this particular scenario is minimum as compared to Fig. 18. As in Fig. 18 speed is set high and therefore the throttle valve is operating with the maximum number of spikes which indicates fuel engagement is high rather than battery operated vehicle propulsion. This automatically optimizes the battery SOC and overall efficiency of the vehicle. Fig. 19 clearly explains what exactly is happening in this proposed method during power shifting in case of speed variation. Here, in Fig. 19, between 120 sec and 140 sec there is an uncertain dip found while shifting the power during speed variation. This is actually happening due to a transient occurring during power shifting. Since, the system itself is following a strategic RBC baseline so in that case impact of switching transients is reflected on Battery SOC. This is also feasible as the proposed system is encapsulated using parallel hybrid vehicle. Frequent switching impact electrical losses and thus the performance might get degraded during heavy traffic or in any busy urban area eventually. That is why the battery is draining a bit faster as compared to normal operation during an economy mode speed followed by the vehicle.

In Table 7, it is clearly shown how this proposed concept is dominating over the rest of the state of the art approach. Now, the question is why it is showing a better outcome as compared to the rest of the approaches. The simple answer is Rule-Based Control (RBC) baseline strategy implemented in this work. The benefits are as follows as compared to other like static rules, deterministic, low computational cost and easy to implement as well. The proposed base line strategy ensures dual parameter (SOC and Fuel optimization) control mechanism. This dual mode back to back cascaded form of connected FLC, which depends on each other identified this proposed method as a cascaded FLC based approach. Since, the throttle is controlled by FLC and thus it is giving an optimum level of fuel efficiency which is actually reflecting a high SOC percentage as well in return. This return is actually missing in the rest of the approaches.

Algorithm 1 Pseudo-code of Cascaded HEV

```
Require: SOC ≥ 97%
Ensure: RPM ≥ 1
  SOC ← FLC01
  Throttle ← FLC02
  SOC% ← Cascaded
  while RPM ≠ 0 do
      if RPM is High then
          Throttle ← FLC02
          SOC ← Optimized                    ▷ Intelligent Power Splitter
      else if RPM is Economic then
          SOC ← FLC01
          SOC% ← Cascaded
      end if
  end while
```

Table 7: Analysis report of battery SOC and fuel efficiency with respect to state of art approach

Sl. No.	State of Art Approach	Battery SOC	Fuel Efficiency	Conclusion
1	FLC [5, ?, 27]	Approx 55%	Negligible Reduction	Mostly designed to protect over discharging
2	ML [?, 7]	Approx 20.64%	57% Reduction	This ensures a slower discharge and better sustainability
3	ANFIS [12, 17]	Approx 54.9%	14.36% Reduction	Small changes in battery SOC and better fuel optimization
4	Proposed	Approx 58%	Approx 50% Reduction	Much better as compared to rest of the methods

In Algorithm 1, it is clearly explained the actual pseudo-code of this entire proposed concept. Here, it is very clear that, in case, if the vehicle runs and somehow the RPM is high enough then to optimize the battery current drawing rate, the system adopts the gasoline in place of battery source. Whereas, if RPM is economic then the system prefers an auto resume to its old battery management system. This is why the

