FUZZY LOGIC-CONTROLLED POWER FLOW MANAGEMENT IN HYBRID ELECTRIC VEHICLES WITH PMSM DRIVES

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Abstract:
Hybrid Electric Vehicles (HEVs) have emerged as a sustainable alternative to conventional vehicles, integrating multiple energy sources to reduce emissions and enhance fuel efficiency. Effective power flow management between these energy sources—typically a battery, internal combustion engine, and electric drive—is critical to the overall system performance. This paper presents a fuzzy logic-based control strategy for real-time power flow optimization in HEVs using Permanent Magnet Synchronous Motor (PMSM) drives. The proposed system dynamically manages energy distribution based on driving conditions, battery state-of-charge, and load demand, aiming to maximize efficiency and ensure component longevity. A comprehensive model is developed in MATLAB/Simulink to simulate and evaluate the system's performance. Simulation results demonstrate that the fuzzy logic controller provides smooth transitions, improved energy efficiency, and optimal utilization of the PMSM drive in varying traffic scenarios. This approach offers a robust and intelligent solution for next-generation hybrid vehicle energy management systems.

I. INTRODUCTION

The global shift towards energy-efficient and environmentally friendly transportation has significantly accelerated the development of Hybrid Electric Vehicles (HEVs). These vehicles combine the benefits of internal combustion engines with electric propulsion systems, resulting in improved fuel economy, reduced emissions, and enhanced overall performance. However, the integration of multiple power sources introduces complexity in managing power flow efficiently, particularly under varying road and load conditions.

Among the core components of HEVs, the Permanent Magnet Synchronous Motor (PMSM) is widely used due to its high torque density, better efficiency, and compact design. Simultaneously, intelligent energy management strategies are essential to coordinate power between the battery, electric motor, and engine. Traditional control methods often struggle to cope with the nonlinearities and dynamic uncertainties present in real-time vehicular operation.

This study proposes a fuzzy logic-based power flow controller designed specifically for PMSM-driven HEVs. Fuzzy logic control offers a robust, rule-based approach capable of handling the system's nonlinear behavior without requiring an exact mathematical model. The controller processes key input parameters—such as vehicle speed, driver demand, and battery state-of-charge—to determine the optimal power split between energy sources.

The objective is to enhance the responsiveness, efficiency, and reliability of the hybrid drive system. A detailed simulation model is developed using MATLAB/Simulink to analyze the effectiveness of the proposed control algorithm. This paper aims to contribute to the advancement of smart control systems in hybrid vehicles, aligning with the broader goals of energy conservation and sustainable mobility.

II. LITERATURE SURVEY

An inter-leaved bidirectional SEPIC converter operating in discontinuous conduction mode (DCM) was used in [14] in order to provide a smooth current for the purpose of charging the battery. As a direct consequence of this, the output voltage was successfully adjusted. On the other hand, as a result of the continual charging and discharging of SC [15], there were only small converter losses. Fuel cells are another alternative to internal combustion engines and batteries that are now in use. PEMFCs, or proton exchange membrane fuel cells, were used in the research described in reference [16], together with a lithium-ion battery and boost converters. A case study on the process of selecting batteries for electric vehicles (EVs) is presented in reference [17].

According to the findings of this study, electric vehicles would benefit most from using lithium-ion batteries. This is because, in comparison to other kinds of batteries, their performance is much higher. HEVs and plug-in HEVs both utilise a variety of energy storage systems (ESS), the most common of which being batteries and super capacitors (SCs). In addition, detailed illustrations of innovative charging strategies for the batteries may be seen in [18].

The article [19] presents a number of control techniques for HEVs as well as an in-depth analysis on EMS for the purpose of transforming a conventional vehicle into a plug-in hybrid electric vehicle (HEV). FLC is employed in order to effectively manage the motor and so limit the amount of energy that must be drawn from the battery in order to do so.

In [20] provides a very good introduction to fuzzy control as well as its extensive use in industrial applications. They also have a lot of different applications. There is provided an in-depth explanation about the mathematical concepts of fuzzy control and fuzzy relations. In addition, a representation of a collection of fuzzy rules, as well as non-linear fuzzy control, adaptive fuzzy control, and a few other things, are provided.

