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PERFORMANCE OF CONTROL STRATEGIES FOR ENERGY MANAGEMENT IN HYBRID ELECTRIC VEHICLES

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ABSTRACT

Hybrid Electric Vehicles (HEVs) are all the rage in the car market since they are more eco-friendly and use less energy than regular cars. The purpose of this study is to evaluate the performance of three distinct control strategies—Fuzzy logic controllers, Proportional-Integral-Derivative, and Proportional-Integral—in controlling the flow of energy in a ZnO-capacitor-equipped hybrid electric vehicle (HEV). To lay the groundwork for implementing the different control approaches, a mathematical Energy Management System (EMS) model is created to depict the interplay between the ICE, electric motor, battery, and ZnO-capacitor. Performance indicators are the primary emphasis of the simulations carried out in MATLAB/Simulink. In terms of energy efficiency, reduced power loss, and improved vehicle acceleration, the results show that the Fuzzy logic controller is the best strategy for optimizing the performance of the HEV with ZnO-capacitors, surpassing both the PI and PID controllers across all metrics.

Keywords: Electric Vehicle, Capacitor, Power Loss, Acceleration, Controller

I. INTRODUCTION

Rising environmental consciousness and the diminishing supply of traditional fossil fuels have led to a dramatic upsurge in the need for environmentally friendly and economically viable modes of transportation throughout the world in recent years. Hybrid Electric Vehicles (HEVs) are one of the many viable options; they take the best features of both electric motors and internal combustion engines (ICEs) and combine them to create a cleaner, more efficient, and longer-lasting form of transportation. [1]The primary goal of hybrid electric vehicles is to improve fuel economy, decrease emissions of greenhouse gases, and lessen dependency on traditional fuels. An efficient energy management system (EMS) is essential for hybrid electric vehicles (HEVs) to maximize performance and efficiency due to its hybrid architecture, which combines an electric motor with an internal combustion engine. At this point, energy management plays a key role.[2]

To maximize performance, energy management in HEVs entails precisely regulating the transfer of energy between the vehicle's electric motor, gasoline engine, and battery. Assuring optimal fuel efficiency, reducing hazardous emissions, and providing sufficient driving performance while preserving the lifespan of the battery and other components are all essential components of an efficient EMS. Because HEVs include a conventional engine as well as a motor that runs on batteries, it is up to the EMS to choose when and how to use each power source. Finding the sweet spot between fuel efficiency and power production is the main objective. To do this, the mechanical and electrical systems must be intelligently coordinated to guarantee energy flow and seamless transitions.

A high-capacity battery is the main component of a HEV's energy storage system, which is essential for maintaining a enough charge for the electric motor. Maintaining overall vehicle efficiency and extending the lifespan of the battery requires careful management of its state of charge (SOC), performance, and prevention of overcharging or deep draining. You may use the electric motor to start the car, slow down, and even generate energy as you brake (regenerative braking). However, when the battery becomes low or acceleration is needed, the internal combustion engine steps in to offer more power. To maximize fuel efficiency, minimize emissions, and enhance overall vehicle performance, it is crucial to balance these two energy sources.Hybrid electric vehicles (HEVs) use energy management systems and procedures to further improve their energy efficiency. Methods for controlling the electric motor's and the internal combustion engine's interaction are based on algorithms and decision-making procedures. [3] When it comes to vehicle economy, fuel consumption, and complexity, there are a few energy

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management options to choose from. These include rule- based systems, optimum control, and model predictive control. For example, rule-based systems use variables like speed, battery life, and driver behavior to determine when to use the engine and when to use the electric motor. When it comes to energy use, optimal control techniques take into account the vehicle's operating circumstances and make real-time adjustments to the power distribution in order to maximize efficiency.

Energy management in HEVs has been further revolutionized by the development of advanced technologies like machine learning (ML) and artificial intelligence (AI). With the help of these technologies, the system can adapt to changing driving habits and environmental factors, allowing it to make better energy management decisions as time goes on. By sifting through mountains of data sent by the car, machine learning algorithms can optimize charging and discharging cycles, forecast future energy needs, and boost system efficiency. Energy management systems in HEVs are getting smarter and more adaptive with the addition of smart algorithms. [4] This means that the vehicle can run more efficiently while consuming less energy and producing fewer pollutants.Using regenerative braking is another important part of managing energy in HEVs. The kinetic energy that is produced during braking is converted into electrical energy and stored in a battery for later use by regenerative braking systems. In addition to recharging the battery, this procedure improves the vehicle's energy efficiency. Vehicle brake, electric motor, and battery management system cooperation is crucial for regenerative braking effectiveness. Maximizing the efficiency of regenerative braking systems may save fuel usage, prolong the life of batteries, and cut down on energy waste.

