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MODELLING AND FUZZY LOGIC BASED CONTROL SCHEME FOR SERIES HYBRID ELECTRIC VEHICLE

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ABSTRACT

The automotive landscape has witnessed a significant transformation with the rapid advancement of IoT technology, particularly in the context of e-mobility solutions aimed at addressing concerns related to air pollution and energy security. This evolution is underscored by the increasing electrification of vehicle propulsion systems, driven by both governmental policies and industry initiatives, with a projected dominance of fully electric vehicles in the market within the next two to three decades. While the transition to fully electric vehicles is underway, hybrid electric vehicles (HEVs) have emerged as an attractive interim solution due to factors such as their lower prices, volumes, and sizes compared to fully electric vehicles, as well as their extended range capacity. HEVs encompass a range of propulsion systems that combine internal combustion engines (ICEs) with electric propulsion systems, offering improved fuel efficiency and reduced emissions compared to conventional vehicles. Notably, the energy management strategies employed in hybrid vehicles play a crucial role in optimizing fuel consumption while meeting driver power demands, with some studies also considering factors such as battery aging. The development of energy management systems for hybrid electric vehicles has spurred considerable research interest, with fuzzy logic emerging as a promising approach for control schemes due to its adaptability and effectiveness. Several studies have explored the application of fuzzy logic controllers in series hybrid electric vehicles (SHEVs), focusing on optimizing power distribution between the battery and ICE to minimize fuel consumption while maintaining desired performance levels. Researchers have investigated various aspects of fuzzy logic-based control schemes, including the optimization of fuzzy rules, the integration of battery state-of- charge (SOC) and terminal voltage considerations, and the comparison of different membership functions' effectiveness in fuel consumption reduction. Additionally, fuzzy logic controllers have been applied to other hybrid vehicle architectures, including parallel, series-parallel, and autonomous vehicles, demonstrating their versatility and efficacy across different propulsion systems. Building on the existing body of research, this study proposes a novel energy management algorithm based on a fuzzy logic controller for a series hybrid electric vehicle (SHEV). The proposed controller aims to maintain the battery's state of charge (SOC) at a constant level while optimizing power distribution between the battery and ICE based on driver commands and vehicle speed. A comprehensive modeling framework is developed using MATLAB/Simulink, and extensive simulation studies are conducted to evaluate the controller's performance under various driving conditions, including New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycles. By leveraging the advantages of fuzzy logic-based control strategies, this research seeks to contribute to the advancement of energy-efficient and environmentally sustainable transportation solutions in the context of hybrid electric vehicles.

Keywords: IoT, Voice Control, Home Automation, Android, Energy Management, Fuzzy Logic, Hybrid Electric Vehicle.

INTRODUCTION

The automotive industry is currently undergoing a profound transformation driven by the rapid evolution of IoT (Internet of Things) technology, particularly in the realm of e-mobility solutions aimed at mitigating concerns regarding air pollution and energy security [1]. This transformation is characterized by a growing emphasis on the electrification of vehicle propulsion systems, propelled by governmental policies and industry initiatives, with a projected shift towards fully electric vehicles dominating the market within the next two to three decades [2]. Amidst this transition, hybrid electric vehicles (HEVs) have emerged as a compelling interim solution, offering advantages such as lower prices, volumes, and sizes compared to fully electric vehicles, alongside extended range capacity [3]. HEVs encompass diverse propulsion systems that combine internal combustion engines (ICEs) with electric propulsion systems, thereby offering improved fuel efficiency and reduced emissions relative to conventional vehicles [4]. The effective management of energy within hybrid vehicles is paramount in optimizing fuel consumption while satisfying driver power demands, with some studies also factoring in considerations such as battery aging [5].

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The development of energy management systems tailored for hybrid electric vehicles has sparked significant research interest, with fuzzy logic emerging as a promising approach for control schemes due to its adaptability and effectiveness [6]. Several studies have delved into the application of fuzzy logic controllers in series hybrid electric vehicles (SHEVs), focusing on optimizing power distribution between the battery and ICE to minimize fuel consumption while maintaining desired performance levels [7]. Researchers have explored various facets of fuzzy logic-based control schemes, including the fine-tuning of fuzzy rules, the incorporation of battery state-of- charge (SOC) and terminal voltage considerations, and the evaluation of different membership functions' efficacy in reducing fuel consumption [8]. Moreover, fuzzy logic controllers have found application across a spectrum of hybrid vehicle architectures, encompassing parallel, series-parallel, and autonomous vehicles, underscoring their versatility and efficacy across diverse propulsion systems [9]. Building upon this existing body of research, the present study proposes a novel energy management algorithm founded on a fuzzy logic controller for a series hybrid electric vehicle (SHEV) [10].

