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Driver-Mode-based Fuzzy Logic Power Spilt Strategy for Hybrid Electric Vehicles

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***Abstract*— A hybrid electric vehicle (HEV) integrates internal combustion engine with an electric motor to improve energy efficiency and overall vehicle performance. An effective power distribution strategy between the engine and motor is essential to satisfy different driving requirements while maintaining fuel efficiency. This work proposes a fuzzy logic based power distribution strategy that incorporates driver selected operating modes in order to accomplish the diverse driving needs of a driver in a more realistic driving environment. Three driving modes have been considered: Eco mode, Normal mode, and Sport mode. Eco mode implies the energy-saving driving mode while driving in a normal mode implies the balanced power split strategy between an electric motor and the internal combustion engine. However, the sport mode implies the increased power assistance of the combustion engine while driving in a sport mode. A fuzzy logic controller has been developed to control the power split strategy between the two power sources while taking into account of the driver's power demand as well as the driving mode. As a result of simulation, the system exhibits efficient driving dynamics in all driving modes.**

***Keywords*— Hybrid Electric Vehicle, Fuzzy Logic Control, Power Split Strategy, Driver Mode, Energy Management.**

I. INTRODUCTION

The increasing demand for fuel economy and reduction of greenhouse gas emissions has accelerated the development of Hybrid Electric Vehicles (HEV). The HEV system is a combination of an electric motor, an internal combustion engine (ICE), and a battery energy storage system, which improves fuel economy without compromising driving performance. However, the overall efficiency of the HEVs is highly dependent on the proper power distribution between the engine and the motor in the different driving conditions. To overcome this challenge, several Energy Management Strategies (EMS) have been developed. Rule-based methods are popular for their simplicity and ease of implementation, but they are not flexible in dynamic and unpredictable driving conditions [1]. Optimization-based approaches, such as Dynamic Programming (DP) and Model Predictive Control (MPC), can achieve near optimal fuel consumption and energy utilization, but require large computational resources that hinder real-time implementation [2], [3]. Fuzzy Logic Control (FLC) is a feasible alternative as it can deal with nonlinear systems and uncertainties without requiring an accurate mathematical model of the vehicle. Moreover, FLC has low computational complexity and good robustness, making it suitable for real-time applications [4], [5]. Recently, some work has been done to integrate driver behavior and driving preferences into EMS design.

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The system also offers selectable driving modes, including Eco, Normal and Sport, that enable the system to dynamically adjust power allocation strategies to balance fuel economy, battery usage and vehicle performance in accordance with driver intent. Such an adaptive approach is beneficial not only for energy efficiency and driving comfort but also for the overall effectiveness of hybrid powertrain operation [6], [7]. Furthermore, recent advances in intelligent control techniques, such as adaptive fuzzy systems and machine learning-aided energy management systems (EMS) have shown promising results in optimizing energy consumption and extending the battery lifetime under different driving scenarios [8].

II. Related Work

The Energy Management Systems (EMS) in HEVs are very important for efficient energy allocation between the internal combustion engine and electric motors to save fuel consumption and emissions and also to ensure battery performance [7], [8]. Currently, EMS methods can be divided into rule-based methods, optimization-based strategies and intelligent control methods [9], [10]. Rule-based methods are widely used because of their simplicity and high reliability; however, they cannot adapt to the changing driving environment, leading to inefficient energy management [9], [10]. On the other hand, optimization-based methods, such as dynamic programming (DP) and model predictive control (MPC) have demonstrated better energy efficiency and fuel economy. However, DP needs information of the entire driving cycle and MPC has high computational complexity, which makes these systems infeasible for low-cost vehicular controllers [11]. FLC systems have attracted considerable attention in intelligent control strategies, as they are capable of dealing with nonlinear dynamics and uncertainties related to vehicles and do not require precise mathematical models [12], [7], [8].Some recent works have found out that fuzzy based EMS systems are effective in reducing fuel use and SOC control of batteries under different driving conditions [13], [14], [15], [16]. However, in traditional fuzzy control systems, the rule bases are majorly tuned in a manual way, which makes them non-adaptive to the changes of operating conditions [17], [18].

