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Energy Management Method for Diesel Hydrogen Hybrid Vehicles and Evaluation of Renewable Energy Applications#

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ABSTRACT

How to maximize the use of renewable energy to achieve the most efficient utilization of energy resources is increasingly drawing attention. Against this backdrop, this study proposes a rule-based energy management strategy optimized by the Sparrow Search Algorithm for a novel diesel-hydrogen hybrid power system, investigating the impact of varying power source limits through simulation. The findings demonstrate that controlling the diesel engine power limit to 40–45 kW and the fuel cell power limit to 5–10 kW maximizes the renewable energy proportion and achieves significant energy conservation, establishing an optimal balance between sustainability and dynamic performance

Keywords: renewable energy resources, advanced energy technologies, energy management systems, fuel cell, hydrogen fuel cell.

NONMENCLATURE

Abbreviations	
EMS	Management System
SOC	State of Charge
DP	Dynamic Programming
SSA	Sparrow Search Algorithm
FC	Fuel Cell
Symbols	
P	Power
kW	Kilowatt

1. INTRODUCTION

In the context of the global energy crisis and increasingly stringent carbon emission regulations worldwide, the development of engines powered by renewable gaseous fuels has emerged as a critical initiative in green engineering[1]. Against this backdrop, the diesel-hydrogen hybrid power system, representing a highly promising technological pathway, has garnered significant attention from both academia and industry in recent years.

The diesel-hydrogen hybrid power system is an innovative powertrain architecture that synergistically integrates three primary power sources: a conventional diesel engine, a hydrogen fuel cell, and a high-efficiency power battery. Herein, the conventional diesel engine provides the base load power, ensuring the high reliability and extended range of the entire system. The hydrogen fuel cell, acting as an auxiliary power source, converts hydrogen into electrical energy, thereby effectively reducing the system's carbon emissions. The power battery, with its advantage of rapid response, meets the system's peak power demands while recovering braking energy to enhance overall efficiency. Through an intelligent Energy Management Strategy (EMS) that scientifically coordinates and allocates power among these three sources, it is possible to achieve long-range, high-performance, high-efficiency, and low-carbon operation for vehicles. This technology can effectively address the limitations of pure electric vehicles in long-haul and commercial applications, promote the transformation of the vehicular energy structure, and contribute to building an environmentally friendly transportation system [2]. However, vehicle operating conditions are influenced by numerous environmental factors, such as road gradient and driver behavior. The complexity and uncertainty of road conditions impart a highly time-varying and stochastic nature to vehicle operating cycles. Consequently, designing an EMS with high robustness, excellent economy, and superior durability presents a significant challenge for fuel cell hybrid vehicles [2]. At present, research on energy management methods for diesel-hydrogen hybrid power systems is limited. The optimal power balance among the diesel engine,

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hydrogen fuel cell, and power battery remains an area for further investigation. Exploring superior energy management strategies is pivotal for the commercialization of diesel-hydrogen hybrid systems.

As the core technology of hybrid electric vehicles, the Energy Management Strategy (EMS) directly determines the vehicle's fuel economy, driving performance, and service life [3]. Existing EMS for hybrid vehicles can be broadly categorized into three types: rule-based, optimization-based, and learning-based strategies [4]. Rule-based strategies, often referred to as online strategies, employ control logic and predefined rules to achieve a local optimum. An advantage of rule-based EMS is their low computational requirement for decision-making. Another benefit is that they do not require a priori knowledge of the future driving cycle[5]. In rule-based algorithms, the model first evaluates the required torque, calculates the necessary power, and then determines the appropriate operating mode [4]. Owing to their intuitive design, ease of implementation, low computational burden, high real-time capability, and good robustness, rule-based EMS are widely adopted in current engineering applications. However, their rules are predefined by engineers, making system performance highly dependent on engineering experience, which makes it difficult to achieve global optimality across all operating conditions. Many researchers are working to overcome this limitation. For instance, Zhu et al. utilized real-world driving data to obtain more representative dynamic programming results, which were then used to optimize and improve rule-based strategies[5] .

