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ENERGY MANAGEMENT STRATEGY FOR HYDROGEN FUEL CELL ELECTRIC VEHICLES: A REVIEW

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Abstract:
With the development of technologies in recent decades and the imposition of international standards to reduce greenhouse gas emissions, car manufacturers have turned their attention to new technologies related to electric/hybrid vehicles and electric fuel cell vehicles. This paper focuses on electric fuel cell vehicles, which optimally combine the fuel cell system with hybrid energy storage systems, represented by batteries and ultracapacitors, to meet the dynamic power demand required by the electric motor and auxiliary systems. This paper compares the latest proposed topologies for fuel cell electric vehicles and reveals the new technologies and DC/DC converters involved to generate up-to-date information for researchers and developers interested in this specialized field.
From a software point of view, the latest energy management strategies are analyzed and compared with the reference strategies, taking into account performance indicators such as energy efficiency, hydrogen consumption and degradation of the subsystems involved, which is the main challenge for car developers. The advantages and disadvantages of three types of strategies (rule-based strategies, optimization-based strategies and learning-based strategies) are discussed. Thus, future software developers can focus on new control algorithms in the area of artificial intelligence developed to meet the challenges posed by new technologies for autonomous vehicles.

Keywords: Fuel cell electric vehicle; DC/DC converter topologies; energy management strategy.

I. Introduction

In order to continue using fossil fuels, which means 80% of the world's energy demand, there are two main problems [1]. The first problem is the limited amount of fossil fuel, and sooner or later these sources will be consumed. Estimates of petroleum companies show that by 2023 there will be a peak in the exploitation of fossil fuels, petrol and natural gas, and then they will start to decline [2].
The second and most important problem is that fossil fuels cause serious environmental problems such as: global warming, acid rain, climate change, pollution, ozone depletion, etc. Estimates show that the worldwide destruction of the environment costs about $5 trillion annually [3].
The solution proposed for the two global problems first appeared in 1970 as the "Hydrogen energy system" [4]. In the last decade through research and development work in universities and laboratories of research institutes around the world shows that hydrogen is an excellent source of energy with many unique properties. It is the cleanest and most efficient fuel [5].
The unique property of hydrogen in electrochemical processes is that it can be converted into electricity in the fuel cell system which makes it much more efficient than the conversion of conventional fuels into mechanical energy [6]. This unique property of hydrogen has led to the manufacture of hydrogen fuel cells and makes them a very good choice for automotive companies [7].
The alternative to fossil fuels found by car manufacturers for fueling vehicles is represented by other energy sources, such as: battery systems, ultracapacitors or fuel cells. Electric Vehicles (EVs) and Fuel Cell Electric

Vehicles (FCEVs) are the most viable solutions for reducing Greenhouse Gases (GHG) and other harmful gases for the environment. Although EVs and FCEVs can reduce emissions to a certain value, they do not reduce them to absolute zero [8].

Thus, the renewable energy transport infrastructure allows FCEVs to become a preferable choice, because they attract great attention in the road and rail transport sector (and not only), without using fossil fuels [9]. FCEVs and FCHEVs use a combination of Fuel Cells (FC), and batteries (B) or/and Ultracapacitors (UC) [10]. The research stages for FCHEVs include the development of vehicles and the improvement of their efficiency. Beside the fuel cell system, they use the battery and/or ultracapacitor pack as a complementary power source to provide the required power on the DC bus. The topologies of FCEVs are described in detail in [11]. To increase the power density and to meet the demand for load power, it is necessary to integrate an energy management system. The energy management strategy of FCEVs is based on many important control techniques [12] such as finite state machine management strategies [13], grey wolf optimizer [14], model predictive control [15,16], fuzzy logic control [17,18], genetic algorithms [19,20], hierarchical prediction [21,22] as well as other control techniques developed so far for the energy management system.

This paper aims to update and introduce the new technologies regarding the FCEVs topology and Energy Management Strategies (EMS). In this regard, the paper will analyze recent research in the field, based on selected reference papers (87% published from 2018 to date), helping potential researchers and developers to get a more detailed picture of FCEV technologies.

II. Topologies of Propulsion Systems and the DC/DC Converters of FCEVs

All Electric Vehicles (AEVs) use only electric power to propel vehicles. AEVs can use as energy backup source a stack of batteries, a Fuel Cell (FC) stack or a hybrid solution, the AEVs being called as Electric Vehicle with Battery (BEV), EV with FC (FCEV) and hybrid EV with FC (FCHEV). In the following we will focus on the last two types [8,23].

Below, Table 1 presents a summary description of FCEV's and Fuel Cell Hybrid Electric Vehicle (FCHEV's) topologies. When it comes to the problem of EMS optimization, it is first necessary to understand the features and modes of operation of the propulsion systems topologies. Multiple topologies have different configurations in terms of design, by modifying the power source connection [24].

Because the direct connection to the electric motor of the vehicle is not efficient due to the different voltage levels of the fuel cell, the battery system and the ultracapacitor, as will be reported in Section 2.1, it is necessary to integrate the DC/DC converters to generate the voltage required by the electric motor [25]. Thus, in the Section 2.3 an analysis of the types of DC/DC converters used in FCEV is described [26].

FCEVs use a full electric propulsion system, and the energy source is based on fuel cell stacks. A FCEV is hydrogen-fueled and the electrochemical process results in water and heat. PEMFC is the ideal choice compared to other types of fuel cell system (FCS) because it operates at a low temperature of 60–80 _C, develops a high-power density and exhibits low corrosion [27].