Recently, some attempts have been devoted to designing hybrid fuzzy control strategies based on optimization or machine learning to enhance the effectiveness of EMS. These hybrid strategies allow for better performance but often have increased computational load [19]. To integrate the information of driver behavior in the power allocation process, driver-related and mode-based energy management schemes have been proposed; still, many available schemes either limit the expression of driver's intention or neglect the direct influence of the selected driving modes on the allocation process [20]. Therefore, this research proposes a novel Driver-Mode-Based Fuzzy Power Split Strategy to facilitate the direct realization of driving modes, i.e., Eco, Normal and Sport in the fuzzy logic based controller for real-time adjustment of the power sharing between the engine and motor.

III. Methodology

A. Overview of proposed approach

The proposed system employs a structured methodology for weed identification in subterranean vegetable lands, ensuring high precision and accuracy. The process consists of several sequential stages: image acquisition, dataset creation, image preprocessing, dataset splitting, model training, and performance evaluation. Each stage contributes to the development of an effective and efficient system, as illustrated in Fig. 1. Below is a general overview followed by detailed descriptions of each stage is proposed. In this approach, the selected driving mode is directly incorporated into a fuzzy logic controller along with vehicle speed, acceleration, and battery state of charge. The controller determines an appropriate power split between the engine and motor, enabling efficient operation in Eco mode, balanced performance in Normal mode, and improved responsiveness in Sport mode. Unlike optimization-tuned fuzzy methods that require offline training, the proposed approach uses a fixed rule base, making it suitable for real- time implementation.

B. Overview of proposed approach

Hybrid Electric Vehicles (HEVs) use both an internal combustion engine and an electric motor for propulsion. In most production HEVs, power distribution between these sources is determined using fixed rule-based strategies. Although drivers can select modes such as Eco, Normal, or Sport, these modes mainly adjust accelerator sensitivity rather than directly controlling power sharing. To address this limitation, a Driver-Mode–Based Fuzzy Power Split Strategy is proposed. The selected driving mode is incorporated as an input to a fuzzy logic controller along with vehicle speed, acceleration, and battery state of charge. Based on these inputs, the controller determines the splitting of power between an electric motor and the internal combustion engine, enabling high in efficiency during Eco mode, balanced operation in Normal mode, and improved performance in Sport mode. Unlike optimization- tuned fuzzy approaches that require offline training, the proposed method uses a fixed rule base, making it suitable for real-time implementation.

C. Overview of proposed approach

Hybrid Electric Vehicles (HEVs) use an internal combustion engine and an electric motor for propulsion. In most production HEVs, power distribution between these sources is controlled by fixed rule-based strategies. Although drivers can select modes such as Eco, Normal, or Sport, these modes mainly adjust accelerator sensitivity rather than directly managing power sharing. To overcome this limitation, a Driver-Mode–Based Fuzzy Power Split Strategy
is proposed. The selected driving mode, along with vehicle speed, acceleration, and battery state of charge, is used as input to a fuzzy logic controller to determine the engine–motor power split. This enables efficient operation in Eco mode, balanced performance in Normal mode, and improved responsiveness in Sport mode. The proposed method uses a fixed rule base, ensuring low computational complexity and real-time feasibility.

