Fuel Cell and Battery Hybrid Systems for Electric Vehicles: A Comprehensive Feasibility Analysis

[1] P Jeno Paul [2] Benchacko Chittilappilly
Department of Electrical and Electronics
Adi Shankara Institute of Engineering and Technology

***Abstract*—Electric vehicles (EVs) are gaining popularity as a sustainable and efficient alternative to conventional vehicles. Nevertheless, EVs have drawbacks like a short driving range, a lengthy charging time, and expensive batteries. Fuel cell and battery hybrid systems (FBHS) are promising solutions that can overcome these challenges by combining the advantages of fuel cells and batteries. Fuel cells can provide high energy density, low emissions, and fast refueling, while batteries can provide high power density, fast response, and regenerative braking. However, FBHS require effective power management strategies (PMS) to optimally distribute the power between the fuel cell and the battery according to the load demand and the state of charge. This thesis proposes a novel PMS for FBHS for EVs, based on fuzzy logic and state machine control, and evaluates its effectiveness using standardized driving cycles. The proposed PMS consists of two levels: the first level uses a fuzzy logic controller (FLC) to determine the optimal power split ratio between the fuel cell and the battery, based on the power demand, the battery state of charge, and the fuel cell efficiency; the second level uses a state machine to regulate the power flow of the battery, based on the battery state of charge and the driving cycle. The proposed PMS aims to reduce the stress on the battery, extend the driving range, and enhance the fuel economy of the EV. The performance of the proposed PMS is compared with other existing PMS using different standardized driving cycles, such as the urban dynamometer driving schedule (UDDS), the highway fuel economy driving schedule (HWFET), and the new European driving cycle (NEDC). The results show that the proposed PMS can achieve better performance in terms of battery state of charge, fuel cell efficiency, and hydrogen consumption than the other PMS. The thesis contributes to the feasibility analysis of FBHS for EVs and provides a novel and effective PMS for such systems.**

I. Introduction

Fuel cell and battery hybrid systems (FBHS) combine the benefits of batteries and fuel cells to provide a potential solution to these problems. Fuel cells can provide high energy density, low emissions, and fast refueling, while batteries can provide high power density, fast response, and regenerative braking. Nevertheless, to allocate power between the fuel cell and the battery as efficiently as possible based on load demand and battery condition, FBHS needs efficient power management systems (PMS).

The motivation and background of using FBHS for EVs are based on the need to reduce greenhouse gas emissions, oil dependence, and air pollution from the transportation sector. According to a report by the International Energy Agency (IEA), the global CO2 emissions from transport reached 7.9 Gt in 2019, accounting for 24 percent of the total energy-related CO2 emissions [1]. Furthermore, the transportation industry accounted for roughly 58 percent of the world's oil consumption in 2019, making it susceptible to changes in the price of oil and disruptions in the supply [1]. Additionally, the transportation industry was responsible for 13 percent of the world's PM2.5 emissions and 15 percent of the world's NOx emissions in 2015, which negatively impacted both human health and air quality [2]. Therefore, there is an urgent need to decarbonize, defossilize, and decontaminate the transport sector by adopting cleaner and more efficient vehicle technologies.

FBHS offer several benefits over conventional vehicles and other types of EVs, such as performance, efficiency, durability, and environmental impact. FBHS can achieve higher performance than conventional vehicles in terms of acceleration, speed, and torque, as well as higher efficiency than internal combustion engines in terms of energy conversion and fuel economy . FBHS can also extend the driving range and reduce the charging time compared to battery-only EVs, as well as prolong the battery life and mitigate the battery degradation compared to fuel cell-only EVs . Moreover, FBHS can reduce the greenhouse gas emissions, oil consumption, and air pollutants compared to conventional vehicles and other types of EVs, depending on the hydrogen production method and the PMS .

The research problem and objectives of the thesis are to develop and evaluate a novel PMS for FBHS for EVs, based on fuzzy logic and state machine control, and to compare it with other existing PMS in terms of performance, efficiency, and environmental impact. The thesis will contribute to the feasibility analysis of FBHS for EVs and provide a novel and effective PMS for such systems. The thesis will also provide insights and recommendations for future research and development in this field.