Summary.png Summary.bb

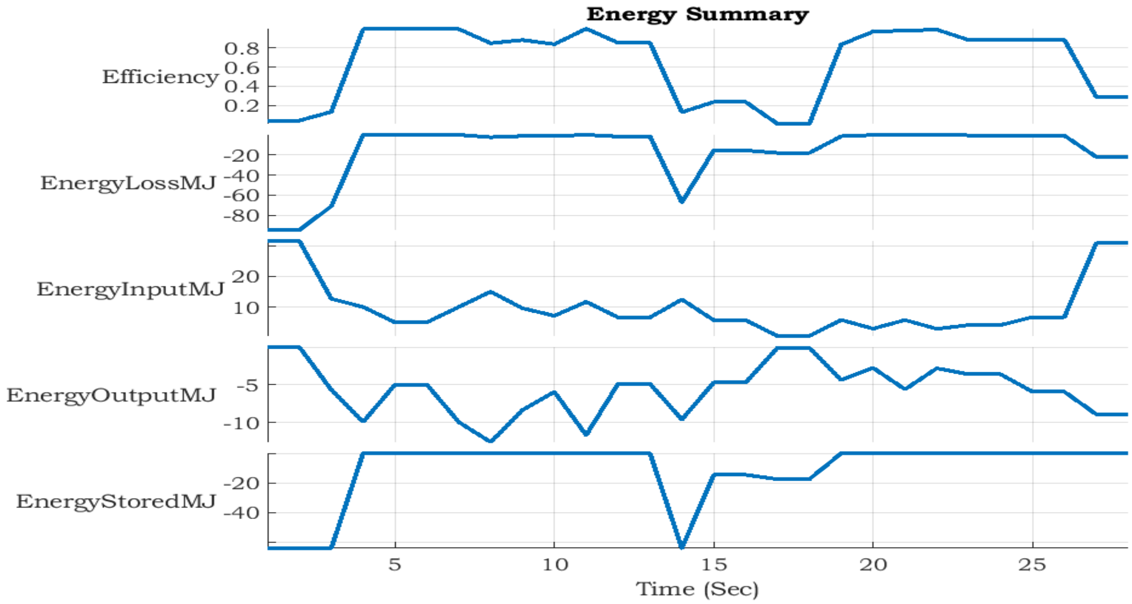
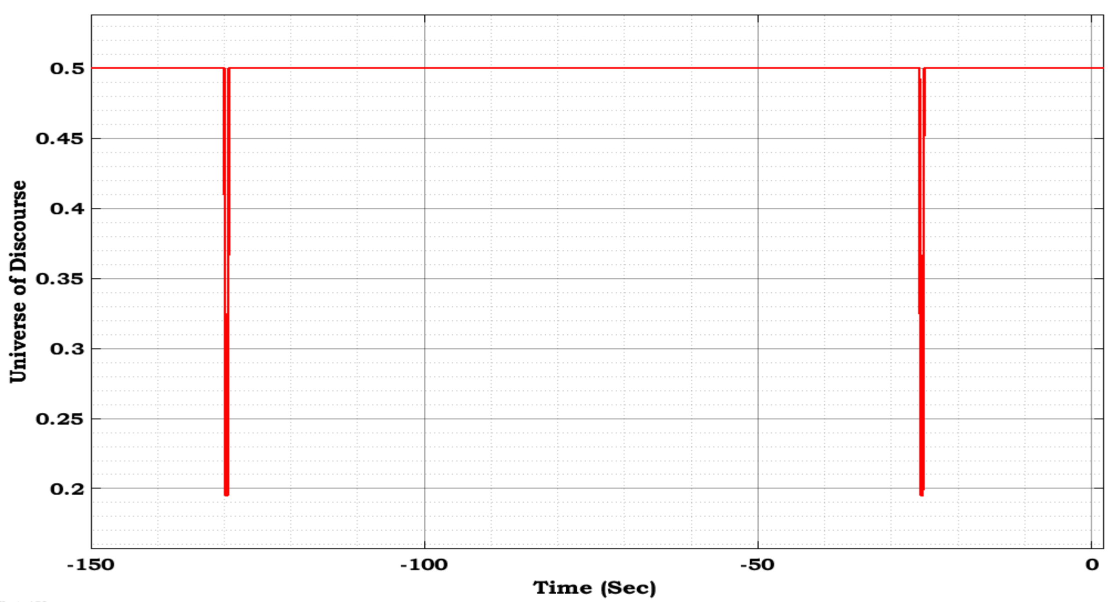