Optimization-based EMS are a class of control methods founded on mathematical optimization theory, with the direct objective of minimizing a specific cost function, such as fuel consumption, emissions, or total system cost. These are further subdivided into global optimization and real-time optimization strategies. Global optimization strategies require complete a priori knowledge of the entire driving cycle to calculate the globally optimal power allocation sequence over the trip. Common global optimization methods include Linear Programming, Dynamic Programming (DP), Stochastic DP, Comprehensive Optimization Method (COA), Genetic Algorithms (GA), and Particle Swarm Optimization (PSO)[6] . These strategies are highly dependent on foreknowledge of the driving conditions and, compared to rule-based strategies, have significantly higher computational complexity. Therefore, they are typically used offline to establish a benchmark for the global optimum achievable in hindsight [5]. In contrast, real-time optimization strategies do not require future information and perform online optimization based on the current or near-future system state. These strategies overcome the non-real-time limitation of global optimization and are a major focus of research for transitioning optimization-based methods to practical engineering applications. For example, Zhu et al. combined a neural network with DP for energy management, using the neural network to predict decision variables while DP performed the computation, successfully mitigating the non-real-time drawback of global optimization [5].

Learning-based EMS represent a class of intelligent control methods that are data-driven and algorithm-centric. Unlike the aforementioned methods, their core principle is to autonomously learn and explore optimal or near-optimal power allocation strategies from historical or real-time data, without relying on precise physical models or predefined rules. In recent years, intelligent control methods, particularly Reinforcement Learning (RL), have become a research hotspot due to their powerful online learning and optimization capabilities. For instance, Yang et al. developed an RL-based EMS for a fuel cell hybrid vehicle that enables real-time classification of driving conditions and prediction of vehicle speed, thereby improving the vehicle's efficiency [2]. Lian et al. accelerated the learning process by optimizing a deep reinforcement learning-based EMS using the Deep Deterministic Policy Gradient (DDPG) algorithm[7]. Nevertheless, in practical applications, rule-based strategies remain predominant due to their low computational requirements and high stability[4].

Based on the current state of research, this paper proposes a novel energy management strategy for diesel-hydrogen vehicles: a rule-based algorithm optimized by the Sparrow Search Algorithm (SSA). This algorithm aims to approximate the global optimal solution with minimal computational overhead, thereby significantly improving the vehicle's fuel and hydrogen economy. The objective is to enhance the economic viability and sustainability of the diesel-hydrogen thermo-electric hybrid power system. Concurrently, this study will calculate the proportion of sustainable energy used in the diesel-hydrogen vehicle and provide an outlook on its future prospects in sustainable energy applications.

2. METHODS

Research on energy management strategies for diesel–hydrogen hybrid vehicles has remained relatively scarce in recent years. To address this gap, this paper introduces an advanced rule-based strategy specifically designed to optimize the energy management of diesel–hydrogen hybrid powertrains.

2.1 Vehicle driving mode

a) Parking Mode

During short-term parking, the fuel cell operates at its minimum power output to extend its service life, whereas in the case of long-term parking (exceeding 5 seconds), the fuel cell is shut down to conserve energy. Fig. 1 shows the state at this mode.

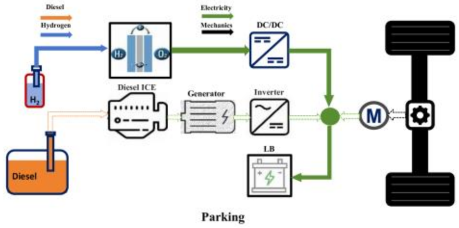

Fig. 1: Parking

b) Regenerative Braking Mode

Regenerative braking means the process that the kinetic energy from slope and declaration is converted to electricity and been stored in battery. Vehicle could be regarded in regenerative braking when the demand power less than zero. Fig. 2 shows the state at this mode.

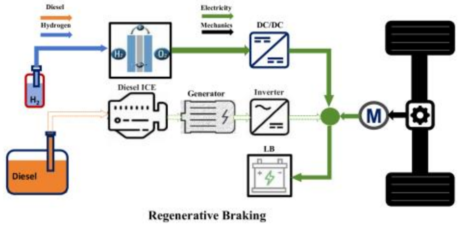

Fig. 2 Generative Braking

c) Fuel Cell Driving Mode

When the power demand falls within the operating range of the fuel cell, the fuel cell supplies nearly the entire required power owing to its relatively high efficiency. If the fluctuation in power demand exceeds the instantaneous load-following capability of the fuel cell, the battery compensates for the remaining demand. Fig.3 shows the state at this mode.

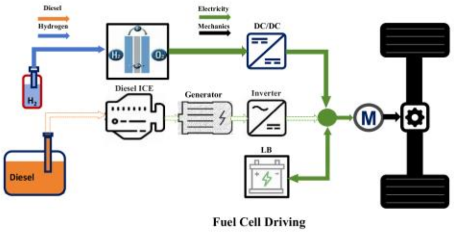

Fig. 3: Fuel Cell Driving

d) Hybrid Driving Mode

Applied when fuel cell fails to cover demand power. Three power resources will contribute to the power supplement together. Fig. 4 shows the state at this mode.