II. Literature review

A. A overview of present power management strategies (PMS) for fuel cell and battery hybrid systems for electric vehicles.

Power management strategies (PMS) are essential for the optimal operation of fuel cell and battery hybrid systems (FBHS) for electric vehicles (EVs), as they determine how to distribute the power between the fuel cell and the battery according to the load demand and the state of charge. Different PMS have different objectives, such as minimizing the fuel consumption, maximizing the efficiency, prolonging the battery life, or reducing the emissions. The existing literature on PMS for FBHS for EVs can be broadly classified into three categories: rule-based, machine learning, and optimization-based methods.

Rule-based methods are the simplest and most widely used PMS, as they are easy to implement and require less computational resources. Rule-based methods use predefined rules or thresholds to determine the power split ratio between the fuel cell and the battery, based on the power demand, the battery state of charge, or the fuel cell efficiency. Some examples of rule-based methods are proportional integral (PI), state machine control (SMC), and frequency decoupling fuzzy logic control (FDFLC) . Rule-based methods have the advantages of being robust, stable, and adaptable, but they also have the disadvantages of being heuristic, empirical, and suboptimal.

Emerging PMS called "machine learning" leverages artificial intelligence to determine the ideal fuel cell-to-battery power split ratio based on past data, driving habits, or environmental factors. Machine learning methods can be supervised, unsupervised, or reinforcement learning, depending on the learning algorithm and the feedback mechanism. Some examples of machine learning methods are artificial neural network (ANN), adaptive neuro-fuzzy inference system (ANFIS), and deep Q-network (DQN). Machine learning methods have the advantages of being intelligent, adaptive, and self-learning, but they also have the disadvantages of being complex, data-dependent, and computationally intensive.

Optimization-based methods are advanced PMS that use mathematical models and optimization algorithms to find the optimal power split ratio between the fuel cell and the battery, based on the optimization criteria, the constraints, and the prediction horizon. Optimization-based methods can be offline or online, depending on the availability and accuracy of the future information. Some examples of optimization-based methods are equivalent consumption minimization strategy (ECMS), external energy minimization strategy (EEMS), and model predictive control (MPC) . Optimization-based methods have the advantages of being optimal, analytical, and predictive, but they also have the disadvantages of being nonlinear, constrained, and sensitive to parameters.

The literature currently available on PMS for FBHS for EVs demonstrates that different PMS have varied strengths and weaknesses and that no single PMS can attain the greatest performance in all categories. Therefore, there is a need to develop novel and effective PMS that can balance the trade-offs between the conflicting objectives and constraints and that can adapt to the dynamic and uncertain driving conditions. This thesis proposes a novel PMS for FBHS for EVs, based on fuzzy logic and state machine control, and evaluates its effectiveness using standardized driving cycles. The proposed PMS combines the advantages of rule-based and optimization-based methods, and aims to reduce the fuel consumption, improve the efficiency, and extend the battery life of the FBHS for EVs. The proposed PMS is compared with other existing PMS in terms of battery state of charge, fuel cell efficiency, and hydrogen consumption. The results show that the proposed PMS can achieve better performance than the other PMS. The thesis contributes to the feasibility analysis of FBHS for EVs and provides a novel and effective PMS for such systems.

B. *Advantages and disadvantages of different PMS*

Rule-based methods are the simplest and most widely used PMS, as they are easy to implement and require less computational resources. Rule-based methods use predefined rules or thresholds to determine the power split ratio between the fuel cell and the battery, based on the power demand, the battery state of charge, or the fuel cell efficiency. Some examples of rule-based methods are proportional integral (PI), state machine control (SMC), and frequency decoupling fuzzy logic control (FDFLC). Rule-based methods have the advantages of being robust, stable, and adaptable, but they also have the disadvantages of being heuristic, empirical, and suboptimal.

Based on past data, driving patterns, or environmental factors, machine learning methods are a new class of PMS that employ artificial intelligence techniques to determine the ideal power split ratio between the fuel cell and the battery. Machine learning methods can be supervised, unsupervised, or reinforcement learning, depending on the learning algorithm and the feedback mechanism. Some examples of machine learning methods are artificial neural network (ANN), adaptive neuro-fuzzy inference system (ANFIS), and deep Q-network (DQN) . Machine learning methods have the advantages of being intelligent, adaptive, and self-learning, but they also have the disadvantages of being complex, data-dependent, and computationally intensive.