Figure 16: Entire energy summary of the existing HEV model

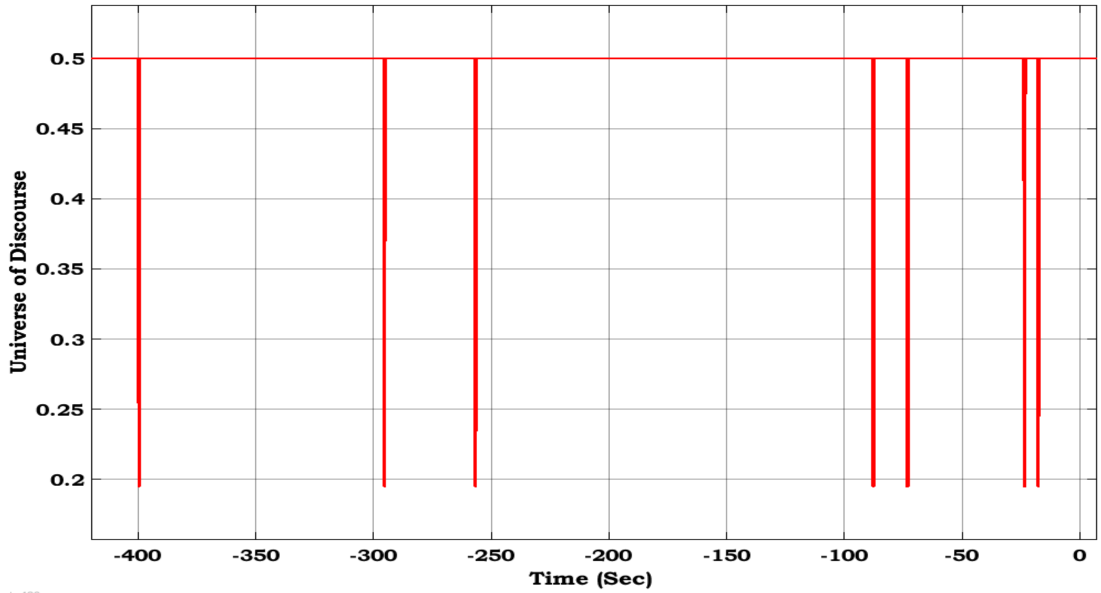


sec.png sec.bb

Figure 17: Scope analysis after 120 sec of simulation

second FLC i.e. FLC02 has been designed by considering battery current and SOC indeed. Whereas, FLC01 is designed by considering RPM for speed analysis and angular velocity, by means of which the direction of the wheel is considered.

In this work a couple of driving cycle test has been considered like UDDS (Urban Dynamometer Driving Schedule) and HWFET (Highway Fuel Economy Test). The analysis report is provided in Table 9. The battery SOC variation based on these back to back test result is also obtained with a very optimum report and is provided in Table 10. Transient response is also a very significant parameter in this case as it ensures



sec.png sec.bb Offset=420

Figure 18: Scope analysis after 400 sec of simulation

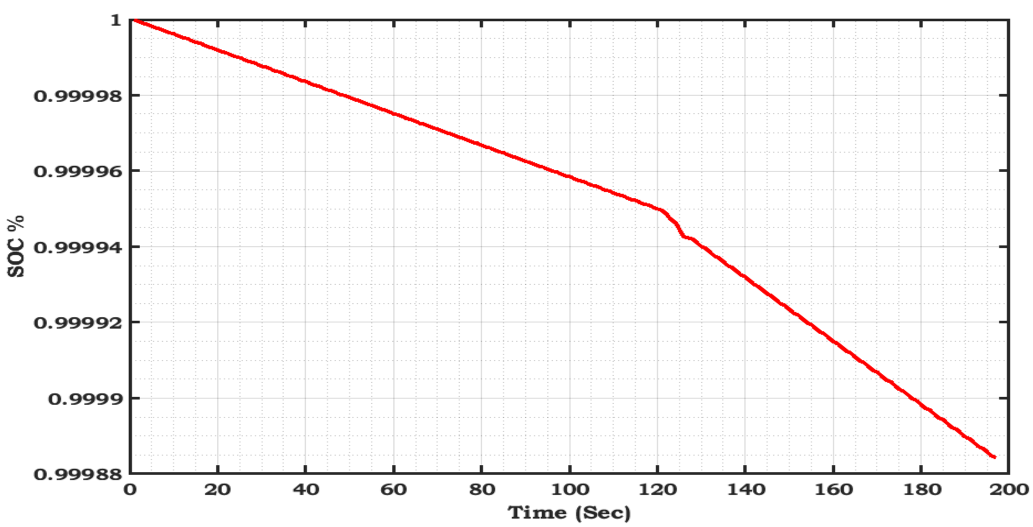


Figure 19: Battery SOC analysis after simulation

a drastic impact on battery SOC itself and is provided in Table 11.

4 Future Research Direction

Algorithm 1 ensures a clear pictorial view of the entire proposed work and its brief motivation as well. The same is reported in this work by validating only simulation under the MATLAB environment. Whereas, certain limitations are also enlisted by considering few future research work on hybrid power management systems by considering both battery and fuel economy as well. Firstly, in terms of simulation this must be