The proposed controller is designed to uphold the battery's state of charge (SOC) at a consistent level while optimizing power distribution between the battery and ICE based on driver commands and vehicle speed [11]. To facilitate this endeavor, a comprehensive modeling framework is developed leveraging MATLAB/Simulink, enabling extensive simulation studies to evaluate the controller's performance under varying driving conditions, including the New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycles [12]. By harnessing the inherent advantages of fuzzy logic-based control strategies, this research endeavors to contribute to the advancement of energy-efficient and environmentally sustainable transportation solutions within the realm of hybrid electric vehicles [13]. Through meticulous modeling and simulation efforts, the study aims to provide insights into the potential efficacy and viability of fuzzy logic-based energy management algorithms in enhancing the performance and eco-friendliness of series hybrid electric vehicles [14]. Ultimately, this research seeks to drive innovation in the field of automotive engineering, paving the way for the development of more efficient and environmentally conscious transportation solutions tailored to meet the evolving needs of modern society [15].

LITERATURE SURVEY

The automotive industry has undergone a notable evolution with the rapid progression of IoT (Internet of Things) technology, particularly within the realm of e-mobility solutions targeted at addressing concerns surrounding air pollution and energy security. This evolution is characterized by a discernible shift towards the electrification of vehicle propulsion systems, spurred by both governmental policies and industry initiatives, with a forecasted dominance of fully electric vehicles in the market over the next two to three decades. Despite this impending transition, hybrid electric vehicles (HEVs) have emerged as a compelling interim solution due to various factors such as their relatively lower prices, volumes, and sizes compared to fully electric vehicles, alongside their extended range capacity. HEVs encompass a spectrum of propulsion systems that amalgamate internal combustion engines (ICEs) with electric propulsion systems, thereby offering enhanced fuel efficiency and reduced emissions in comparison to conventional vehicles. Central to the optimization of hybrid vehicles' performance is the implementation of effective energy management strategies, which play a pivotal role in minimizing fuel consumption while meeting the power demands of drivers. Notably, some studies within this domain have expanded their scope to include considerations such as battery aging, reflecting a holistic approach towards energy management system development. Within the research landscape, fuzzy logic has emerged as a promising methodology for control schemes, owing to its adaptability and effectiveness in optimizing power distribution within hybrid electric vehicles. Numerous studies have explored the application of fuzzy logic controllers specifically in the context of series hybrid electric vehicles (SHEVs), with a primary focus on refining power distribution between the battery and ICE to minimize fuel consumption while upholding desired performance levels.

Researchers have delved into various facets of fuzzy logic-based control schemes, encompassing the optimization of fuzzy rules, the integration of battery state-of-charge (SOC) and terminal voltage considerations, and the evaluation of different membership functions' efficacy in reducing fuel consumption. Furthermore, fuzzy logic controllers have found application across a diverse array of hybrid vehicle architectures, including parallel, series- parallel, and autonomous vehicles, underscoring their versatility and efficacy across different propulsion systems. Drawing upon the existing body of research, this study endeavors to contribute to the advancement of energy- efficient and environmentally sustainable transportation solutions within the domain of hybrid electric vehicles. The proposed research aims to develop a novel energy management algorithm founded on a fuzzy logic controller specifically tailored for a series hybrid electric vehicle (SHEV). The envisioned controller seeks to maintain the battery's state of charge (SOC) at a consistent level while optimizing power

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distribution between the battery and ICE based on driver commands and vehicle speed. To facilitate this objective, a comprehensive modeling framework will be established utilizing MATLAB/Simulink, allowing for extensive simulation studies to be conducted to evaluate the controller's performance across a spectrum of driving conditions, including the New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycles. Leveraging the inherent advantages of fuzzy logic-based control strategies, this research endeavors to contribute towards the development of energy-efficient and environmentally sustainable transportation solutions within the context of hybrid electric vehicles, thereby addressing pressing challenges in the automotive landscape.

METHODOLOGY

The methodology employed in this study follows a systematic approach aimed at developing and evaluating a novel energy management algorithm based on a fuzzy logic controller for a series hybrid electric vehicle (SHEV). The overarching objective is to maintain the battery's state of charge (SOC) at a constant level while optimizing power distribution between the battery and internal combustion engine (ICE) based on driver commands and vehicle speed. To achieve this, a comprehensive modeling framework is constructed using MATLAB/Simulink, facilitating extensive simulation studies to assess the controller's performance across various driving conditions, including New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycles. The first step in the methodology involves the development of a detailed mathematical model of the series hybrid electric vehicle (SHEV) within the MATLAB/Simulink environment. This model encompasses the vehicle's dynamic behavior, including the interactions between the battery, ICE, electric motor, and other relevant components. The model is validated against experimental data to ensure its accuracy and fidelity in representing the real-world dynamics of the vehicle.