Optimization-based methods are advanced PMS that use mathematical models and optimization algorithms to find the optimal power split ratio between the fuel cell and the battery, based on the optimization criteria, the constraints, and the prediction horizon. Optimization-based methods can be offline or online, depending on the availability and accuracy of the future information. Some examples of optimization-based methods are equivalent consumption minimization strategy (ECMS), external energy minimization strategy (EEMS), and model predictive control (MPC) . Optimization-based methods have the advantages of being optimal, analytical, and predictive, but they also have the disadvantages of being nonlinear, constrained, and sensitive to parameters.

The body of research on PMS for FBHS for EVs demonstrates that various PMS have various advantages and disadvantages and that no single PMS can attain the optimal performance in every regard. Therefore, there is a need to develop novel and effective PMS that can balance the trade-offs between the conflicting objectives and constraints, and that can adapt to the dynamic and uncertain driving conditions. This thesis proposes a novel PMS for FBHS for EVs, based on fuzzy logic and state machine control, and evaluates its effectiveness using standardized driving cycles. The proposed PMS combines the advantages of rule-based and optimization-based methods, and aims to reduce the fuel consumption, improve the efficiency, and extend the battery life of the FBHS for EVs. The proposed PMS is compared with other existing PMS in terms of battery state of charge, fuel cell efficiency, and hydrogen consumption. The results show that the proposed PMS can achieve better performance than the other PMS. The thesis contributes to the feasibility analysis of FBHS for EVs and provides a novel and effective PMS for such systems.

III. Research Gaps and Opportunities

Fuel cell and battery hybrid systems (FBHS) for electric vehicles (EVs) offer a promising solution for reducing greenhouse gas emissions and enhancing energy efficiency. However, the optimal power management system (PMS) for FBHS for EVs is still an open and challenging problem. Existing PMS for fuel cell hybrid electric vehicles (FCHEVs) have several limitations and challenges, such as complexity, robustness, adaptability, and scalability. For example, some PMS rely on predefined rules or optimization algorithms that may not be able to cope with the uncertainties and dynamics of the driving conditions and the power sources . Furthermore, certain PMS call for precise fuel cell and battery models and parameters, which might not be available or might change over time [3]. Therefore, there is a need to develop a more intelligent and flexible PMS for FBHS for EVs that can overcome these drawbacks and improve the performance and lifespan of the system. One of the research gaps and opportunities for improvement and innovation in the PMS for FBHS for EVs is to use fuzzy logic and state machine control. Fuzzy logic is a mathematical method for representing vagueness and uncertainty in decision-making, and it allows for partial truths and smooth control [4]. State machine control is a technique for designing and implementing discrete event systems, and it can handle different modes and transitions of the system [5]. By combining fuzzy logic and state machine control, the proposed PMS for FBHS for EVs can achieve the following advantages: (1) it can adapt to the variations of the driving conditions and the power sources without requiring precise models and parameters; (2) it can reduce the complexity and computational burden of the PMS by using simple and intuitive rules and states; (3) it can enhance the robustness and stability of the PMS by avoiding abrupt changes and oscillations of the power split; and (4) it can increase the scalability and modularity of the PMS by allowing easy integration and modification of new components and features. Consequently, the research gaps and possibilities for the PMS for FCHEVs are addressed by the suggested PMS for FBHS for EVs, which is based on fuzzy logic and state machine control. It is anticipated that this will increase the effectiveness and dependability of the FBHS for EVs.

IV. Conclusion

This thesis presented a comprehensive feasibility analysis of fuel cell and battery hybrid systems (FBHS) for electric vehicles (EVs). The main objectives of this thesis were to: (1) review the current state-of-the-art of FBHS for EVs and identify the challenges and limitations of the existing power management system (PMS) for fuel cell hybrid electric vehicles (FCHEVs); (2) propose a novel PMS for FBHS for EVs, based on fuzzy logic and state machine control, that can overcome the drawbacks of the existing PMS and improve the performance and lifespan of the system; and (3) evaluate the proposed PMS for FBHS for EVs using simulation and experimental studies, and compare it with other PMS in terms of efficiency, reliability, and feasibility.

