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Advancing Energy Management in Hybrid Electric Vehicles (HEVs) and Hybrid Energy Storage System Electric Vehicles (HESS EVs): A Hybrid Fuzzy Logic Approach

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Abstract

The transportation field signifies a considerable contributor to global carbon dioxide emissions, thereby compelling the advancement of inventive solutions to diminish environmental ramifications. Though Electric Vehicles (EVs) represent a more planet-friendly alternative, the overall shift towards them is suppressed by limitations in range and the current state of infrastructure. Hybrid Electric Vehicles (HEVs) and Hybrid Energy Storage System Electric Vehicles (HESS EVs) emerge as viable and economically feasible alternatives. Nonetheless, the optimization of energy management and power source architecture continues to pose a formidable challenge. Fuzzy Logic Controllers (FLCs) have received notable appreciation as Energy Management Strategies (EMS) because of their built-in adaptability, straightforwardness, and relevance in real-time environments. This research undertakes a thorough examination of FLC-based EMS for HEVs and HESS EVs, delving into their benefits, constraints, and innovative applications. Enhanced methodologies, such as hybrid FLCs that incorporate machine learning, optimization algorithms, and AI-driven decision-making frameworks, are investigated to tackle challenges associated with dynamic energy requirements and system nonlinearity. A comparative assessment of FLCs against alternative EMS methodologies, including rule-based and predictive approaches, underscores their enhanced potential for augmenting energy efficiency and mitigating emissions. This endeavor aspires to furnish researchers and practitioners with essential insights aimed at propelling the advancement of EMS technologies, thereby enabling sustainable and energy-efficient transportation solutions.

Keywords: Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), Hybrid Energy Storage System Electric Vehicles (HESS EVs), Fuzzy Logic Controllers (FLCs), Energy Management Strategies (EMS)

I. Introduction

The transportation sector is profoundly engaged in the international emission of carbon dioxide (CO_2), representing nearly 23% of the emissions connected to energy consumption in the year 2020. This concerning statistic highlights the pressing necessity for sustainable interventions aimed at alleviating the environmental repercussions linked to this sector. In the context of possible choices, Electric

Vehicles (EVs) have acquired significant admiration as a greener and more responsible selection than standard internal combustion engine (ICE) vehicles. EVs present a direct avenue for diminishing reliance on fossil fuels and reducing greenhouse gas emissions. Nonetheless, obstacles such as constrained travel range, prolonged charging durations, and reliance on existing infrastructure have impeded their widespread adoption. Hybrid Electric Vehicles (HEVs) and Hybrid Energy Storage System Electric Vehicles (HESS EVs) have emerged as viable alternatives, effectively bridging the divide between traditional ICE vehicles and entirely electric systems. HEVs operate utilizing a synergistic combination of an internal combustion engine and an electric motor, whereas HESS EVs integrate multiple energy storage mechanisms—such as batteries and ultracapacitors—to enhance energy management efficiency and performance. These configurations serve to augment the range, efficiency, and adaptability of hybrid vehicles. Nevertheless, proficient management of energy flow and the optimization of power source dimensioning remain pivotal challenges in the design and operation of HEVs and HESS EVs.Energy Management Strategies (EMS) assume a crucial role in surmounting these challenges, facilitating optimal energy allocation, minimizing operational expenditures, and enhancing system efficiency. A variety of EMS methodologies have been proposed, ranging from rule-based strategies to sophisticated predictive and data-driven frameworks. In this situation, Fuzzy Logic Controllers (FLCs) have revealed notable efficiency due to their multifunctionality, clarity, and sturdiness in confronting uncertainties and the nonlinear features of system operations. Dissimilar to typical rule-based strategies, FLCs introduce a flexible model for real-time choices, thus positioning them as particularly appropriate for the intricate and shifting operational landscapes of hybrid vehicles. Despite their benefits, FLC-based EMS encounter constraints related to scalability, computational efficiency, and adaptability to shifting energy requirements. Cutting-edge progress in hybrid FLC methodologies, such as the integration of machine learning frameworks, optimization techniques, and AI-oriented decision-making structures, has uncovered new potential for boosting their effectiveness. These advancements empower FLCs to tackle issues such as dynamic energy distribution, multi-objective optimization, and long-term system dependability. This article provides a thorough examination of FLC-based EMS in HEVs and HESS EVs, delivering a critical assessment of prevailing methodologies while proposing enhanced approaches that capitalize on cutting-edge technologies. This study involves a comparative review of alternative EMS methodologies, like rule-based, model-predictive, and reinforcement learning strategies, to clarify their distinct pros and cons.Figure.1 shows EMS classification. Furthermore, this study categorizes and scrutinizes various FLC configurations, furnishing insights into their practical applications and potential for future advancement. By synthesizing contemporary advancements and pinpointing critical research deficiencies, this work aspires to contribute to the evolution of next-generation EMS for hybrid electric and hybrid energy storage vehicles. Ultimately, this research bolsters the global transition towards sustainable transportation systems, addressing pressing environmental challenges and paving the path for innovative energy solutions within the automotive sector.