Chao Gao, Jian, and others [21] focused on improving the overall health of the battery as well as the discharge current of the battery. In order to maximize the effectiveness of the membership function of the FLC for HEV, the gold ratio cut-off method was used. In [22] authors contains representations of a number of fuzzy theories, including fuzzy classification, fuzzy diagnosis, and the applications of these ideas. Siemens, based in Germany, is currently working on a number of applications that are connected to fuzzy control. Examples of these categories are also described, including things like optimization theory, fuzzy data analysis, and fuzzy expert systems, amongst other things. The presentation also includes a variety of different optimization strategies for fuzzy controllers, such as generic algorithms (GA) and Rosen brok's algorithms. In addition, a comprehensive explanation of the multilevel qualitative optimization of fuzzy controllers may be found in [23].

FLC was employed for the rule-based approach that Hajer Marzougui et al. [24] developed. A control for flatness was used for either the fuel cells or the ultra capacitor. In HEVs, a rule-based algorithm was used to divide the power needs between the sources of power and the load, disregarding any losses that may have been caused by the converters. The cost of this EMS is significant despite its flexibility and the fact that it does not need any of the vehicle's trajectory to be known in advance. In [25], the current fluctuation of the battery was reduced as much as possible, and the Karush–Kuhn–Tucker (KKT) conditions were used to control the flow of power from the SC.

III. SYSTEM DESIGN

3.1 Proposed Model

The whole system's block diagram is shown in Figure 1, which may be seen here. In order to create a model of the system, mathematical equations are used in the Simulink/MATLAB environment. During the driving mode, SC provides assistance to the charge of the battery pack. There is an alternative method of putting energy storage devices to use in HEVs. A number of researchers make use of series combination in accordance with their methodology. Additionally, the parallel coupling of a fuel cell with a battery or SC was suggested; however, this would drive up the cost of the cars. The most common and desired configuration is a battery in parallel with SC. The use of these storage devices in series offers a vehicle a higher efficiency, but it also makes the car heavier and increases the amount of energy that is lost [36]. SC functions as a battery backup and safeguards the battery from inrush current. SC is capable of providing steady power and has a high power density. Despite having a low energy density, it can both provide and absorb peak current. It has the potential to improve the overall efficiency of the vehicle as well as the longevity of the battery life. The power production from a regenerative braking system is not a problem for it. An SC/battery HES for EVs is suggested and investigated in this paper as a result of the many benefits associated with this system.

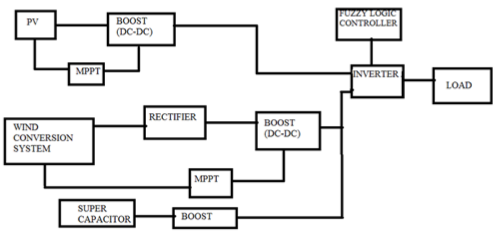

Figure 1. Proposed block diagram.

The functional architecture of the whole system is shown in figure 1, which may be seen at this location. In the context of Simulink and MATLAB, mathematical equations are utilized for the purpose of constructing a model of the system. During the mode in which the vehicle is being driven, SC contributes to the charging of the battery pack. There is another way of putting energy storage devices to work in HEVs than the one described above. Numerous researchers include series combination into their approach in order to get the best results possible. In addition, it was proposed to couple a fuel cell with a battery or a SC in parallel; but, doing so would drive up the price of the vehicles. The battery in parallel with the SC setup is by far the most popular and desirable combination. When used in series, these energy storage devices enable a vehicle to operate at a greater efficiency; nevertheless, this results in the vehicle being heavier and increasing the quantity of energy that is wasted . SC serves as a backup for the battery and protects the battery from inrush current. The power density of SC is very great, and it is able to provide constant power. In spite of the fact that it has a low energy density, it is able to both provide and absorb peak current. It has the ability to increase both the overall efficiency of the vehicle and the length of the life of the battery. [Case in point:] It is not an issue for it to produce electricity from a regenerative braking system because of its design. This research makes the suggestion of a SC/battery HES for EVs and investigates its viability as a consequence of the many advantages that are related with this system.

3.2 Fuzzy Logic controller

The FLC is a conventional structure, as shown in Figure 2. The inputs are the speed error (e) and the change in speed error, and the output is the change in the q-axis reference current. The membership function is employed, and the input and output scaling factors are computed. The FLC is responsible for carrying out the rule base, with the fuzzy variables e and ce serving as the inputs. The defuzzification unit is responsible for handling the number of iqs that are produced as the output.

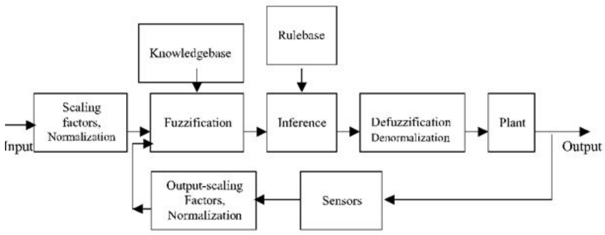

Figure 2. FLC controlling strategy.