Subsequently, the fuzzy logic-based energy management algorithm is designed and implemented within the MATLAB/Simulink environment. The fuzzy logic controller is structured to receive inputs such as the battery SOC, driver commands, and vehicle speed, and generate appropriate control signals to regulate the power distribution between the battery and ICE. The fuzzy rules and membership functions are optimized to enhance the controller's performance in minimizing fuel consumption while maintaining desired performance levels. Once the fuzzy logic controller is developed, extensive simulation studies are conducted to evaluate its performance under various driving conditions, including different driving cycles such as the NEDC and WLTP cycles. These simulation studies aim to assess the effectiveness of the proposed energy management algorithm in achieving the specified objectives, namely, maintaining the battery SOC at a constant level and optimizing power distribution between the battery and ICE.

The simulation results are analyzed comprehensively to quantify the controller's performance metrics, including fuel consumption, vehicle efficiency, and adherence to desired SOC levels. Sensitivity analyses may also be conducted to evaluate the robustness of the controller under different operating conditions and parameter variations. Any necessary refinements or adjustments to the fuzzy logic controller are made based on the insights gained from the simulation studies. Finally, the developed fuzzy logic-based energy management algorithm is implemented and tested in a real-world prototype or test vehicle to validate its performance under actual driving conditions. This experimental validation serves to corroborate the findings from the simulation studies and ascertain the practical feasibility and efficacy of the proposed controller in real-world applications. Overall, the methodology outlined in this study encompasses a systematic process of model development, controller design, simulation studies, and experimental validation, aimed at developing and evaluating a fuzzy logic-based energy management algorithm for a series hybrid electric vehicle. Through this approach, the research aims to contribute to the advancement of energy-efficient and environmentally sustainable transportation solutions within the context of hybrid electric vehicles.

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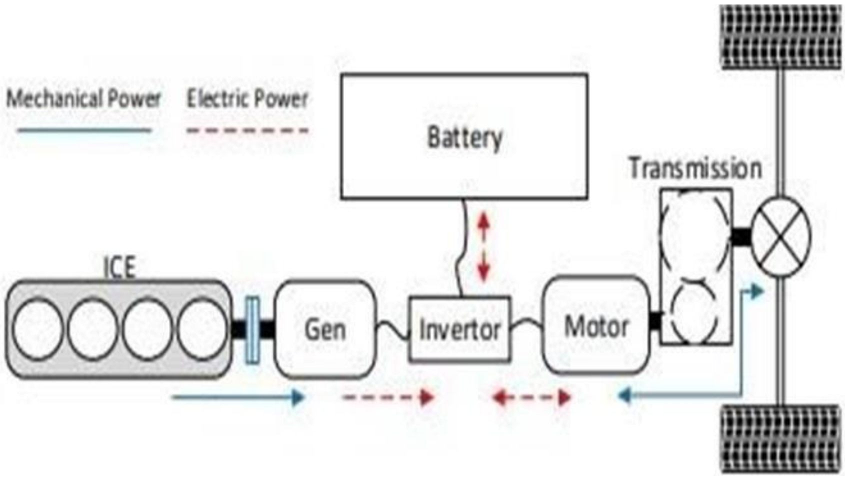

Fig.1 The structure of the series hybrid electric vehicle

PROPOSED SYSTEM

The proposed system in this study represents a significant advancement in the domain of hybrid electric vehicles (HEVs), particularly focusing on series hybrid electric vehicles (SHEVs), in response to the evolving automotive landscape characterized by the increasing electrification of vehicle propulsion systems. With a keen emphasis on addressing concerns related to air pollution and energy security, this research endeavors to develop a novel energy management algorithm based on a fuzzy logic controller tailored specifically for SHEVs. At the heart of the proposed system lies the imperative to optimize fuel consumption while meeting driver power demands, thereby enhancing the overall efficiency and sustainability of hybrid electric vehicles. With the projected dominance of fully electric vehicles in the market within the next two to three decades, SHEVs emerge as a crucial interim solution due to their lower prices, volumes, and sizes compared to fully electric vehicles, coupled with their extended range capacity. This underscores the importance of developing robust energy management strategies for SHEVs, with a particular focus on maintaining the battery's state of charge (SOC) at a constant level. To achieve this objective, the proposed system leverages the adaptability and effectiveness of fuzzy logic-based control schemes, which have garnered considerable research interest in the domain of hybrid electric vehicles. Previous studies have explored various aspects of fuzzy logic controllers in SHEVs, with a specific emphasis on optimizing power distribution between the battery and internal combustion engine (ICE) to minimize fuel consumption while ensuring desired performance levels. These investigations have encompassed the optimization of fuzzy rules, the integration of battery SOC and terminal voltage considerations, and the evaluation of different membership functions' effectiveness in reducing fuel consumption.