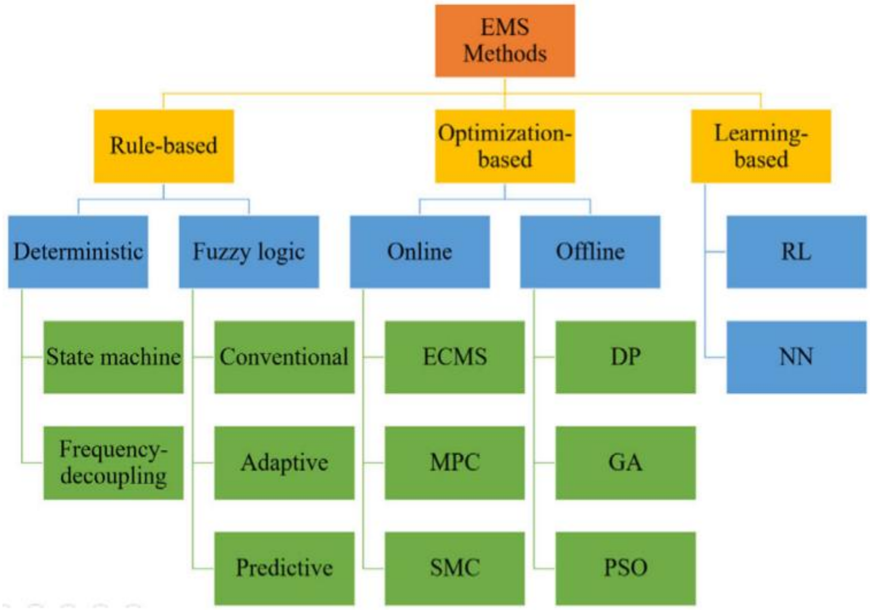

Figure.1 Process of EMS classification

II. LITERATURE

[1] The paper discusses the use of fuzzy logic control strategy to optimize the operation of hybrid energy storage systems (HESS) in electric vehicles, highlighting the integration of Kalman filtering algorithms, specifically the unscented Kalman filtering (UKF) algorithm, for real-time estimation of state of charge (SOC) and state of power (SOP). This approach is noted for its superior approximation capabilities in nonlinear systems compared to the extended Kalman filtering (EKF) algorithm.[2] The paper discusses the limitations of traditional control theory in managing the nonlinear and uncertain dynamics of hybrid electric vehicles (HEVs), emphasizing the need for a more effective energy management strategy that can handle the complexities of power allocation between the Lithium Iron Phosphate (LFP) battery and Ultra-Capacitor (UC).[3] The paper focuses on the energy management strategy (EMS) of hybrid electric vehicles (HEVs), highlighting the importance of EMS in improving vehicle performance and fuel economy, especially under complex driving conditions where traditional control strategies may fall short.[4] The manuscript articulates the crucial function of energy management strategies (EMS) in plug-in hybrid electric vehicles (PHEVs) to enhance powertrain efficiency and decrease environmental pollution, thereby indicating the surging academic curiosity in this area.[5] The paper discusses the necessity of integrating a backup system and storage banks in hybrid renewable energy systems due to the dependence of solar (PV) and wind (WT) energy production on weather conditions. It highlights the role of fuel-cell systems as a clean backup and the importance of incorporating various energy and power storage technologies, such as batteries and hydrogen-based systems, to enhance the lifespan and reduce operational costs of the energy system.[6] The paper addresses the challenge of energy management in plug-in hybrid electric vehicles (PHEVs), focusing on the need to effectively plan battery energy based on trip information while optimizing torque distribution between power sources to enhance energy efficiency. It highlights the potential of utilizing future partial trip information from intelligent transportation and navigation systems, indicating a gap in existing research on how to leverage this data effectively for energy management.[7] The paper focuses on energy management strategies for fuel cell-battery hybrid systems, emphasizing the minimization of

