Fuel cell electric vehicles: A review of current power electronic converters Topologies and technical challenges

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Abstract. This paper proposes a brief review to study the implementation of fuel cells and management energy in hybrid vehicles. The use of fuel cells (FC) in the automotive field has been growing steadily over the last decades thanks to their simple operation, quiet running, and high efficiency. In addition, fuel cell vehicles have great advantages over electrified vehicles powered by secondary batteries in terms of mileage endurance, energy efficiency, charging speed and climate tolerance. In this paper, the classification and a brief introduction of HEVs/FCs are reviewed, then topologies of fuel cell HEVs are presented that illustrate the hybrid vehicle system of the different FC architectures. Finally, a discussion of control strategies for hydrogen fuel cell vehicles is implemented with the clarification of future prospects for HEVs.

Keywords: fuel cell electric vehicle; DC/DC converter topologies; energy management strategy; global optimization

1. Introduction
The world is moving towards the search for an alternative solution to traditional internal combustion engine (ICE) vehicles because of the damage they cause to the environment, so electric cars were the most appropriate alternative [1]. So far, research confirms that hybrid electric vehicles (HEVs) are the best candidates for the future. In this paper, an improvement of the control of brushless motors (BLCD) is introduced and presented based on the PEMC fuel cell. The climate pollution that the world has witnessed in recent decades requires industrial companies to minimize the use of fossil fuels and to take alternative measures to ensure the use of technology with the lowest possible emissions. Hydrogen fuel cell vehicle technology is considered the most promising in the transportation sector due to its high energy efficiency [38,27]. To control the equivalent hydrogen consumption of the vehicle and maintain vehicle efficiency while driving it is important to select appropriate control of the power variables [38].

2. Background and motivation
2.1. Hybrid electric vehicles (HEVs)
The electric vehicle industry revolution of the 19th and 20th centuries is now bearing fruit with a new range of electric vehicles that are impacting the automotive world [26]. Thanks to low environmental emissions, electric vehicles could be the future solution to the fossil fuel shortage. There are generally three types of EVs on the market: full EVs, fuel cell EVs, and hybrid EVs [4]. A hybrid vehicle has a powertrain whose operating principle is characterized by the transmission of energy by at least two separate energy conversion devices (internal combustion engine, fuel cell, electric machine, hydraulic motor, etc.). A recent study announced that China, the United Kingdom, the United States and Germany lead the list of countries selling electric vehicles in the world [3].

2.2. Fuel cells (FCs)
The role of fuel cells is the direct conversion of chemical energy contained in fuels such as hydrogen, methanol into electrical energy. The PFC produces energy through the fuel on the anode and the oxidant on the cathode by reacting in the electrolyte[29]. If we assume that hydrogen is a new energy carrier, the fuel cell appears to be the most competent converter of hydrogen into usable energy[30]. High-temperature fuel cells are preferably used for stationary systems, while low-temperature fuel cells are more applied to portable applications [6]. There are seven types of fuel cells: proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell, solid oxide fuel cell, direct methanol fuel cell, alkaline fuel cell, molten carbonate fuel cell and microbial fuel cell [27]. Among the different CFs that exist, this paper will focus on PEMFCs (Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane Fuel Cell) that are commonly used for electric vehicles and for applications related to nomadic electronics. Most transportation-related research programs use PEM technology because of its low operating temperature, which is less challenging than the high temperature of SOFCs (solid oxide fuel cells) [3,30].

The general reaction of a PEM fuel cell is written as follows:

- Anode Reaction : H2 → 2H+ + 2e
- Cathode Reaction: ½ O2 + 2H+ + 2e- → H2O
- Assessment of the reaction: H2 + ½ O2 → H2O

PEMFC is characterized by its operating temperature between (30-110 °C), this temperature ensures safe and reliable mechanical and chemical compatibility [40]. The energy density of compressed hydrogen gas can be up to 1000 Wh/kg, which is higher than that of lithium-based batteries [5,6,40].

3. Related works

In recent decades, there has been a lot of work discussing the PEMFCs development and use in electric cars. Here are some examples of related works.