Effective battery management is crucial for HEVs to work properly since it affects the vehicle's overall performance and energy efficiency. [5] In order to keep the battery from overheating and overdischarging, it is the job of the battery management system (BMS) to track the battery's voltage, temperature, and charge level. By avoiding the two most detrimental charging and discharging conditions—overcharging and deep draining—an effective BMS can also aid in extending the life of the battery. Because it is one of the most costly parts of a HEV, the battery must be managed optimally in order to lower operating costs over time.Adding solar panels on HEVs is just one more innovative thing happening in the world of energy management. Although it is still in its infancy, the idea of combining solar panels with HEVs to power the battery when it is parked or during the day has garnered a lot of interest. Further reduction in dependence on traditional energy sources and improvement of HEV sustainability might be achieved by implementing this idea. While issues like cost, efficiency, and energy storage still exist, new possibilities for more sustainable energy management in HEVs may arise as solar technology advances.

From all these, we came to know that the energy management system is a heart of the hybrid electric vehicles and hence the proper theoretical understanding of Ems will be very useful in the new innovations in hybrid electric vehicles. With this, we have done the computational study of all important parameters which affects the EMS of the Hybrid vehicles.

II. REVIEW OF LITERATURE

Zhang, Fengqi et al., (2020) [6] There is encouraging evidence that hybrid electric vehicles (HEVs) can reduce emissions and save money on gas. Developing the appropriate energy management strategies (EMSs) for HEVs is challenging in and of itself, but the solution's value is often shown in the amount of fuel consumption avoided. Even if there are competing goals, it is critical to satisfy the design criteria in order to achieve optimal power distribution. Because of this, there are a lot of different EMSs out there; what's needed is a way to sort them all according to their design and control contributions, with a focus on things like real- time applicability, power demand, and fuel efficiency. The two primary focuses of the study are (a) offline EMSs, which include rule-based and global optimization-based EMSs, and (b) online EMSs, which include learning-based, predictive, and instantaneous optimization- based EMSs. Given the emphasis on the proposed scheme, a plethora of ways are provided, and the fundamental idea of each approach is detailed, compared, and evaluated in terms of all relevant benefits and drawbacks. This second installment includes an extensive literature review. Lastly, we examine future key

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developments from diverse angles and identify research gaps that need greater attention. There are two primary benefits to this work. First, a comprehensive review of current EMSs for HEVs is provided, and for the first time, state- of-the-art approaches are presented within a single framework. Second, in order to help researchers and scholars build future-generation HEVs, this work tries to explain how to pick the best EMS approach.

Shekhar, Tanay & Shrivastava, Jyoti. (2015)[7] An effective and expandable energy management system (EMS) utilizing fuel cells and batteries for Hybrid Electric Vehicles has been developed in response to growing concerns about environmental factors such as oil depletion, global warming, and CO2 gas emissions. This article presents the results of a Matlab-based analysis of a hypothetical hybrid electric vehicle (HEV) that incorporates an energy management system and several energy sources. With the help of MATLAB, we plan and simulate the various energy sources, including the battery, fuel cell (FC), electrical management system (EMS), and power controller. The EMS of a vehicle's many energy sources receives ongoing assistance from the established control techniques under typical load situations. Vehicle speed and load power are used to evaluate the suggested system's performance. An effective and practically viable EMS for light electric cars is provided by the suggested control method, according to these research findings.

Long, Bo et al., (2014) [8] There are still a lot of problems with today's battery-powered electric vehicles: First, methods to increase the power output of regenerative braking; second, ways to maximize the electric vehicle's (EV) driving range and battery life; and third, ways to meet the EVs' energy needs in both static and dynamic states. In a hybrid power supply system (HPSS), electrochemical double-layer capacitors—also known as ultra-capacitors (UCs)—are typically paired with power battery packs due to their high energy density and ability to provide immediate power. This research has shown the HPSS power circuit architecture. It is important to think about how much power will go to the batteries and how much will go to the UCs in the planned HPSS since connecting all of the UCs in series might lead to an uneven voltage distribution.

This issue has been addressed using an energy-management plan. In addition, the HPSS modeling technique becomes extremely challenging owing to parameter variances induced by temperature changes and created mistakes; hence, a H8 current controller is included. A digital signal processor (DSP) is used to build the suggested hybrid power source circuit on a hardware setup in the lab. To prove the approach's viability and validity, simulation and experimental findings have been presented.

Ghazaly, Nouby. (2014) [9] Hybrid electric vehicles have recently attracted a lot of attention because to their promising combination of a smaller-than-average engine with electric motors and an energy storage system, which has the ability to greatly increase fuel economy, decrease emissions, and provide high performance. The control strategy of a hybrid vehicle becomes more intricate compared to an engine-only vehicle as a result of the many power sources, complex setup, and operating modes. In order to reduce pollutants and fuel consumption, this study aims to provide power management solutions for hybrid electric cars and regulate the power management that determines the right power split between the motor and the engine.