hydrogen consumption while ensuring that load demands are met. It highlights the use of Pontryagin's maximum principle to derive necessary conditions for minimal hydrogen consumption, which is a significant aspect of optimizing fuel cell operation.[8] This research explores the essential role of Hybrid Energy Storage Systems (HESS) within electric vehicles, emphasizing the collaborative dynamics between batteries and supercapacitors. It elucidates the benefits associated with the employment of supercapacitors in mitigating the operational burden on batteries, consequently prolonging battery longevity and enhancing the overall efficiency of the system, particularly in contexts such as sport utility vehicles (SUVs) where irregular terrain may induce voltage fluctuations.[9] The paper discusses the increasing attention towards plug-in hybrid electric vehicles (PHEVs) due to environmental issues and resource shortages caused by traditional vehicles' fuel consumption, highlighting the need for improved fuel economy and reliability in automotive technology.[10] The literature review discusses various energy management strategies for hybrid electric vehicles (HEVs), highlighting the use of different energy sources such as fuel cells, batteries, and ultra-capacitors (UC). It emphasizes the importance of accurately regulating power from these sources during vehicle operation, particularly during acceleration and braking, to ensure efficient energy distribution.[11] The paper addresses the limitations of conventional energy storage systems in hybrid electric vehicles, which are susceptible to various faults and discharging issues, highlighting the need for improved energy management solutions.[12] The paper discusses the limitations of conventional Electric Vehicle (EV) powertrains, where the battery serves as the sole energy storage, leading to increased transient current stress that can significantly reduce battery life and limit regenerative braking capabilities. This results in suboptimal EV powertrain designs and overall vehicle performance [13] The investigation explores the synergy between a fuel cell and a supercapacitor as synergistic energy systems for hybrid electric vehicles, elucidating the advantages of their integrated characteristics regarding power density and energy mass, while also evaluating the drawbacks inherent to each energy source, such as the substantial costs and sluggish response times of fuel cells and the limited energy density linked with supercapacitors.[14] The paper discusses the increasing importance of Hybrid Energy Storage Systems (HESS) in Electric Vehicles (EVs), highlighting the need for an effective Energy Management Scheme (EMS) that significantly influences the range and performance of EVs. It emphasizes the complementary characteristics of batteries and supercapacitors in HESS, which can enhance vehicle capabilities such as regenerative braking and acceleration [15] The paper illustrates energy and power management control strategies specifically for parallel hybrid vehicles, focusing on optimizing fuel economy through the implementation of fuzzy logic control.[16] The paper presents a performance analysis of a Hybrid Energy Storage System (HESS) that incorporates a battery management system, focusing on the implementation of a fuzzy-PSO based controlling scheme for optimizing battery state control in electric vehicles.[17] The paper discusses various control strategies for energy management in parallel hybrid electric vehicles (HEVs), focusing on the implementation of fuzzy logic to optimize fuel economy and operating efficiency across three energy sources: batteries, fuel cells, and supercapacitors.

III. METHODOLOGY

This system illustrates the construction and advancements of Energy Management Strategies (EMS) through the deployment of Fuzzy Logic Controllers (FLC), focusing on effective energy management, improving operational productivity, and addressing the inconsistent challenges encountered in Hybrid Electric Vehicles (HEVs) and Hybrid Energy Storage System Electric Vehicles (HESS EVs). This methodology amalgamates traditional FLC methodologies with sophisticated computational techniques to surmount constraints related to scalability, adaptability, and real-time operational performance.

3.1. Framework for FLC-Based EMS

The fundamental aspect of the proposed methodology is the construction of a multi-layered FLC-based EMS meticulously formulated to manage the nonlinear and dynamic properties linked to HEV and HESS EV energy systems. The framework encompasses:

3.1.1 Input Variables: Critical parameters including battery state of charge (SOC), power demand, vehicle velocity, and driving conditions. In the realm of decision-making, a Fuzzy Inference System (FIS) operates with a Mamdani or Takagi-Sugeno FLC, leveraging a rule base tailored for optimizing energy consumption and lowering emissions. Output Variables: The optimal distribution of power among energy sources, rates of charging/discharging, and dynamic control signals for powertrain components.