FCEVs powertrain can be separated into three categories: fuel cell and battery (FC + B), Fuel Cell + Ultracapacitor (FC + UC) and Fuel Cell + Battery + Ultracapacitor (FC + B + UC) [28]. Because FC + B + UC configuration is complex and due to the fact that ultracapacitors have low energy density, FC + B is the main design configuration and is applied in most FCEVs [29].

III. Energy Management Strategy for Fuel Cell Electric Vehicle

In order to achieve a viable FCEV, with an opening to the market for marketing purposes by the manufacturers of the automotive industry, the main challenge is to develop a control strategy for energy management. These strategies lead to the improvement of the performances both from an energy point of view and of the reliability of the components, the most essential thing when we speak of the maintenance of a vehicle after commercialization [17]. Reducing hydrogen consumption by optimizing energy consumption is the subject of much research [18–25]. In addition to assessing fuel consumption, control strategies also play a role in preventing the degradation of energy storage systems, represented by batteries and the ultracapacitor [16–19]. Figure 5 describes the classifications of the energy management strategies.

Analysis of Rule-Based Strategies Methodology in FCEV

The control based on rule sets has a very good efficiency in accordance with the embedded processors, but usually it is based on empirical laws and the results are not among the most optimal. Rule-based strategies are suitable for online implementations because they are based on simple sets of rules (e.g., if-then-else), but the parameters of these rules may be affected by driving conditions Thus, according to Figure 6, rule-based strategies contain several types of control techniques with different implementations and present various advantages [20] and disadvantages related to adaptivity and optimality problems [11]. The criterion of the rule-based energy management strategy requires power capability prediction and an accurate SOC [12].

Q. Zhang and G. Li [113] describe in their work a control technique based on game theory for the distribution of power flow in the FC + B configuration. They approached this strategy because there are situations when the energy demand is uncertain during the driving cycle. In this case FC and B have played the role of two non-cooperating players each maximizing their own utility, which has led to uncertain energy demand behavior. This type of control, along with a fuzzy logic controller, used for correction, has had favorable results both for fuel reduction and for preventing battery degradation to a minimum level being very advantageous. As a main disadvantage, a thorough knowledge of each type of control is required; the technique being addressed cannot be extrapolated directly to other hybridization configurations. Given the importance of preventing the degradation of energy storage systems,

P. Rahimirad et al. [14] study the effect of temperature on these systems using different rule-based strategies. The study shows that, considering or not considering the effect of temperature led to significant errors associated with estimates of battery life. In this regard, a number of strategies have been used by them:

State Machine Control Strategy—it has the advantage of being easy to use by defining some states the FC power being calculated from the State-of-Charge (SOC) of the battery and the power of the load, and the disadvantage that the request to switch control when the mode is changed affects the output power;

Classical Proportional–Integral (PI) Control Strategy—is used for online setting, for control of the battery SOC and better tracking; the output of the regulator is the power of the battery and together with the power of the load led to obtaining the reference power of the FC;

Frequency Decoupling And Fuzzy Logic Strategy—allows FCS to offer a low frequency at the output, while the rest of the systems work at high frequencies. The main advantage of this strategy is that the average battery power tends to zero, ensuring a reduced range of batteries SOC;

Equivalent Consumption Minimization Strategy (ECMS)—this strategy is based on the minimization of an instant cost function for determining the power distribution, achieved from the FCS fuel consumption and the equivalent consumption of the battery and ultracapacitor systems. The advantage is to minimize fuel consumption and the equivalent consumption required to maintain the battery SOC;

External Energy Maximization Strategy (EEMS)—the strategy is to maximize the energy of the battery and ultracapacitor systems keeping the SOC within their limits.

The main advantage is that cost function does not need to estimate the equivalent energy of the energy sources, determined empirically. It is produced by external energy sources over a certain period of time.

Y. Wang et al. [19] approach the hybridized FC + B + UC configuration and describe in their work a rule-based power distribution strategy. The development of the power distribution strategy aims at the safety and the life of the energy storage systems. The Bayes Monte Carlo method performs the prediction of the remaining capacity and power supply of the battery and ultracapacitor. The advantage of using the Rule-based power splitting strategy is that the power demand, reliability and safety of the vehicle meet all the criteria of energy consumption and of the remaining capacities and power supply.

IV. Conclusions

The evolution of the technology in the automotive field and the worldwide imposing of the pollution norms, by reducing the greenhouse gases emissions, has caused more and more researchers to focus on the design aspects of the propulsion systems and at the same time on the development of software and new technologies that are able to manage the demand of power from the systems that make up EV and FCEV. In this regard, various configurations of FCEV's topologies have been presented with the purpose of a suitable choice by users in various applications. For complete information, comparisons have been made of the different types of DC/DC converters and equipment that serves to match the ESS components' output voltage to those required for the electric motor and auxiliary systems.

In order to improve the energy performance, a series of EMSs was analyzed, presenting the fundamental principles of the existing techniques with the advantages and disadvantages of their use, the main objectives being to reduce the consumption of hydrogen and to prevent the degradation of ESSs. Thus, the progress made by software developers in the field of artificial intelligence gives researchers the possibility to have maximum potential in the design abilities of the new control algorithms, by hybridization with existing techniques in order to eliminate the uncertainties regarding the robustness of the EMS.

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