By comparing the resulting speed response with that of the "standard design," the primary objective of the control system is to ascertain whether or not the "case design" for the high-performance PMSM drive is effective. The 'standard design' is the first thing that is developed, and this is done on the basis of the speed response to the step rated speed command (209 rad/s) when there is no load and the rated inertia is present. The specifications for the design are defined such that there is a speed overshoot of no more than 0.1 rad/s, and the rising time must be as short as possible taking into account the restricted current capabilities of the inverter. The scaling factors are selected both for fuzzification and for the purpose of obtaining the factors play an important role for the FLC and have an effect on the stability, oscillations, and damping of the system; as a result, they need to be selected with the utmost care [11]. Fuzzification is another reason why these scaling factors are selected. To normalize the speed error and the change in speed error, respectively.

The value of the factor has been determined in such a way that it is possible to get the rated current under the rated circumstances. It is via trial and error that the fine adjustment to the specification is accomplished. In order to get the best possible drive performance, the constants have been set to the following values: The next stage involves determining the membership functions of e, ce, and cu. These functions are crucial to the FLC's operation and are the primary subject of this particular piece of writing. The designs for the two distinct fuzzy sets that were created are seen in Figures 3 and 4, respectively. The geometry of the fuzzy sets on the two extreme ends of the universe of discourse is considered to be trapezoidal, but the shape of all other intermediate fuzzy sets is triangular, and the traditional method assumes that they overlap with one another. The breadth of the triangle membership function is split evenly in a range called the Universe of Discourse, and each section overlaps the next. Tables II and III, respectively, provide the fuzzy rule-base matrix for what is known as "standard design" and "case design." As was said before, the rules of the 'standard design' are defined by common criteria found in a large number of publications, but the rules of the 'case design' parameters are determined by a standard technique while simultaneously minimizing the number of fuzzy rule-bases. The linguistic components employed are identical to those found in the vast majority of published works. For the duration of the computing time period, the Fixed step mode will be used. The Dormand-Prince numerical approach and a Mamdani-type fuzzy inference are used in the process of solving differential equations numerically. In this particular investigation, the values of constants, membership functions, and fuzzy sets for input/output variables are determined via a process of trial and error.

Table I provides definitions for seven terms: NL, which stands for negative large; NM, which stands for negative medium; NS, which stands for negative small; ZE, which stands for zero; PS, which stands for positive small; PM, which stands for positive medium; and PL, which stands for positive large. It has designated three terms: N, which stands for negative; ZE, which stands for zero; and P, which stands for positive. Every fuzzy variable belongs to at least one of the subsets, with the degree of membership ranging from 0 to 1 for each fuzzy variable. As was noted before, the rules have been expressed in the form of a matrix for the sake of convenience, and they should be read as follows: If the "speed error is NS" and the "change in speed error is PS," then the "change in q-axis reference current is ZE," respectively. With the exception of the number of rules, all of the scaling factors, the form of membership function, the technique of fuzzification, and the method of defuzzification are specified and maintained at a consistent level throughout the study.

Change in Error		Error						
	E / CE	NB	NM	NS	ZE	PS	PM	PB
	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	ZB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

Table 1. FLC control rule table.

IV. RESULTS

This section gives the detailed analysis of simulation results, which are implemented by using Matlab/Simulink Tool. Figure 3 shows the Simulink model of proposed hybrid EMS system, which contain the various blocks such as PV panel, fuel cells, super capacitor and battery storage system for PMSM drive of hybrid electrical vehicle with FLC. Further, Figure 4 shows the proposed Simulink model, which is equipped with super capacitor. Figure 5 shows the output voltage generated from EMS. Figure 6 shows the PMSM output response, which is measured in rad/s.

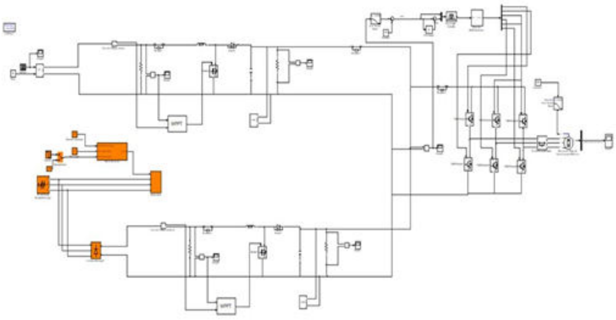

Figure 3.Simulink model.