Table 8: Analysis report of overall system related to HEV performances

System Name	Efficiency	Energy Loss (MJ)	Energy Input (MJ)	Energy Output (MJ)	Energy Stored (MJ)
HevIps Reference Application	0.0413	-94.4889	31.5398	0	-64.2198
Passenger Car	0.0413	-94.4889	31.5398	0	-64.2198
Drivetrain	0.1321	-71.1665	12.6792	-5.6645	-64.1999
Differential and Compliance	0.9955	-0.0453	9.992	-9.9467	-5.24E-05
Front Axle Compliance 1	0.9996	-0.002	4.9797	-4.9777	-2.58E-05
Front Axle Compliance 2	0.9996	-0.002	4.9797	-4.9777	-2.58E-05
Open Differential	0.9959	-0.0413	9.9961	-9.9549	-9.06E-07
Gearbox	0.8485	-2.3675	14.9886	-12.6208	4.20E-04
P1	0.8817	-1.2052	9.578	-8.3724	4.22E-04
P2	0.838	-1.1621	7.1131	-5.951	-2.94E-06
Torque Coupler	1	-1.59E-04	11.6901	-11.69	1.33E-07
Vehicle	0.8528	-1.6824	6.5837	-4.8775	0.0238
Vehicle Body 3 DOF Longitudinal	0.8531	-1.6824	6.5837	-4.8775	0.0238
Wheels and Brakes	0.1278	-67.0712	12.4553	-9.6081	-64.224
Longitudinal Wheel - Front 1	0.2351	-15.5553	5.7008	-4.7045	-14.559
Longitudinal Wheel - Front 2	0.2351	-15.5553	5.7008	-4.7045	-14.559
Longitudinal Wheel - Rear 1	0.008	-17.9803	0.5269	-0.0996	-17.553
Longitudinal Wheel - Rear 2	0.008	-17.9803	0.5269	-0.0996	-17.553
Electric Plant	0.8352	-1.4205	5.7695	-4.3697	-0.0199
Battery and DC-DC Converter	0.9698	-0.1742	2.9163	-2.762	-0.0199
DC-DC Converter	0.98	-0.1147	5.7346	-5.6199	0
Nickel-metal Hydride Battery Pack	0.9896	-0.0595	2.8579	-2.8183	-0.0199
Generator	0.8823	-0.482	4.0962	-3.6142	0
Mapped Generator	0.8823	-0.482	4.0962	-3.6142	0
Motor	0.8858	-0.7643	6.69	-5.9257	0
Mapped Motor	0.8858	-0.7643	6.69	-5.9257	0
Engine	0.2893	-21.9019	30.8179	-8.916	0
Mapped SI Engine	0.2893	-21.9019	30.8179	-8.916	0

Table 9: Analysis report of fuel consumption based on driving cycle

Driving Cycle	Fuel Consumption	Improvement vs ICE
UDDS	**4.2 L/100 km**	∼38% reduction
HWFET	**4.9 L/100 km**	∼30% reduction

Table 10: Analysis report of battery SOC variation based on driving cycle

Cycle	Initial SOC (%)	Final SOC (%)	SOC Range (%)
UDDS	60	54	5460
HWFET	60	58	5860

Table 11: Analysis report of transient response

Event Type	Observation
Acceleration (0100 km/h)	∼11.2 seconds (with motor assist)
Engine Start Delay	∼0.4 seconds (engine-on trigger at high load)
Motor Response Time	<0.2 seconds (instant torque delivery)
Regenerative Braking Delay	∼0.1 seconds (smooth engagement)

resolved by considering fractional fuzzy logic rather than this typical fuzzy inference mechanism. As fractional fuzzy logic ensures a single output rather than multiple outputs after defuzzification process. Again, it is also very true that this simulation based output is very challenging in terms of real world feasibility indeed. In that case Hardware-in-Loop (HIL) testing must be considered in the future for further clarification and to ensure the expectation of real world applicability for the betterment of automobile industry and errorfree engineering. Somehow it is also true that the gearing mechanism is the biggest burden for HEVs optimum efficiency due to certain transmission losses that occur due to multiple gearing mechanism. So in that case this research could take a new turn if the entire HEV runs with a minimum number of gearing mechanisms.

5 Conclusion

In this paper, an intelligent power split strategy for the HEV is discussed and reported by considering optimum fuel consumption and better efficiency as well. The overall output of the proposed strategy is compared that of a conventional system and reported in this work. The analysis report ensures that the cascaded fuzzy control system is far superior compared to a typical single stage fuzzy logic control system to maintain a dual power source based optimum synchronization for any HEV operation. The optimum control of the throttle of the IC engine leads the proposed concept to a better side as compared to the previous version of hybrid technology. Since, electric vehicles are now less considered due to the problem of installing charging stations. This is due to the high cost and frequent maintenance indeed. Another contradictory issue arises in the case of supply to the charging stations. Electric vehicles with larger batteries might be disturbing the environment during the manufacturing process. So, in future hybrid electric vehicles will be the only option left for a sustainable mankind and development as well. The proposed concept might add some potential benefits to the future products if considered commercially.

Whereas, this proposed method might be upgraded by replacing the planetary gearing mechanism. This mechanism is widely followed in EVs for controlling torque to the driving motors. Due to this planetary gear and some wearing and tearing issues the overall system might be lagging. This must be considered seriously in terms of poor fuel efficiency as well as battery efficiency. This is clear from Table 8, which shows approximately 85% efficiency. And it is also seen that somehow if the number of gears is more, in that case each gear will cost around 1% transmission loss. So, in that case reducing gears is one of the best solutions. This has also been considered by Tesla a long time back but spur or might be if applicable compound gearing gives a better efficiency to the HEVs especially by reducing losses.

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