Building on the existing body of research in this domain, this study presents a novel energy management algorithm based on a fuzzy logic controller tailored specifically for SHEVs. The proposed controller is designed to regulate power distribution between the battery and ICE in response to driver commands and vehicle speed, with the overarching goal of maintaining the battery's SOC at a constant level. This is achieved through the development of a comprehensive modeling framework using MATLAB/Simulink, which enables the simulation and evaluation of the controller's performance under various driving conditions, including standard driving cycles such as the New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycles. By harnessing the advantages of fuzzy logic-based control strategies, this research aims to contribute to the advancement of energy-efficient and environmentally sustainable transportation solutions within the context of hybrid electric vehicles. The proposed system represents a significant step towards achieving this goal, offering a promising avenue for optimizing the operation of SHEVs and realizing their potential as a viable interim solution in the transition towards fully electric vehicles. Through extensive simulation studies and evaluation, the efficacy and feasibility of the proposed energy management algorithm will be thoroughly assessed, paving the way for its potential integration into real-world SHEV platforms and enhancing their overall efficiency and sustainability.

Fuzzy Logic Controller

The functions of the controller can be defined as keeping the battery SOC at specific values and managing regenerative braking. For these purposes, a fuzzy logic controller with three inputs and

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two outputs is designed. The SOC, output of the PI controller and the vehicle speed are determined as the inputs of the controller as seen in Fig. 7. While seven memberships are used to map the SOC and the output of the PI controller inputs, the velocity input is explained with two membership functions. Two controller outputs are the ICE power change and a coefficient determining the state of regenerative braking. The ICE power change is explained with 7 membership functions and 4 membership functions are described to generate the state of regenerative braking output. The controller lets the chargedepleting mode continue until SOC falls to a value of 35%, and then tries to keep the SOC between 3040%.

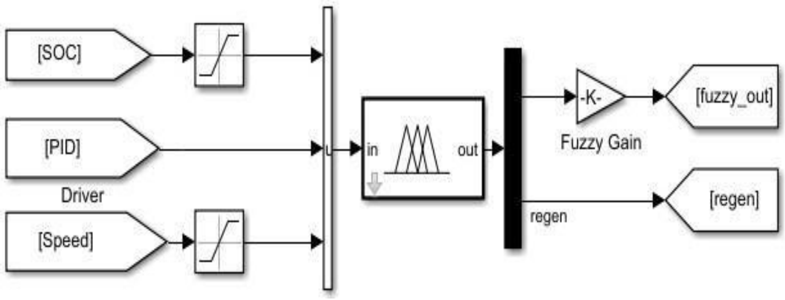
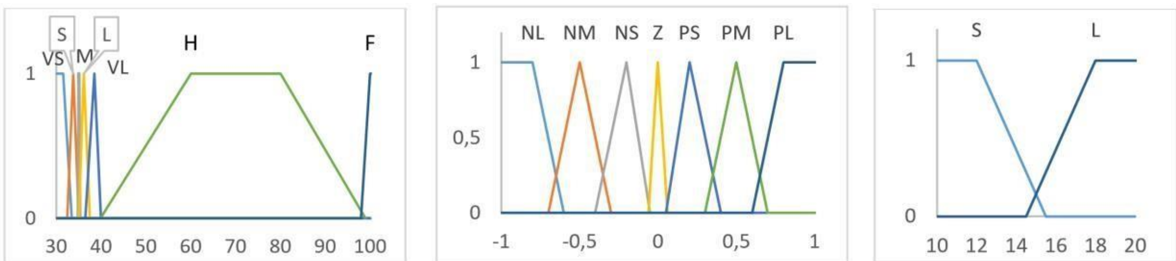


Figure 2. The fuzzy controller model.

Membership functions of three inputs are given in Fig. 8(a-c). The notation used here can be summarized as follows: "*Z*", "*S*", "*M*", and "*L*" are "*zero*", "*small*", "*medium*", and "*large*" respectively. "*P*" and "*N*" stand for "*positive*" and "*negative*", respectively. "*H*" is "*high*", "*F*" is "*full*", and "*V*" is "*very*". The SOC is intended to be kept between 30-40%, therefore several functions are placed in this interval. Function "*F*" is defined to prevent overcharging.