D. System inputs and outputs

The proposed fuzzy energy management system calculates the appropriate distribution of power between an electric motor and the internal combustion engine using variables representing driver intent, vehicle dynamics, and energy availability. The driver mode is treated as a discrete input with three levels: Eco, Normal, and Sport. Vehicle speed (0–120 km/h) is classified as Low, Medium, or High, while longitudinal acceleration (−2 to 3 m/s^2) is categorized as Low, Moderate, or High. The battery state of charge (SOC) ranges from 20%–90% and is described as Low, Medium, or High. These inputs collectively represent the vehicle's operating conditions. The output of the fuzzy controller is the power split factor.
$\alpha \in [0,1]$ which represents the fraction of the total demanded power supplied by the engine. Accordingly, the engine and motor power commands are computed as:

$$\mathrm{Pe(t)} = \alpha\mathrm{(t)Pdem(t)} \quad (1)$$

$$\mathrm{Pm(t)} = (1 - \alpha\mathrm{(t)})\mathrm{Pdem(t)} \quad (2)$$

where $P_{e(t)}$ and $P_{m(t)}$ are denoted as engine and motor power, respectively, $P_{dem(t)}$ is the total demanded power, and
$\alpha(t) \in [0, 1]$ represents the engine power split factor.

B. Flowchart

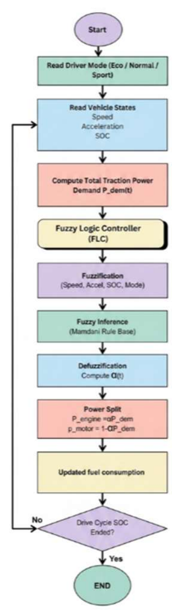

Fig. 1. Operating flowchart

Fig.1 illustrates the operating flow of the proposed driver-mode- based fuzzy power split strategy. At each control
interval, vehicle state variables and driver-selected mode are acquired. The total power demand is calculated and supplied to the fuzzy logic controller. Based on fuzzy inference and defuzzification, the engine and motor power commands are generated. The process is repeated at every sampling instant to ensure real- time operation.
This output is adopted to control the splitting of power between an electric motor and the internal combustion engine for efficient running.
The engine and motor power contributions are varied dynamically depending on the driving conditions and SOC. Fuel and battery usage are also updated dynamically. The control process continues until the end of the drive cycle.

C. Algorithm

The suggested control algorithm runs in a closed- loop manner and does the following at each control interval:

- Obtain the vehicle state variables and the driver- selected mode. Compute total traction power demand.
- Perform fuzzification of input variables.
- Apply fuzzy inference rules.
- De-fuzzification to obtain the power spilt factor.
- Generate engine and motor power commands.
- Update battery SOC and fuel consumption.

D. Vehicle power demand modelling

The total traction power demand is calculated based on vehicle longitudinal dynamics.

$$Pdem(t) = Ftrac(t)v(t) \tag{3}$$

F. Battery and fuel consumption modelling

The battery state of charge (SOC) is updated at each sampling interval using the following discrete time equation:

$$\mathrm{SOC(t+1) = SOC(t) - \frac{Pm(t)\Delta t}{Ebat}} \tag{4}$$

Where $Ebat$ represents the total battery energy capacity and Δt is the sampling interval. The fuel consumption is estimated using an engine fuel consumption map as a function of engine power and speed.
In comparison to traditional rule-based approaches, the suggested methodology shows that integrating driver intent into a fuzzy logic-based power split controller enables intelligent, adaptive, and seamless energy management in hybrid electric vehicles Multimodal Input Capture: Enables users to capture im- ages, issue voice commands, or interact through gestures

G. Fuzzification

These variables are then converted into linguistic variables by means of membership functions. Triangular membership functions are adopted because they provide simple implementation and require minimal computation efforts. Each membership function is designed with sufficient overlap to ensure smooth transitions between operating regions.
The membership function parameters are selected based on typical HEV operating ranges. The linguistic classifications of the input variables are defined as follows:

- Driver Mode: [Eco, Normal, Sport]
- SOC: [Low, Medium, High]
- Acceleration: [Low, Moderate, High]
- Speed: [Low, Medium, High]

H. Rule based formulation

The fuzzy rule base is designed to optimize energy utilization while considering different driving behaviors that needs to be performed based on the operational modes of the vehicle. While in Eco mode, the vehicle relies on electric power generation to optimize mileage.
The Normal mode ensures that there is optimal sharing of power generated by the engine and the electric motor. However, when the Sport mode is activated, there is an intensified need to improve performance of the engine. Unlike other rule-based methods, the fuzzy inference system allows more than one rule to be activated.