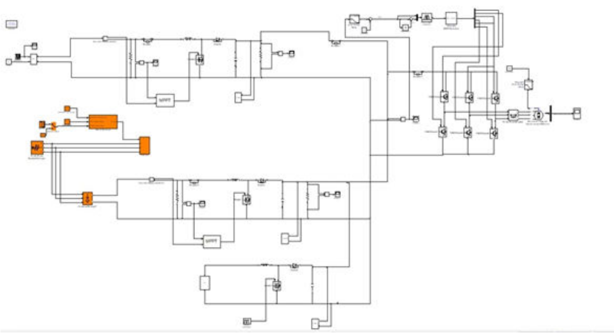

Figure 4.Simulink model with super capacitor.

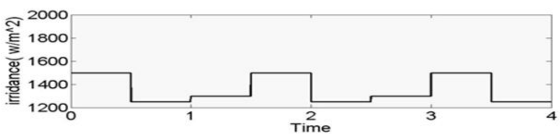

Figure 5. Solar irridation.

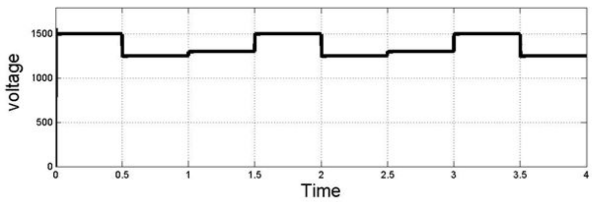

Figure 6. solar dc-dc converter input volta.

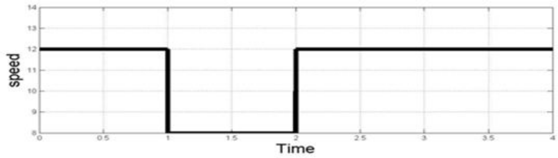

Figure8. Window input speed.

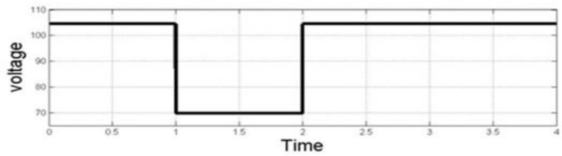

Figure9. Wind dc-dc converter input voltage.

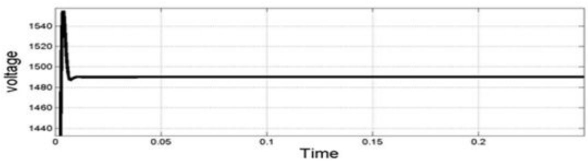

Figure10. Wind dc-dc converter output voltage.

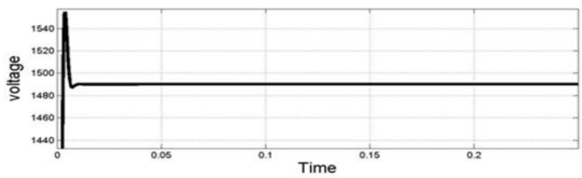

Figure11. Super capacitor output voltage.

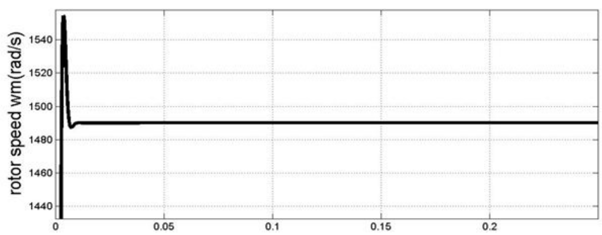

Figure 12. PMSM output response.

V. CONCLUSION

This research demonstrates the effectiveness of a fuzzy logic-controlled power management system for Hybrid Electric Vehicles employing PMSM drives. The controller successfully interprets variable driving inputs and system conditions to optimize the distribution of power among the vehicle's energy sources. Simulation results validate that the fuzzy logic approach enhances system efficiency, maintains battery health, and ensures smooth drive control even in highly dynamic environments.

The intelligent controller provides adaptability and robustness that conventional control methods often lack, particularly when addressing the nonlinear and uncertain nature of hybrid powertrains. The integration with PMSM drives further improves energy efficiency due to their inherent advantages in torque handling and control precision.

In summary, fuzzy logic-based control proves to be a practical and scalable solution for HEV energy management, paving the way for smarter, cleaner, and more efficient transportation systems. Future work may include experimental validation, integration with renewable energy charging systems, and hybridization with machine learning algorithms for predictive control enhancements.

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