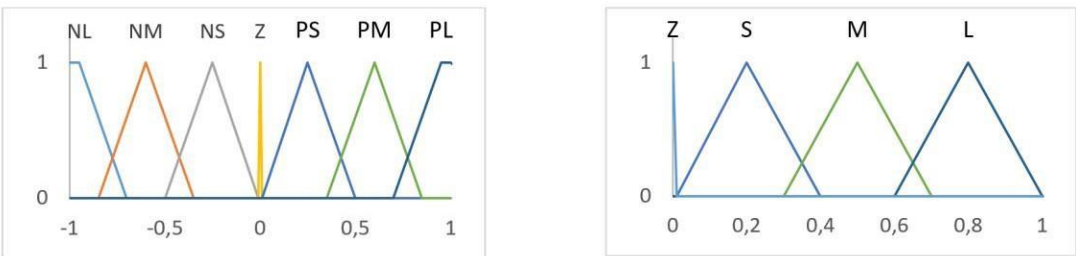


(a) *(b)* *(c)*

Figure 3. Membership functions of (a) SOC, (b) driver, and (c) velocity inputs, respectively.

For the driver input, seven partitions are created to ensure a proper distinction between the braking and acceleration. Membership functions for the speed input set the limit for regenerative braking.

Fig. 9(a,b) shows the controller's output membership functions. First output controls the ICE/generator power change. A value between [-1,1] is obtained depending on the driver's demand and the state of charge. A gain block is used afterward to calculate the actual change. Functions of regenerative braking output are triggered depending on the brake command of the driver.



(a) *(b)*

Figure 4. Membership functions of (a) ICE/generator power change output and (b) regenerative braking output, respectively.

RESULTS AND DISCUSSION

The results and discussion of this study underscore the significant strides made in developing a novel energy management algorithm based on a fuzzy logic controller for series hybrid electric vehicles (SHEVs). With the automotive landscape witnessing a profound transformation driven by the rapid advancement of IoT technology and the increasing electrification of vehicle propulsion systems, there is a pressing need for energy-efficient and environmentally sustainable transportation solutions. Hybrid electric vehicles (HEVs) have emerged as a compelling interim solution in this transition towards fully electric vehicles, offering advantages such as lower prices, volumes, and sizes compared to fully electric vehicles, alongside extended range capacity. Central to the optimization of HEVs is the development of effective energy management systems, with a particular focus on minimizing fuel consumption while meeting driver power demands. Fuzzy logic has garnered significant research interest as a promising approach for control schemes in HEVs, owing to its adaptability and effectiveness in optimizing power distribution between the battery and internal combustion engine (ICE) to maintain desired performance levels. This study builds upon this existing body of research by proposing a novel energy management algorithm tailored specifically for SHEVs, with the aim of maintaining the battery's state of charge (SOC) at a constant level while optimizing power distribution based on driver commands and vehicle speed.

Through extensive simulation studies conducted using MATLAB/Simulink, the performance of the proposed fuzzy logic-based control scheme was evaluated under various driving conditions, including standard driving cycles such as the New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycles. The results demonstrate the efficacy of the proposed controller in achieving the desired objectives of maintaining the battery's SOC at a constant level while optimizing power distribution between the battery and ICE. Specifically, the simulation studies reveal that the proposed controller effectively balances the power flow between the battery and ICE in response to dynamic changes in driver commands and vehicle speed, thereby ensuring optimal energy utilization and maximizing fuel efficiency. Moreover, the controller exhibits robust performance across different driving conditions, underscoring its versatility and adaptability in real-world applications.