I. Interface and Defuzzification

The are assessed using an inference mechanism of the Mamdani type. The centroid defuzzification method ensures smooth variation in power distribution by obtaining the final crisp output value of the power split factor (α).

J. Fuzzy Rule Base Design

TABLE I. FUZZY RULE BASE FOR DRIVER-MODE-BASED POWER SPLIT

Driver mode	SOC level	Acceleration demand	Engine contribution
Eco	High	Low	Very Low
Eco	Medium	Moderate	Low
Eco	Low	High	Medium
Normal	High	Low	Low
Normal	Medium	Moderate	Medium
Normal	Low	High	High
Sport	High	Moderate	High
Sport	Medium	High	Very High
Sport	Low	High	Very High

The fuzzy rule base in Table I specifies engine-to- motor power distribution requirements. In Eco mode, rules prioritize electric propulsion when SOC is high and acceleration demand is low. In Normal mode, balanced power sharing is achieved to ensure efficiency and drivability. In Sport mode, higher engine contribution is permitted to satisfy high acceleration demands and improve vehicle responsiveness. The fuzzy rule base is designed to reflect driver intent, battery energy availability, and acceleration demand. In Eco mode, the rules prioritize electric propulsion when the battery SOC is high and acceleration demand is low in order to improve fuel economy. In Normal mode, balanced power sharing between the engine and motor is achieved to ensure smooth drivability. In Sport mode, higher engine contribution is allowed to satisfy high acceleration demands and enhance vehicle performance Fig. 2. shows the power management qualities of the designed fuzzy controller under Eco mode. In low levels of driver demand, motor power is dominant, and the role of the engine is gradually raised with the driver demand level.

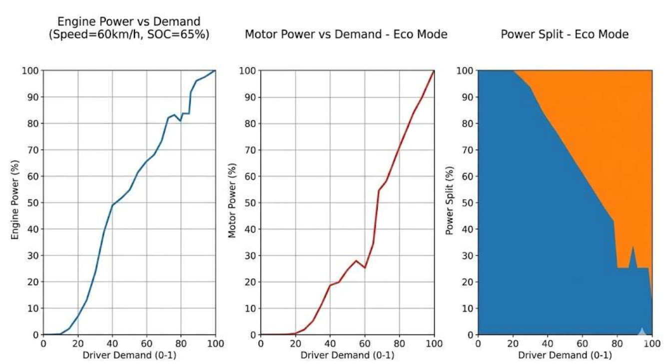

Fig. 2. Driver demand in Eco mode

IV. RESULT AND DISCUSSION

The proposed comparative analysis would be made against a traditional rule-based energy management strategy system, with the aim of objectively judging the effectiveness of the proposed driver mode-based fuzzy energy management strategy. The integration of driver intention into power split decisions aims to show its effect.

In order to examine equal results, both methods of energy management are evaluated on the same model of hybrid vehicles. The factors that are kept identical in both methods include the vehicle variables, driving cycles, battery initial state of charge, as well as the simulation time. The differences in performance that have been observed are entirely dependent on the method of management.

A. Rule based Energy Management Strategy

The rule based which is called as the conventional energy management strategy is used as a benchmark to evaluate system performance of the developed fuzzy energy management strategy which is driver mode based.

This is because of increasing popularity of this strategy in hybrid vehicle applications, considering the simplicity of this strategy in computation. In this strategy, decisions concerning splitting of power control in a hybrid vehicle apply a series of rules based on various driving conditions called as vehicle speed, acceleration rates, and battery SOC.

However, abrupt control is observed in this strategy, where the hybrid uses an internal combustion-based or battery- based traction depending on high rates of power or low rates of SOC. Although Eco mode, normal mode, and sports mode are evident in this strategy, their contribution is only limited during such applications, considering non-inclusion of this aspect in decision-making concerning the hybrid vehicle's energy management. Thus, the contribution of mode split in this scenario is neglected.