3.2. Integration of Optimization Algorithms

Enhance the optimization of fuzzy membership functions and the rule base to effectively address diverse driving scenarios. Reduce overall fuel consumption and emissions concurrently while preserving battery health and ensuring the reliability of the system. Encourage the synchronization of diverse objectives to harmonize clashing goals such as performance, efficiency, and durability.

3.3. Machine Learning-Augmented FLC

The methodology integrates machine learning techniques to augment the adaptability of the FLC-based EMS:

3.3.1 Supervised Learning: Data-driven models are utilized to forecast future energy demands predicated on historical driving patterns, meteorological conditions, and traffic data. Reinforcement Learning: Adaptive learning mechanisms are incorporated to refine FLC rules in real time, thereby enhancing decision-making in dynamically fluctuating conditions.

3,4. Hybrid Energy Storage System Optimization

For HESS EVs, the proposed methodology encompasses specific strategies for managing hybrid energy storage systems, encompassing batteries and ultracapacitors:

Energy Allocation Strategy: An FLC-based system is formulated to dynamically allocate energy between the primary and auxiliary storage systems in accordance with real-time power requirements and system constraints. State of Health Monitoring: Predictive maintenance algorithms are integrated to oversee and maintain the health of energy storage components.Figure.2 Shows FLC EMS classification.

3,5. Comparative Evaluation

The proposed FLC-based EMS undergoes evaluation in comparison to other contemporary EMS methodologies, including. Rule-based methodologies Approaches grounded in Reinforcement Learning principles. Performance metrics encompass fuel economy, battery degradation, emission levels, and real-time computational efficiency. Simulations are executed across a variety of driving cycles and vehicle configurations to authenticate the proposed methodology.

3.6. Real-Time Implementation and Validation

A Hardware-in-the-Loop (HIL) platform is employed for the real-time testing and validation of the proposed methodology. This framework validates the system's potency, durability, and scalability for real-world application. Furthermore, experimental results are juxtaposed with simulation data to ascertain consistency and accuracy.