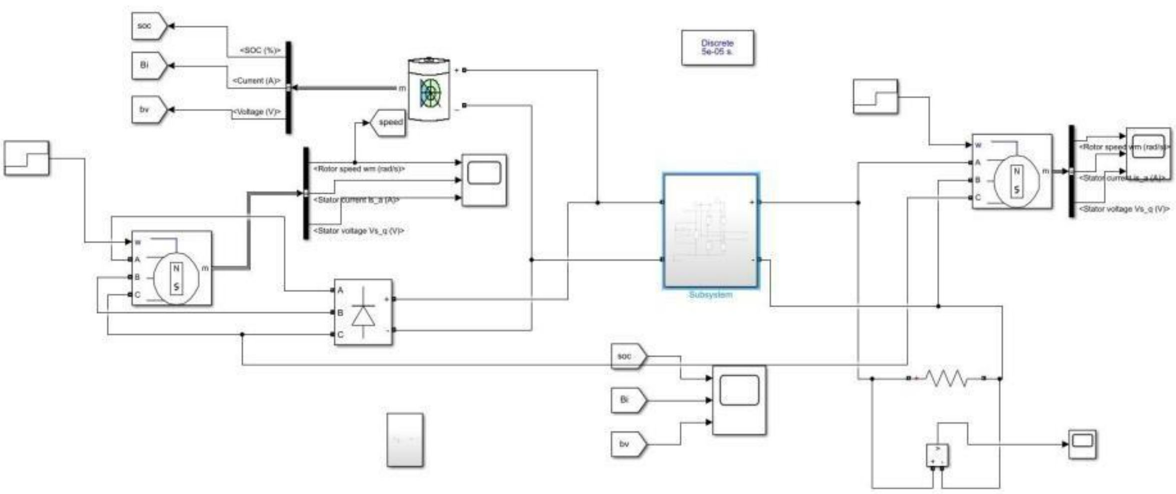


Fig 5. Circuit 1

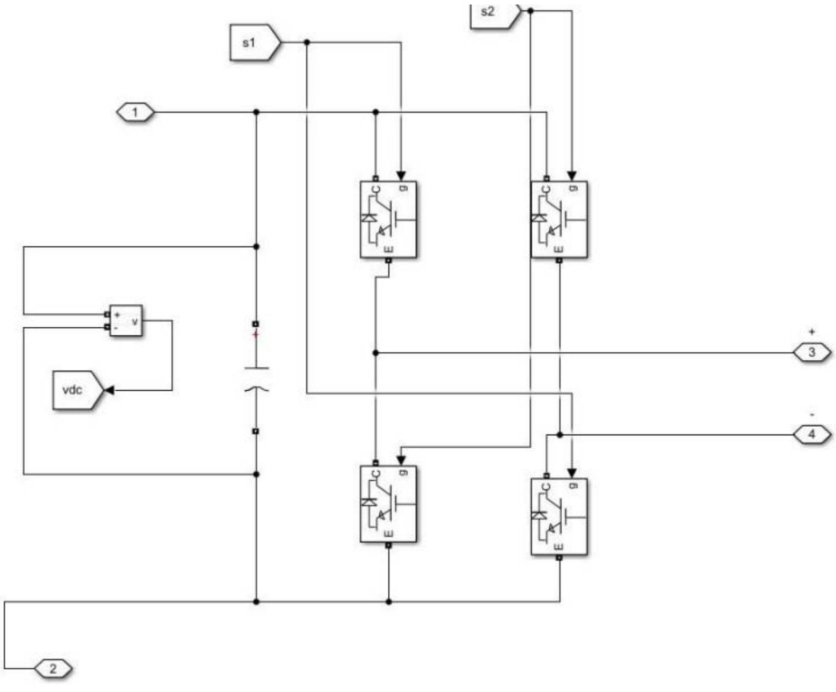


Fig 6. Inverter subsystem

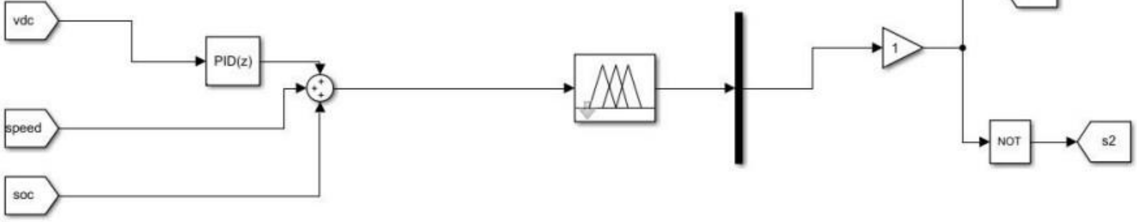


Fig 7. Flc subsystem

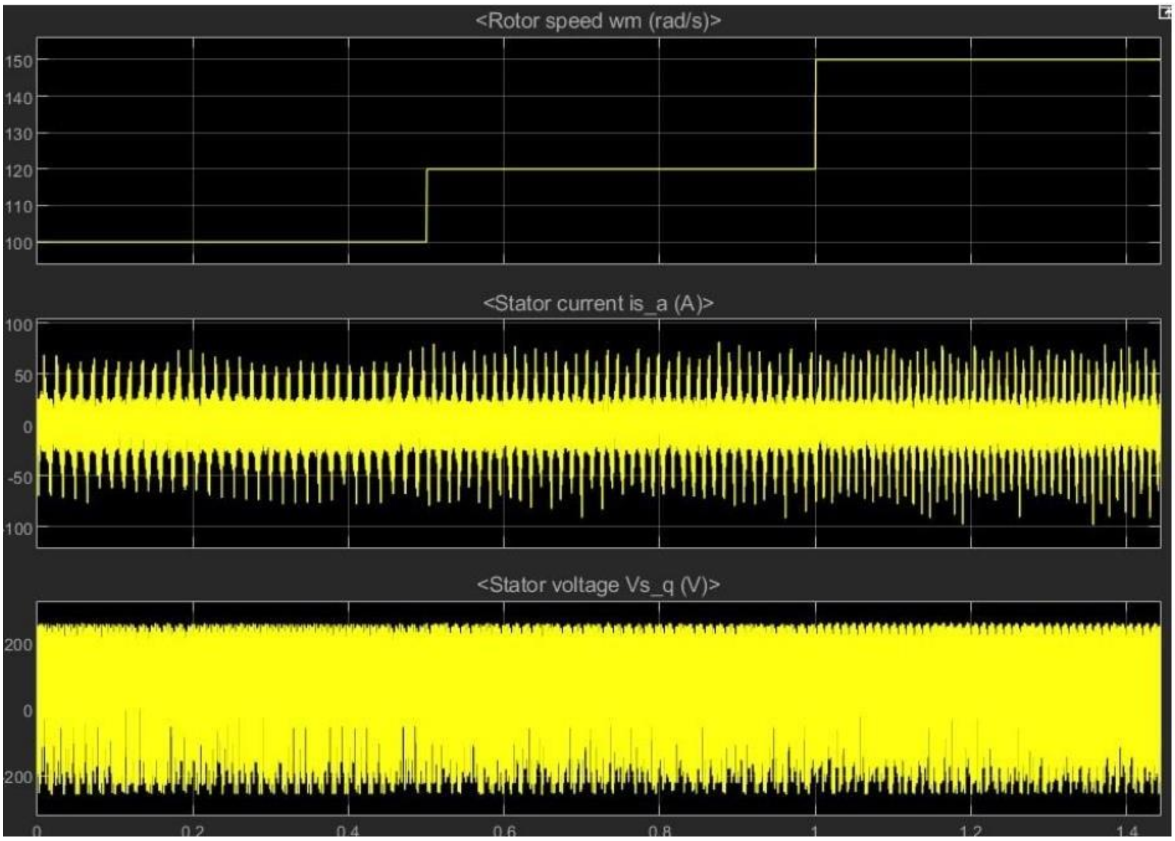


Fig 8. Simulation results 1

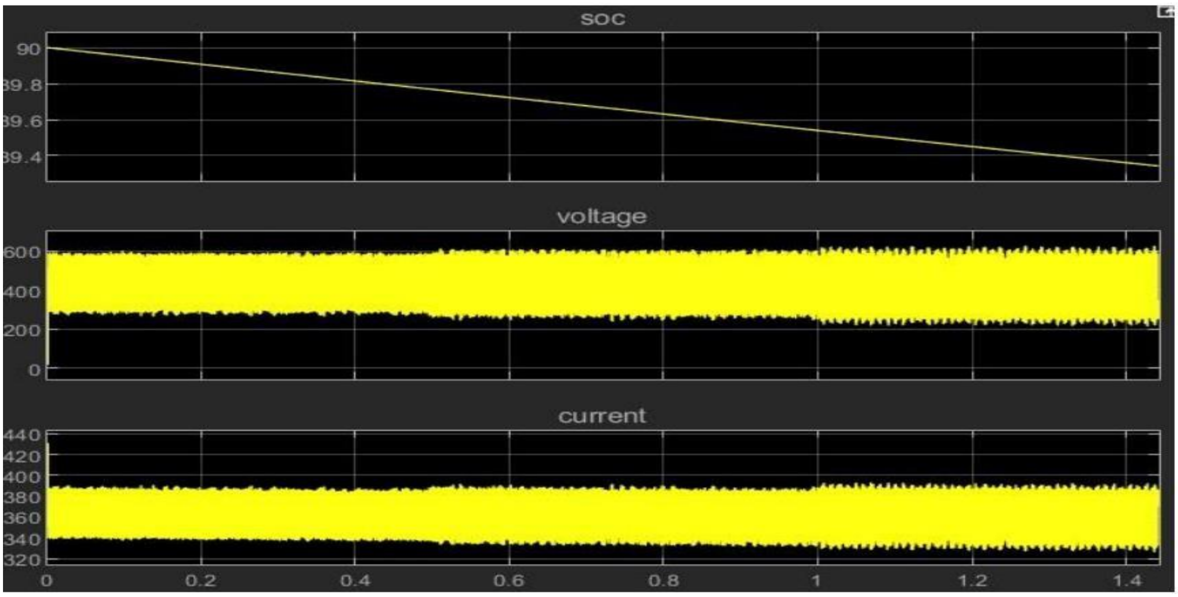


Fig 9. Simulation results 2

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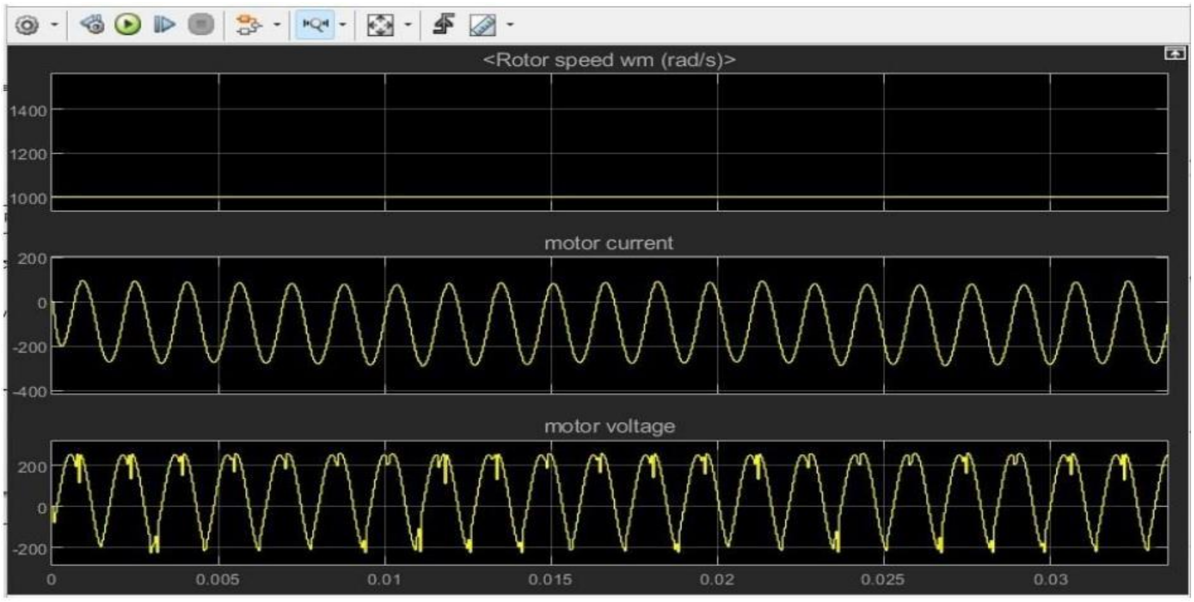

Fig 10. Simulation results 3

It can be noted that the SOC - velocity plane does not affect the rules. Rules are heavily dependent on driver demand. The velocity and SOC inputs are mostly there to set the limits for regenerative braking. ICE power change rules yield negative values above 40% SOC to stop the engine from charging the battery beyond this limit. The power of the ICE is only increased if the SOC is below 35%, or around 35% and the driver demand is high. This output yields the highest values when the SOC is very low and the demand is very high.

Furthermore, the discussion delves into the implications of the study findings in advancing energy-efficient and environmentally sustainable transportation solutions in the context of hybrid electric vehicles. By leveraging the advantages of fuzzy logic-based control