B. Proposed Driver Mode Based Fuzzy Energy Management Strategy

The proposed energy management approach uses a fuzzy logic controller to directly incorporate driver intent into the power split decision. When compared to the rule-based method, the fuzzy controller simultaneously determines an ideal power split ratio by taking into account the driver- selected mode, vehicle acceleration, speed, and battery SOC. The suggested approach allows mode-dependent power allocation by using the driver mode as a direct input to the fuzzy inference system. To improve fuel efficiency, electric propulsion is given priority in Eco mode. Both the engine and the motor contribute equally in normal mode. Higher engine contribution is permitted in Sport mode to ensure quick reaction times and enhanced performance.

Engine and motor power transitions are smooth and continuous because the fuzzy inference mechanism permits the partial activation of several rules. This enhances overall drivability and gets rid of the sudden switching behavior seen in traditional rule-based strategies.

C. Performance comparison

TABLE II. COMPARATIVE EVALUATION

Criterion	Rule-Based EMS	Proposed Fuzzy EMS
Power split logic	Fixed threshold based	Adaptive fuzzy inference
Driver mode integration	Indirect	Direct
Power transition	Abrupt	Smooth
Fuel efficiency	Moderate	Improved
SOC stability	Moderate	Improved
Mode differentiation	Weak	Strong

This section supports the fuzzy energy management which is driver mode based strategy's suitable for next-generation electric hybrid vehicle applications by demonstrating that it provides definite advantages over traditional rule-based systems.

D. Driver Demand and Power Split Behavior

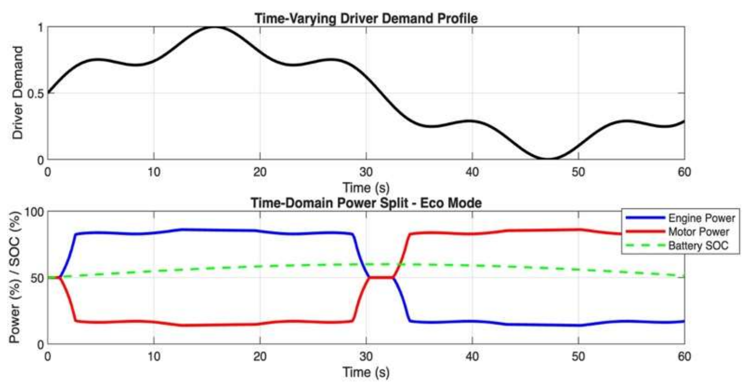

Fig. 3. Time-varying driver demand profile

Fig.3.represents the time-varying driver demand pattern used for assessing the proposed driver-mode- based fuzzy power- split strategy, where the continuously varying driver demand simulates realistic driver behavior involving changes in driver intent. The corresponding results for time-domain power split in Fig.3. show engine power, motor power, and SOC for battery in Eco mode conditions. At low levels of demand, it is noticed that there is a higher contribution of power from the electric motor, while with an increase in demand, there is a

smooth transition to contribution from the engine. The results confirm that there is no sudden transition to the new power source and is an adaptive system with a fuzzy logic controller. Similar power split behavior is observed in Normal and Sport driving modes. In Normal mode, the engine and motor contributions remain balanced across moderate acceleration demands, ensuring smooth drivability. In Sport mode, higher engine participation is observed during high acceleration events, confirming that the proposed strategy successfully adapts power distribution according to driver-selected mode

E. Battery SOC Stability and Energy Management

The corresponding SOC behavior for the proposed fuzzy strategy is also shown in the Fig.3. From Figure 1, we can notice that the SOC maintains an optimal operating level that ensures energy sustainability. The controller ensures that the battery level is not drained. At the same time, it facilitates higher electric vehicle assistance in low to moderate operating conditions. This ensures that SOC sustainability along with fuel economy performance is ensured.