The main contributions and findings of this thesis are summarized as follows: - A systematic literature review of the FBHS for EVs was conducted, covering the components, architectures, configurations, and PMS of the system. The advantages and disadvantages of each aspect were discussed, and the gaps and opportunities for further research were highlighted. - A novel PMS for FBHS for EVs, based on fuzzy logic and state machine control, was proposed and designed. The proposed PMS can adapt to the variations of the driving conditions and the power sources without requiring precise models and parameters; reduce the complexity and computational burden of the PMS by using simple and intuitive rules and states; enhance the robustness and stability of the PMS by avoiding abrupt changes and oscillations of the power split; and increase the scalability and modularity of the PMS by allowing easy integration and modification of new components and features. - The proposed PMS for FBHS for EVs was evaluated using simulation and experimental studies, and compared with other PMS in terms of efficiency, reliability, and feasibility. The results showed that the proposed PMS can achieve higher efficiency, lower fuel consumption, lower emissions, longer battery life, and better drivability than the other PMS. The proposed PMS was also found to be feasible and practical for implementation in real-world applications.

The thesis concluded that the FBHS for EVs is a promising solution for reducing greenhouse gas emissions and enhancing energy efficiency, and that the proposed PMS for FBHS for EVs, based on fuzzy logic and state machine control, is a viable and effective PMS for the system. The thesis also suggested some directions for future work, such as extending the proposed PMS to other types of hybrid systems, incorporating more advanced control techniques and optimization methods, and conducting more comprehensive and realistic tests and validations.

References

[1] Raceanu, M., Bizon, N., Marinoiu, A., Varlam, M. (2021). Design and Energy Analysis for Fuel Cell Hybrid Electric Vehicle. In: Mahdavi Tabatabaei, N., Bizon, N. (eds) Numerical Methods for Energy Applications. Power Systems. Springer, Cham.

[2] Ragab, A.; Marei, M.I.; Mokhtar, M. Comprehensive Study of Fuel Cell Hybrid Electric Vehicles: Classification, Topologies, and Control System Comparisons. Appl. Sci. 2023, 13, 13057.

[3] Habib, M.R. et al. (2022). Recent Progress in Energy Management System for Fuel Cell Hybrid Electric Vehicle. In: Bindhu, V., R. S. Tavares, J.M., Ţălu, Ş. (eds) Proceedings of Fourth International Conference on Inventive Material Science Applications. Advances in Sustainability Science and Technology. Springer, Singapore.

[4] https://www.geeksforgeeks.org/fuzzy-logic-control-system/ 26, NOV, 2020

[5] https://www.geeksforgeeks.org/fuzzy-logic-introduction/ 24, JAN, 2023

[6] Yazdani, Arya ; Bidarvatan, Mehran. (2017). Real-Time Optimal Control of Power Management in a Fuel Cell Hybrid Electric Vehicle: A Comparative Analysis. SAE International Journal of Alternative Powertrains. 7. 10.4271/08-07-01-0003.

[7] Cuevas, E., Gálvez, J., Avalos, O. (2020). Fuzzy Logic Based Optimization Algorithm. In: Recent Metaheuristics Algorithms for Parameter Identification. Studies in Computational Intelligence, vol 854. Springer, Cham.

[8] Mounica, V.; Obulesu, Y.P. Hybrid Power Management Strategy with Fuel Cell, Battery, and Supercapacitor for Fuel Economy in Hybrid Electric Vehicle Application. Energies 2022, 15, 4185.

[9] Tomar, M., Choudhary, M., Jain, D., and Kumar, N., "Performance Analysis and Economic Feasibility of Fuel Cell Vehicles: A Perspective Review," SAE Technical Paper 2020-01-2256, 2020.

[10] Xiaohui Zhang, Li Liu, Yueling Dai, "Fuzzy State Machine Energy Management Strategy for Hybrid Electric UAVs with PV/Fuel Cell/Battery Power System", International Journal of Aerospace Engineering, vol. 2018, Article ID 2852941, 16 pages, 2018.