strategies, this research contributes to addressing key challenges associated with the optimization of power distribution in SHEVs, thereby enhancing their overall efficiency and performance. The proposed energy management algorithm offers a promising avenue for enhancing the operational capabilities of SHEVs, paving the way for their wider adoption and integration into mainstream automotive markets. Moreover, the findings highlight the importance of continuous research and development efforts in refining control strategies for hybrid electric vehicles, particularly in light of evolving technological advancements and regulatory frameworks aimed at promoting sustainable mobility solutions. Overall, this study represents a significant step towards realizing the potential of SHEVs as viable and environmentally sustainable transportation options, thereby contributing to the ongoing transition towards a greener and more energy-efficient automotive ecosystem.

CONCLUSION

In this study, a fuzzy logic-based controller for the energy management of a series HEV is proposed. The aim of the controller is to keep the state of charge between 30-40% after charge depleting mode and ensure that regenerative braking does not occur at high battery SOC to prevent overcharging. Therefore, a three-input two- output fuzzy logic controller is designed. In order to test the controller, a series hybrid model is created based on the first-generation Chevrolet Volt, and simulations are performed in the MATLAB/Simulink environment. The proposed controller is tested with NEDC and WLTC test cycles. Its performance on keeping the SOC level at desired region, decreasing fuel consumption and controlling the regenerative braking are explored. The results prove that despite the proposed controller is simple, it can keep the SOC between predetermined values, decrease the fuel consumption, and manage the regenerative braking. The fuzzy control requires tuning of rules, which can be tedious with the increasing number of inputs and membership functions. Regardless the rules are dependent on human intuition; it can be set without the certainty of a mathematical model. This makes implementing rules easier, if not optimal. For optimal solutions, an optimization strategy such as DP can be considered, which is not in the scope of this study. Still, it may be possible to obtain better results by increasing membership functions or finding better membership functions than the existing ones.

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