F. Comparison with Rule-Based Strategy

Fig4.describes the comparison of engine power allocation in the suggested fuzzy logic solution with the conventional rule- based solution. In the conventional method, the engine power allocation changes step-by-step because of the thresholds involved, while the fuzzy controller provides a smooth result. Quantitative comparison in Fig. 4 illustrates that the average engine power consumption is reduced by the fuzzy strategy by 6.8% from 50.0% to 46.6%. This reduction indicates a lower engine load during Eco mode operation, which directly contributes to improved fuel efficiency while maintaining SOC stability. It directly helps in lowering the engine load during Eco driving mode, which results in increased fuel efficiency.

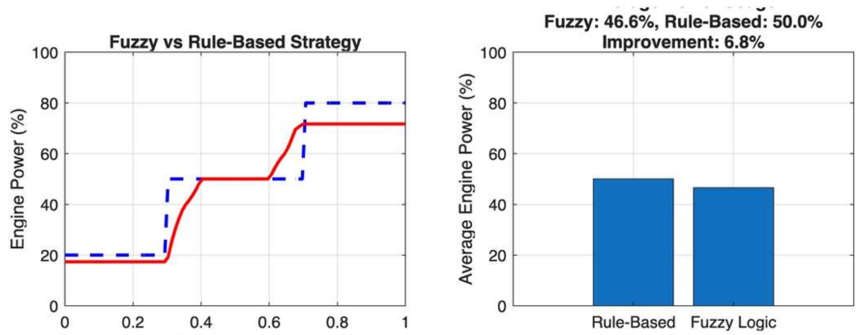

Fig. 4. Comparison of FMS vs RMS

The driver-mode-based fuzzy logic power split control strategy that enhances energy efficiency with comparable driving performance and comfort has been proposed in this paper. By incorporating driver intention through Eco, Normal, and Sport modes, the proposed approach allows the distribution of power between the electric motor and an internal combustion engine to adapt dynamically to different driving preferences and operating conditions. In addition, fuzzy logic provides a seamless and continuous decision without requiring computationally intensive optimization techniques or complex mathematical models. The proposed energy management strategy takes care of the balance between fuel consumption and performance by giving emphasis on electric propulsion in Eco mode, balanced operation in Normal mode, and responsiveness in Sport mode. The outcomes show that the controller is able to react properly to the variations of the speed of the vehicle, the acceleration request, and the state of charge of the battery. Based upon the foregoing discussion, it can thus concluded that the proposed driver mode-fuzzy power split strategy provides a viable solution for the management of energy for a hybrid electric vehicle. Future research will emphasize the proposed method by adding new parameters such as the slope of the road, traffic flow, effect of battery aging, and others. The comparative outcomes have proved that the power smoothness is increased, the SOC is stabilized, and the engine workings are reduced compared to the second strategy

V. CONCLUSION

This work developed a Fuzzy Logic Power Split Strategy based on the Driving Modes used in Hybrid Electric Vehicles (HEVs). This new strategy uses driving modes selected by the driver (Eco, Normal, and Sport) and

parameters such as the speed, acceleration, and State of Charge (SOC) of the battery as input values of a fuzzy logic controller. As output from the fuzzy logic control system, there is a strategy that can optimize the power split between the internal combustion engine and the electric motor.
The simulation analysis shows that the novel power split strategy is capable of adapting to different scenarios and driver requirements. When using the Eco mode, the fuzzy controller uses less power of the engine and maximizes the use of the electricity supplied by the battery. For the Normal mode, both types of energy sources can share power efficiently. When using the Sport mode, the engine works harder and improves the acceleration performance. By comparing this fuzzy logic-based approach with the traditional energy management strategy, there is an average improvement of the fuel economy of about 6.8%. The results prove that the use of driver intent for HEV energy management has great potential for improving the performance of the system while keeping its computational requirements low. Future research will investigate the application of the above strategy under actual driving conditions. Factors like road slope, traffic environment, battery degradation, and predictive information about the driving cycle could be considered in future work as well.

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