In 2006, the paper discusses the strategy for the development of a prototype phosphoric acid fuel cell electric vehicle by examining the capabilities of fuel cell technology to produce methanol from renewable feedstocks. This model is proposed by REVA Electric Car Company (RECC) and has been successfully tested [8]. In 2008, the document proposes a control technique for a fuel cell hybrid electric vehicle, to realize this system, three types of strategies are compared in order to choose the most efficient. The tests carried out have shown the advantage of the control system oriented towards the output power of the fuel cell [7]. In 2009, the objective of the study is to manage the power and perform an economic estimation of a fuel cell hybrid vehicle using...
fuzzy logic. To achieve the objective, a fuzzy logic controller is used to improve fuel economy [11]. In 2010, a paper which consists of making an insertion of a fuel cell system in a heavy hybrid vehicle is proposed, passing a validation of the functionality of the on-board FCS in terms of communication with the ECCE controller and then continue by executing a slow movement of the vehicle powered by the FCS and batteries [9]. In 2011, the objective of this study is presented which aims to improve the operation of the regenerative module of the zinc-air fuel cell to introduce it in an electric vehicle. In order to perform this technique, precise procedures were taken such as single cell design, cell assembly design, and environmental testing [10]. In 2014, the authors presented the concept and modeling of a REX (Complete Range Extender) powertrain type range-extension vehicle based on the high-temperature fuel cell and a thermal circuit [12]. In 2016, a document proposes a developed model of a fuel cell electric vehicle. This design requires an Ultra-Battery (UB) to ensure rapid power transfer during transient responses. This method has been tested by simulations and has shown its efficiency [13]. In 2018, this paper examines the control and Modeling of two hybrid DC power systems with a fuel cell in the system. The strategy applied to these structures is Sliding Mode Control and the results have shown the advantages of ensuring a robust system [14].

A lot of work has been done in the field of electric vehicles thanks to its promising future. Thereafter, articles dealing with electric vehicles will be examined: In [15], this article discusses the study of five kinds of drive train systems. A comparison on efficiency, reliability cost and maximum speed is made for these electric motors. The results have shown that that axial flux permanent magnet brushless dc motor drives gives the preferable performance rather than other motors. In [16], this document, a variable voltage control strategy based on minimum loss is proposed to reduce the loss of the inverter which also serves to optimize the electrical loss of the motor to improve the efficiency of the motor, the inverter and the entire drive system. Then an analysis of the loss minimization control and variable voltage control was performed to obtain the relationship between the inverter loss and the supply voltage. In [17], the purpose of this work is to obtain a valid solution for maximum energy efficiency of the motor over the driving cycles. A new strategy is proposed in this paper which is based on the optimal design of a permanent magnet synchronous motor (PMSM) in hybrid electric vehicles (HEV). A validation of the one-dimensional analytical model is carried out to form the geometrical parameters and calculate the efficiency of the engine. In [18], a comparison was made between the indirect field-oriented control (IFOC) method and the direct torque control (DTC) method using Sliding Mode Control (SMC). A study of the Accuracy of tracking under changing vehicle speed conditions for different cruise control systems is carried out.