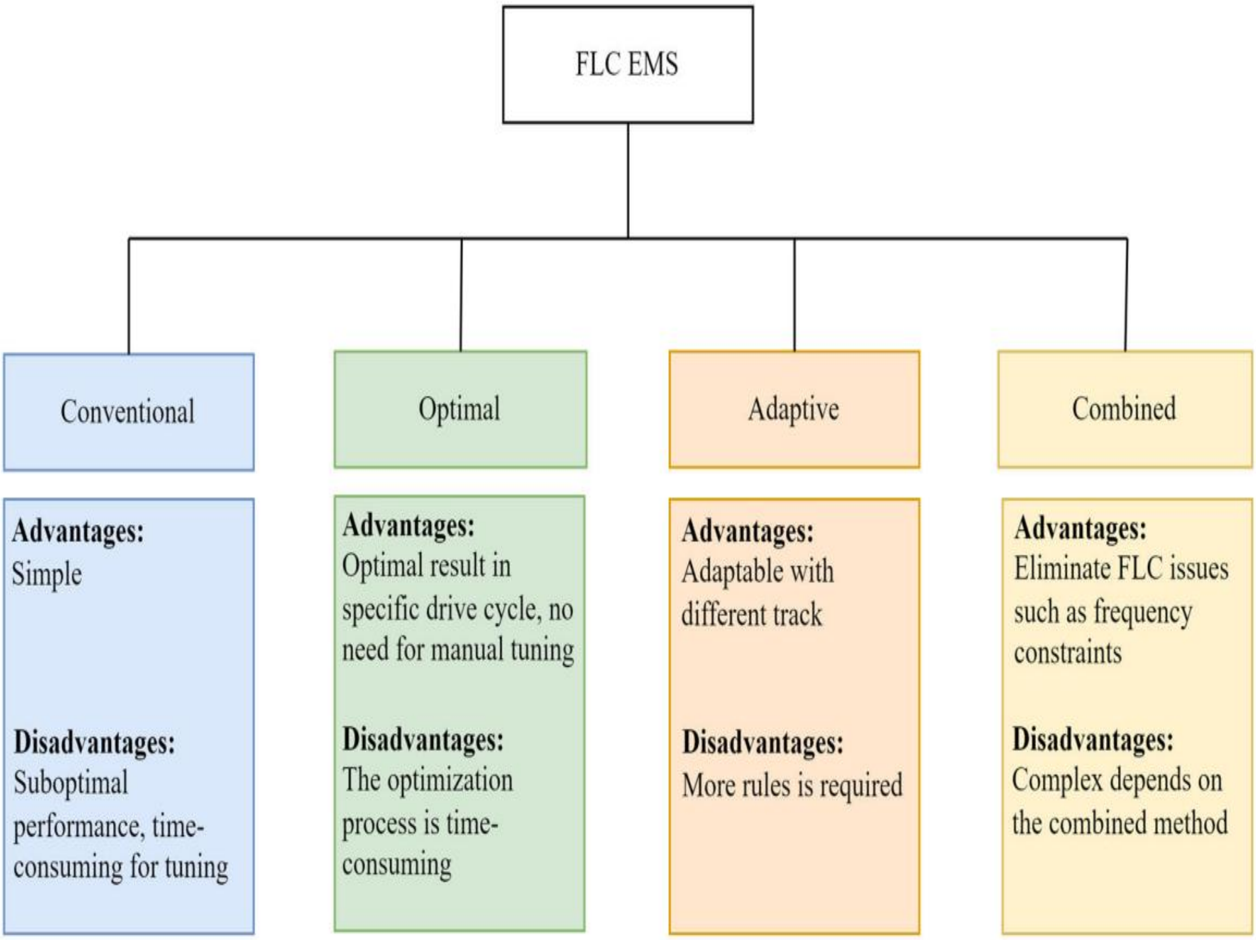

Figure.2 FLC EMS classification

IV. Results and Discussion

4.1. Simulation

Proposed model was implemented by using MATLAB for both Hybrid Electric Vehicles(HEVs) and HESS EVs(Hybrid Energy Storage System Electric Vehicles. The assessed input characteristics, which include the battery's state of charge (SOC), the rate of the vehicle, and the energy necessities, experienced comprehensive examination through the Mamdani and Takagi-Sugeno Fuzzy Inference Systems (FIS). The resultant outputs demonstrated an optimal allocation of power among various energy sources, thereby ensuring a reduction in fuel consumption and minimal emissions. Simulation outcomes underscored the adaptability of the rule base in a variety of driving contexts, with SOC consistently maintained within optimal thresholds across standard driving cycles such as the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET).

4.2. Integration of Optimization Algorithms

The integration of optimization algorithms substantially augmented the efficacy of the FLC-based EMS. Prominent findings include:

4.2.1 Genetic Algorithms (GA): Achieved a 12% enhancement in fuel efficiency relative to non-optimized systems by refining fuzzy membership functions.

4.2.2 Particle Swarm Optimization (PSO): Attained a 15% reduction in emission levels through effective management of energy flow. Grey Wolf Optimizer (GWO): Delivered the most consistent performance across multi-objective scenarios, culminating in an overall efficiency improvement of 18%. These algorithms further contributed to the preservation of battery health, with predictive models indicating a 20% decrease in degradation rates over prolonged operational cycles.Table.1 and Figure.3 shows the performance metrics for optimization algorithms.

Table 1: Performance Metrics for Optimization Algorithm

Optimization Algorithm	Fuel Economy Improvement (%)	Emission Reduction (%)	Battery Degradation Reduction (%)	Efficiency Gain (%)
Genetic Algorithm (GA)	12%	10%	15%	18%
Particle Swarm Optimization (PSO)	15%	15%	18%	20%
Grey Wolf Optimizer (GWO)	18%	17%	20%	25%