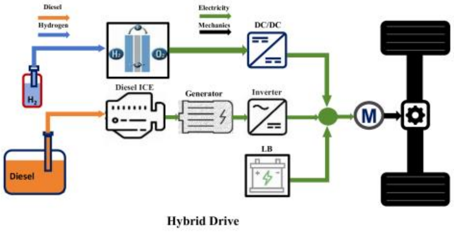

Fig. 4 Hybrid Driving

2.2 Rule-Based Energy Management

In the rule-based energy management framework, the algorithm initiates by performing a diagnostic check of the vehicle's hardware components. Should any faults be identified, a maintenance alert is triggered. Afterward, the model evaluates the torque demand and derives the corresponding power requirement to establish the proper operating mode. The algorithm of rule-based EMS is shown in Fig. 5.

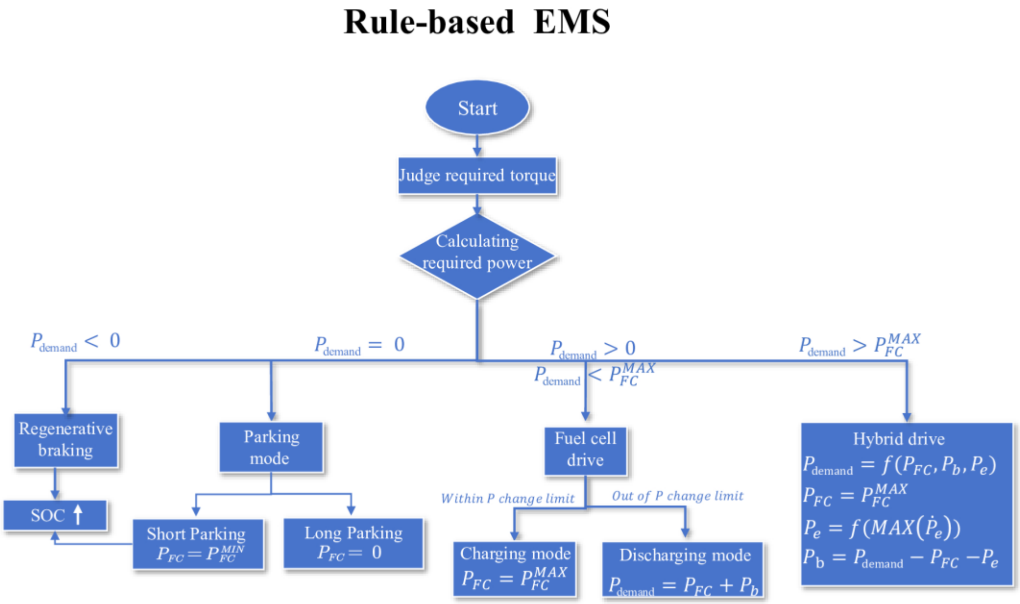

Fig. 5 The structure of Rule-based EMS

According to the variation in power demand, the strategy is divided into four operating modes. In parking and regenerative braking modes, the system charges the battery based on its state of charge. When the power demand is relatively low, the fuel cell fulfills the requirement with higher efficiency, and the vehicle operates in a fuel cell–dominant driving mode. In scenarios of sudden power demand fluctuations, the battery can promptly supply additional power to ensure stability. Finally, when the power demand exceeds the operating range of the fuel cell, the vehicle switches to hybrid driving mode, in which the three power sources cooperate to deliver power.

3. DISCUSSIONS

The diesel-hydrogen hybrid power system synergistically integrates three primary power sources: a conventional diesel engine, a hydrogen fuel cell, and a high-efficiency power battery. Herein, the hydrogen fuel cell converts the chemical energy of hydrogen into electrical energy via an electrochemical reaction, directly providing power output for the vehicle while also being capable of charging the power battery. Throughout the entire reaction process within the fuel cell, water is the sole byproduct, resulting in zero greenhouse gas emissions. Furthermore, the hydrogen source is renewable. Hydrogen produced through the electrolysis of water using electricity from renewable sources—such as solar, wind, or hydropower—is termed "green hydrogen," as the entire process is green, non-polluting, and sustainable. Therefore, in the diesel-hydrogen hybrid power system discussed in this paper, the hydrogen fuel cell serves as the renewable energy component.