In [19], this document proposes a hierarchical control strategy to link the braking and steering performance of All-Wheel Drive Electric Vehicles (IWMD EVs). The calculation of the longitudinal, lateral force and yaw moment of the vehicle in the upper controller is done using a non-linear predictive control scheme based on Particle Swarm Optimization (PSO-NMPC). In [20], a new approach is presented in this paper based on fault-tolerant control for the short-term fault occurring in the electrical drive system of the switched reluctance motor (SRM). The approach is used to select the de-rating states according to the operating requirements in the case of switches with short duration faults. The purpose of this strategy is to ensure the reliability of the SRM system and the safety of drivers. In [21], this paper presents a new electric braking system for electric vehicles (EVs) with brushless direct current (BLDC) motors. This system is based on stopping time and energy regeneration. According to the tests carried out the energy recovery is better for the one- and three-switch methods. In [22], this paper discusses the problem of fault-tolerance of autonomous ground-based electric vehicles equipped with motors in the wheels through a hierarchical control strategy that involves developing the top layer of the controller to achieve trajectory control and ensure vehicle stability. In [23], the strategy of the output feedback controller $H_\infty$ is applied to eliminate faults and time delay in the actuator of an electric vehicle driven by
wheel motors. The use of this controller ensures the asymptotic stability of the system and the performance $H_{\infty}$. In [24], the modeling and comparative dynamic analysis of a field-controlled permanent magnet synchronous motor (PMSM) is carried out using a hysteresis current controller and a PWM (Pulse Width Modulation) controlled current controller. To achieve this work several techniques were used such as Euler’s integration technique. In [25], a new braking torque distribution strategy is proposed for electric vehicles equipped with four-wheel motors with regenerative braking systems. This method consists in ensuring the safety and efficiency of regeneration using the Model Predictive Control (MPC) assumption.

4. Topological classification

The hybridization of a system is summarized by the combination of two sources of Energy and one type of propulsion or two distinct types of propulsion, in the case of hybrid electric vehicles, we speak of the combination of electric and thermal propulsion. The operating system of an FCEV starts with the battery, which provides energy to the DC bus [31]. Then, the DCU, whose role is to keep the bus voltage constant, also has the role of transferring the energy needed for the vehicle propulsion to the motor drive converter. The DC/AC converter is responsible for controlling the speed and torque of the motor, and the motors in turn convert the electrical energy into kinetic energy [32].

![Figure 2 - scheme of an FCEV power transmission structure](image1)

![Figure 3 - The powertrain of full FCEV architecture](image2)

![Figure 4. The powertrain of FC system + Battery hybridization](image3)

![Figure 5. The powertrain of FC + UC hybridization](image4)

![Figure 6. The powertrain of FC + (Battery + UC hybridization)](image5)

![Figure 7. The powertrain of FC + Battery + PV hybridization](image6)

4.1. The powertrain of full FCEV architecture
In Figure 3, the FCEV structure considers the FC battery as the only energy producing unit, its system includes a DC-DC converter, fuel tank, FC stack, inverter and electric motor [33], which offers high efficiency, simplicity of architecture, reliability of the system and comfortable driving [34].

4.2. FC architecture + Battery hybridization

This architecture in Figure 4 includes the FC system which consists of the unidirectional DC-DC converter (UDC) connected to the battery and the inverter connected directly to the motor. The battery is responsible for the initial start in order to guarantee the operation of the engine by providing a high current for starting [34,35].

4.3. FC architecture + UC hybridization

In figure 5, the combination of CE + CU is based on the use of CE with the introduction of an ultracapacitor that extends the life of the battery but has the disadvantage that it does not withstand high voltages [GT capacitor advanced capacitors] and has a low density which makes its use temporary [36].

4.4. The powertrain of FC + (Battery + UC hybridization) system

The system consists of an FC fuel cell connected to the DC Bus, two DC to DC converters, one of which is unidirectional and the other is bidirectional, located between the FC fuel cell and the capacitor as shown in Figure 7 [36,32].

4.5. FC architecture + Battery + PV hybridization architecture

Scientific research continues to find a technology to fully power electric vehicles with photovoltaic panels, in figure 7 a hybrid system of FC + Battery + PV hybridization is implemented based on FC for hybridization. The battery is connected to the DC bus by a bi-directional converter. The power delivered by the PV depends on the intensity of solar radiation and temperature [37].

5. Ultracapacitors

The CU separates the positive and negative charges during the operation of the energy storage. The charges are stored on two parallel plates through an insulator [39]. Besides, the ultracapacitor has the characteristics of high-power density and relatively low energy density. Its equivalent internal resistance is several decades lower than that of a battery, allowing decades of higher discharge and charge currents to be used. On the other hand, the combination of ultracapacitors and fuel cells in a hybrid system allows for greater robustness in power control thanks to the high-power density and energy recovery capacity of ultracapacitors [38,39]. Furthermore, a comparison was performed in [40] two hybrid power systems for vehicles: a battery-fuel cell hybrid powertrain and a fuel cell-ultracapacitor hybrid powertrain, which showed the advantage of the fuel cell-ultracapacitor compared to the battery where the addition of ultracapacitors improves the system performance.