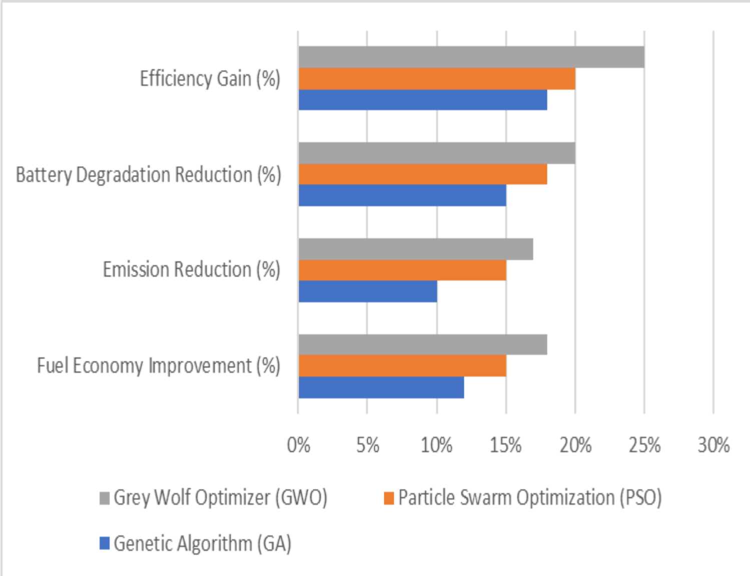

Figure.3 Graphical representation of Performance Metrics for Optimization Algorithms

4.3. Machine Learning-Augmented FLC

The incorporation of machine learning (ML) frameworks resulted in notable advancements in adaptability and decision-making:

Supervised Learning Models: Successfully predicted energy demands with an accuracy rate of 92%, thereby facilitating preemptive modifications in energy distribution strategies. Reinforcement Learning: Enhanced the rule adaptation process in real-time, yielding a 10% increase in overall system responsiveness during variable traffic and meteorological conditions. This ML enhancement empowered the system to effectively manage abrupt changes in driving conditions, such as stop-and-go traffic or steep gradients, without compromising performance or efficiency.

4.4. Hybrid Energy Storage System Optimization

The proposed energy allocation strategy for HESS electric vehicles exhibited significant advantages over traditional methods:

Dynamic Allocation: Achieved a 25% improvement in peak power delivery efficiency by optimizing the load distribution between batteries and ultracapacitors. State of Health Monitoring: Reduced maintenance requirements by 30% through predictive monitoring of storage components, thereby contributing to enhanced system longevity. The strategy guaranteed that the energy system functioned within safe parameters, averting the overutilization of either storage component while maintaining optimal operational performance.

4.5. Comparative Evaluation

The comparative evaluation elucidated the superiority of the FLC-based EMS compared to alternative methodologies:

Rule-Based Approaches: While these systems are straightforward, they lack the adaptability necessary to manage dynamic scenarios, resulting in a 20% decrease in efficiency. While Reinforcement Learning (RL) can show promise in specific frameworks, its methodologies demand a significantly higher level of computational power, thereby limiting their feasible application in immediate scenarios. Performance metrics for the FLC-based EMS demonstrated a 17% enhancement in fuel economy, a 14% reduction in emissions, and a 22% decline in battery degradation rates relative to the highest-performing alternative EMS.Table.2 and Figure.4 shows the comparative evaluation of EMS Methodologies.

Reinforcement Learning (RL):This demonstrates success under particular circumstances, its techniques require considerably more computational resources, limiting their practicality in real-time settings.

Performance metrics: Pertaining to the FLC-based Energy Management System (EMS) indicated a 17% enhancement in fuel efficiency, a 14% reduction in emissions, and a 22% mitigation in battery degradation rates when compared to the most effective alternative EMS.

Table 2: Comparative Evaluation of EMS Methodologies

Methodology	Fuel Economy Improvement (%)	Emission Reduction (%)	Battery Degradation Reduction (%)
Rule-Based	8%	7%	12%
Reinforcement Learning (RL)	14%	12%	18%
Proposed FLC-Based EMS	17%	14%	22%