To investigate the impact of varying power source limits on the utilization of renewable energy and the efficiency of the diesel-hydrogen hybrid system, this study conducts multiple sets of simulation experiments based on the MATLAB simulation platform. By adjusting the power limit of the diesel engine (ranging from 40 to 65 kW) and the fuel cell (ranging from 5 to 15 kW), the variation patterns of the efficiencies of the two power sources, the system's renewable energy proportion, and its overall efficiency were comprehensively analyzed. The "renewable energy proportion" metric is specifically defined as the percentage of cumulative energy supplied by the fuel cell (powered by green hydrogen) relative to the sum of the cumulative energy from both the fuel cell and the diesel engine (Renewable Energy % = [Cumulative FC Energy] / [Cumulative FC Energy + Cumulative Diesel Energy]). This metric directly reflects the system's degree of reliance on and utilization efficiency of renewable energy. The analysis of the simulation results is presented below. The calculation of vehicle speed and total demand power is shown in Fig 6, and various types of demand power are shown in Fig 7.

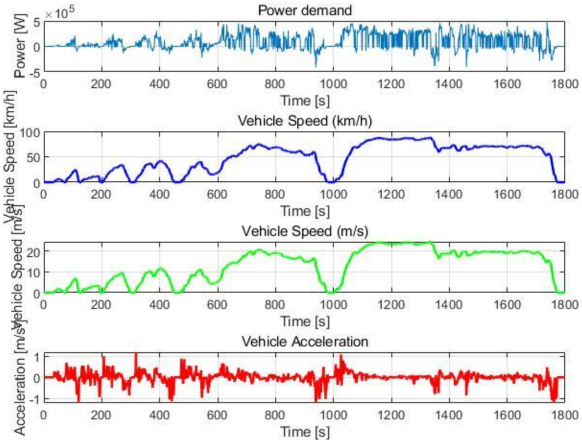

Fig. 6 Vehicle Speed and Power Demand

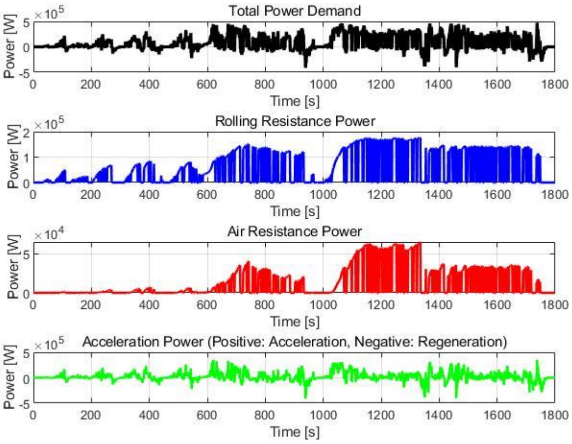

Fig. 7 Breakdown of Total Power Demand

3.1 Analysis of the Variation in Renewable Energy Proportion

a) Influence of the Diesel Engine Power Limit

This study established five levels for the diesel engine power limit, from 40 kW to 65 kW, for experimental analysis. The results indicate that, with other parameters held constant, the renewable energy proportion exhibits a significant monotonic decrease as the diesel engine power limit increases. The underlying reason is that an increased power limit for the diesel engine allows it to reach the "ideal power" more rapidly under high-power demand scenarios. Consequently, the system's energy management strategy prioritizes the use of the diesel engine over the fuel cell and power battery for primary power output. This results in an increase in the cumulative energy supplied by the diesel engine and a decrease in that from the fuel cell, causing the renewable energy proportion over the entire cycle to decline as the diesel engine power limit is raised. The diesel consumption and hydrogen consumption are shown in Fig 8.

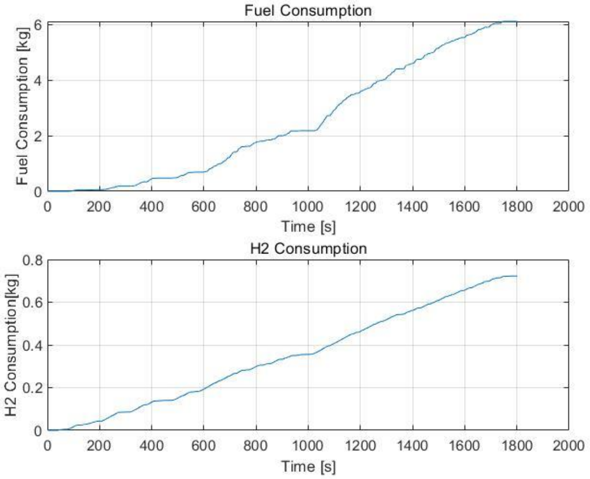

Fig. 8 Fuel Consumption & Hydrogen Consumption

b) Influence of the Fuel Cell Power Limit

This study established three levels for the fuel cell power limit, from 5 kW to 15 kW, for experimental analysis. The results show that, with other parameters held constant, the renewable energy proportion demonstrates a slight upward trend as the fuel cell power limit is reduced. For example, when the diesel engine power limit was set to 40 kW, decreasing the fuel cell power limit from 15 kW to 5 kW resulted in the renewable energy proportion increasing from 33.39% to 34.46%, an increment of only 1.07 percentage points. The data reveal that the magnitude of the fuel cell power limit's impact on the renewable energy proportion is far smaller than that of the diesel engine power limit. This is attributed to the fact that the overall energy contribution from the fuel cell is inherently lower, and its maximum power is significantly less than that of the diesel engine.