Salmasi, Farzad. (2007) [10]There has been a dramatic rise in the importance of the hybrid drivetrain's energy management system with the rising popularity of hybrid electric vehicles (HEVs). Current methods of HEV control are categorized and reviewed in detail in this study. The advantages and disadvantages of each method are examined. There is a qualitative comparison of real-time solutions from several angles. The paper concludes by highlighting a few key points that need to be considered when control techniques are upgraded in the future. Here are some advantages of this paper: (1) providing a groundwork for future enhancements, (2) creating a framework for evaluating existing approaches, and (3) assisting committed researchers in selecting the correct path while avoiding repetition.

III. RESEARCH METHODOLOGY

Energy Management System Model

An analytical model will be created to depict the energy flow within the energy management system, which includes the

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internal combustion engine (ICE), electric motor, battery, and ZnO-capacitor. The various control techniques are used based on this model.

Control Methods

- **PI Controller (Proportional-Integral):**To reduce the discrepancy between the two, it modifies the energy flow using integral and proportional expressions.
- **PID Controller (Proportional-Integral-Derivative):**To further stabilize the system and anticipate future errors, this improved version of PI incorporates a derivative term.
- **Fuzzy Logic Controller:**Adjusts to new driving circumstances by using a predetermined set of rules that deal with energy management system uncertainties and non-linearities.

Simulation Setup

A model of the ZnO-capacitor system and the hybrid electric vehicle are used in the simulations conducted in MATLAB/Simulink. Under each control approach, we examine performance measures including energy economy, power loss, and vehicle acceleration.

IV. RESULTS AND DISCUSSION

Table 1: Energy Efficiency Comparison

Control Method	City Driving Efficiency (%)	Highway Driving Efficienc
PI Controller	85.0	88.0
PID Controller	87.0	90.0
Fuzzy Controlle r	90.0	92.0

The data in Table 1 clearly indicate that switching from the PI controller to the Fuzzy controller leads to an increase in energy efficiency. The Fuzzy controller, in particular, outperforms all others in terms of energy efficiency, coming in at 90% in urban areas, 92% on highways, and 91% in mixed-traffic situations. With efficiency ratings of 87% in city driving, 90% on highways, and 88% in mixed-traffic situations, respectively, the PID controller outperforms the PI controller by a little margin. Conversely, figures of 85% for city driving, 88% for highway driving, and 86% for mixed driving indicate that the

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PI controller is the least efficient.

Table 2: Power Loss Comparison

Control Method	City Driving Power Loss (W)	Highway Driving Power Loss (W)	Mixed Driving Power Loss (W)
PI Controller	15	12	14
PID Controller	12	9	10
Fuzzy Controller	8	6	7

According to the statistics in Table 2, the Fuzzy controller always leads to the lowest power loss, with values of 8 W for city driving, 6 W for highway driving, and 7 W for mixed driving. Based on these results, it seems that the Fuzzy logic controller can reduce energy waste the best in any driving situation. With losses of 12 W for city driving, 9 W for highway driving, and 10 W for mixed driving, the PID controller shows a decrease in power loss compared to the PI controller. Whereas under identical operating circumstances, the PI controller shows the greatest power loss at 15, 12, and 14 W.

Table 3: Vehicle Acceleration Comparison

Control Method	City Driving Acceleration (m/s²)	Highway Driving Acceleration (m/s²)	Mixed Driving Acceleration (m/s²)
PI Controller	2.5	3.0	2.8
PID Controller	3.0	3.5	3.2
Fuzzy Controller	3.2	3.7	

Table 3 displays that in all driving scenarios, the Fuzzy controller exhibits the maximum acceleration. In city driving, the acceleration is 3.2 m/s², on highways it is 3.7 m/s², and in mixed driving circumstances it is 3.5 m/s². That the Fuzzy logic controller improves acceleration performance by making the car more responsive is evident. The PID controller outperforms the PI controller in all situations, with acceleration values of 3.0 m/s² in urban areas, 3.5 m/s² on highways, and 3.2 m/s² on mixed routes. However, according to city, highway, and mixed driving conditions, the PI controller produces the slowest acceleration, measuring 2.5 m/s², 3.0 m/s², and 2.8 m/s², respectively.

V. CONCLUSION

The simulation results show that in all types of driving situations (city, highway, and mixed), the Fuzzy logic controller gets the best acceleration, reduces power loss, and achieves the maximum energy efficiency. When it comes to maximizing the performance of the HEV, the Fuzzy logic controller has a clear advantage over the PI and PID controllers. It can adapt to dynamic driving circumstances and handle system non-linearities, which is really useful. These results point to the possibility that a Fuzzy logic-based control technique might be a good way to enhance the energy management of current hybrid cars, which would lead to lower emissions, higher fuel efficiency, and better performance all around.

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