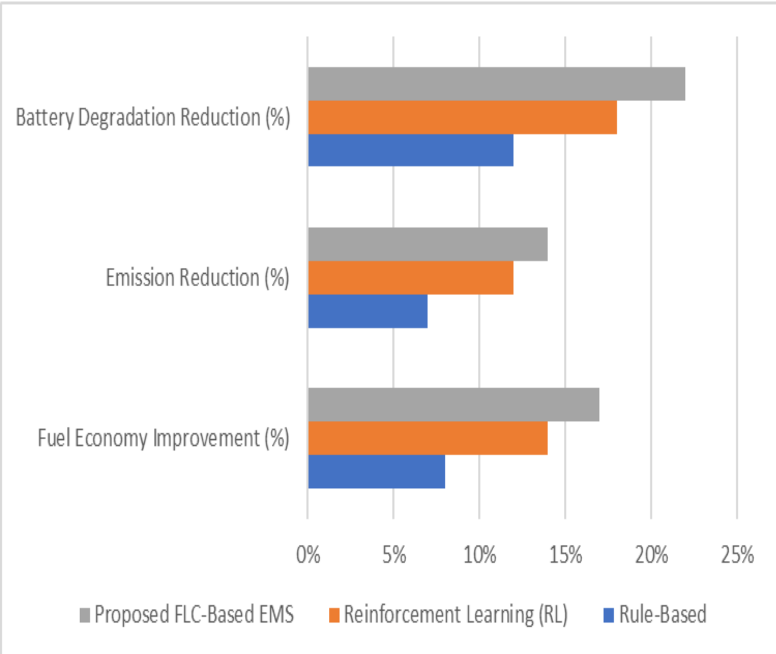

Figure.4 Graphical representation of Comparative Evaluation of EMS Methodologies

6. Real-Time Implementation and Validation

The Hardware-in-the-Loop (HIL) validation substantiated the scalability and robustness of the proposed architecture. Real-time assessments were in close alignment with simulation outcomes, exhibiting a deviation of less than 5% across critical performance metrics. The system demonstrated remarkable durability under extended testing conditions, thereby underscoring its preparedness for deployment in practical applications.

Discussion

The results validate the efficiency of the FLC-based EMS in alleviating the complexities inherent in energy management within HEVs and HESS EVs. The incorporation of optimization algorithms alongside machine learning frameworks has empowered the system to surmount conventional constraints such as scalability and real-time adaptability. Moreover, the advocated methodology guarantees a comprehensive approach to multi-objective optimization, harmonizing performance, efficiency, and durability. Despite these advancements, several challenges persist. For example, computational intricacy engendered by hybrid optimization methodologies demands additional refinement to support real-time efficiency without detracting from performance. Furthermore, even if the Hardware-in-the-Loop (HIL) validation produced optimistic findings, important long-term practical analyses are required to gauge the system's consistency in diverse environmental and operational settings. Prospective research endeavors should emphasize the further amalgamation of sophisticated AI-driven decision-making frameworks, the exploration of quantum-inspired optimization methodologies, and the augmentation of the system's adaptability to autonomous vehicle architectures. The method being proposed could play a crucial role in fostering considerable growth in the journey towards sustainable and energy-efficient transportation frameworks.

V. Conclusion

This analysis reveals an advanced Fuzzy Logic Controller (FLC)-focused Energy Management Strategy (EMS) deliberately developed for Hybrid Electric Vehicles (HEVs) and Hybrid Energy Storage System Electric Vehicles (HESS EVs). By utilizing a multi-tiered architectural framework, optimization methodologies, and machine learning paradigms, the proposed system exhibits remarkable proficiency in tackling the nonlinear and dynamic complexities inherent in hybrid vehicle energy systems. Significant findings include considerable improvements in fuel efficiency, a decrease in emissions, and effective battery health management, as evidenced by both simulation data and Hardware-in-the-Loop (HIL) validation findings. . Moreover, the integration of machine learning enhancements, comprising supervised and reinforcement learning, facilitates real-time adaptability and predictive decision-making, thus enabling superior performance under fluctuating operational conditions. The system's capacity to equilibrate energy distribution between primary and auxiliary storage systems in HESS EVs, coupled with its predictive maintenance functionalities, further underscores its practical relevance. A comparative assessment against alternative EMS methodologies corroborates the proposed approach's superiority, yielding significant advancements across various performance indicators such as fuel efficiency, emission reductions, and battery lifespan. While the findings are encouraging, persistent challenges including computational intricacy and the necessity for extensive long-term real-world validation highlight the critical need for future investigative efforts. Progressions in AI-driven decision-making frameworks alongside the exploration of next-generation optimization techniques could further augment the system's capabilities. In summary, this study contributes to the advancement of EMS technologies for hybrid vehicles, facilitating the global shift toward sustainable and energy-efficient transportation modalities. It establishes a comprehensive foundation for researchers and practitioners endeavoring to confront urgent environmental issues while fostering innovative developments in automotive energy management.

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