3.2 Analysis of Power Source Efficiency and Overall Efficiency

The results show that the fuel cell power limit has a negligible effect on the efficiency of the fuel cell itself; its efficiency remained stable at 0.51 across all experimental groups in the table. However, the fuel cell power limit cannot be increased substantially. A higher limit would cause the fuel cell's power to fluctuate abruptly in short periods. While this could improve dynamic response, it would also intensify the dynamic load on the membrane electrode assembly (MEA), thereby reducing the fuel cell's service life. Conversely, a smaller power limit ensures a smoother power regulation, creating a more stable reaction environment at the MEA interface. This can effectively mitigate damage from hydro-thermal cycling and chemical stress, thus extending the battery's lifespan. The curve of battery SOC variation is shown in Fig 9.

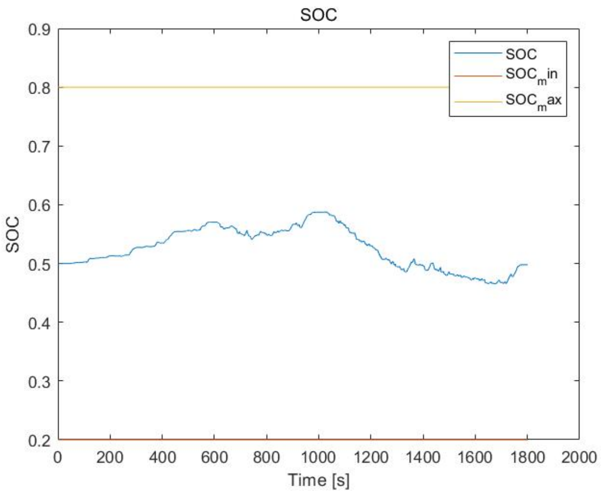

Fig. 9 SOC

The diesel engine's efficiency, on the other hand, slowly decreases as its power limit increases. When the fuel cell power limit was 10 kW, increasing the diesel engine power limit from 40 kW to 65 kW caused the engine's efficiency to drop from 0.484 to 0.435, a decrease of 0.049. This is because a higher power limit for the diesel engine leads to greater power output in high-demand scenarios. Since the engine's operation over a full cycle includes both high-power and low-power conditions, the overall efficiency decreases as the proportion of high-power operation within the cycle increases.

Synthesizing the analysis of the experimental results, a direction for optimizing the diesel-hydrogen hybrid power system can be derived: while ensuring that the vehicle's power demands are met, controlling the diesel engine power limit to a range of 40–45 kW and the hydrogen fuel cell power limit to 5–10 kW can maximize the renewable energy proportion and achieve energy conservation and emission reduction, all while maintaining adequate dynamic response.

4. CONCLUSIONS

Under conditions of sustained high-power output, the diesel engine serves as the primary power source. For transient high-power demands, the power battery acts as the main power source, while for sustained low-power output, the fuel cell assumes this role. This study demonstrates that adjusting the power limits of the diesel engine and fuel cell significantly impacts the system's reliance on renewable energy and overall efficiency.

Increasing the diesel engine's power limit leads to a notable decrease in the renewable energy proportion, as the system prioritizes the diesel engine for high-power demands, which is reflected in the fuel consumption trends, according to Fig. 8. Conversely, the fuel cell's power limit has a lesser effect on the renewable energy ratio but is critical for ensuring the longevity of the membrane electrode assembly by avoiding abrupt power fluctuations. The stable operation and energy buffering capability of the power battery were confirmed by the state of charge (SOC) profile, which remained within safe operating limits throughout the cycle, as one may find out from Fig. 9

To optimize the diesel-hydrogen hybrid system, a balance must be struck between performance and sustainability. The findings suggest that by controlling the diesel engine power limit within a 40–45 kW range and the hydrogen fuel cell power limit between 5–10 kW, it is possible to maximize the use of renewable energy and achieve significant energy conservation and emission reduction without compromising the vehicle's dynamic response.

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