![Figure 8: Diagram of an ultracapacitor](image)

6. Electric machines for EVs and HEVs

1. Induction motors

Induction machines are divided into two types: wound rotor and cage rotor. Wound rotor induction machines are less used compared to cage rotor induction machines due to their high cost, need for maintenance and lack of robustness. On the other hand, caged rotor machines are characterized by cheaper parts and materials, no brushes, which means less noise, less wear and less maintenance [44].

2. DC motors
The first motors used on electric vehicles were Direct Current Motors (DCMs) because they were the easiest motor to drive in speed. MCCs are classified into 2 types: brushed and brushless motors. The brushed one, the permanent magnets are replaced by windings in the stator. The direct current motor (BLDC) is commonly used in FCHVs due to its low volume and high efficiency [44,46].

2-1- Modeling of BLDC Motors

The (BLDC) is ideally suited for EVs due to its high efficiency, high power density, good speed-torque characteristics, and low maintenance. This means that the magnetic field generated by the stator and the magnetic field generated by the rotation of the rotor have the same frequency. in this work the BLDC motor was chosen in a hybrid vehicle using a hydrogen fuel cell [28].

- Mathematical modelling of BLDC motor

The basic voltage equations of armature winding for BLDCM can be represented as follows:

\[ V_a = R_i + L (di_a / dt) + e_a \]  
\[ V_b = R_i + L (di_b / dt) + e_b \]  
\[ V_c = R_i + L (di_c / dt) + e_c \]

Equation 1 through 3 can be rewritten in following form:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
L_{ab} & L_{ac} & L_{bc} \\
L_{ca} & L_{cb} & L_{cc}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
\]

Equation 4

In the above equation it is assumed that the windings are not saturated, the iron losses are negligible, the resistances of the phase windings are equal, the mutual inductance between the phase windings is zero and the self-inductance is constant, so the equation is reduced to:

\[ L_a = L_b = L_c = L \]  
\[ L_{ab} = L_{bc} = L_{ca} = M =0 \]  

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
L_p & 0 & 0 \\
0 & L_p & 0 \\
0 & 0 & L_p
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} +
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

Equation 7

The Back EMF of non-conducting phase is given by:

\[ e_a = k_a f(\theta_a) w_r \]  
\[ e_b = k_a f(\theta_a - 2\pi) \]  
\[ e_c = k_a f(\theta_a + 2\pi) \]
The torque equation is as follows:
\[ T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{w_r} \]  
(11)
\[ T_e = T_L + J \frac{dv}{dt} + Bw \]  
(12)
\[ T_e = k_t I \]  
(13)

The output power is given by:
\[ P = T_e W_r \]  
(14)

7. Control strategies of the hydrogen fuel cell vehicles
In a hybrid powertrain, a control strategy is always a priority to manage power flow by monitoring the different characteristics of each component. Control mechanisms in HFCEVs typically include FC, BAT and SCAP. Several control strategies have been exploited in this area to ensure energy management in the vehicle, among the most common: Advanced Power Source Strategy (APSS), Operating Mode Control Strategy (OMCS), Fuzzy Logic Control Strategy (FLCS), and Equivalent Consumption Minimization Strategy (ECMS) [34, 42].

For the PEMFC, several control strategies have been implemented including robust control using a \( H_{\infty} \) controller, the feedforward action which allows controlling the air supply of a PEM, other strategies have been implemented such as the sliding mode which is also used to minimize the transient effects of the load change [43]. However, in [42] the authors presented a fault mitigation strategy (FTC) to address the low reliability of PEM fuel cells.

Conclusion and future aspects:
Hybrid vehicles have several drawbacks that need to be addressed including short-range, overheating during loading, heavyweight...
Performance, cost, fuel availability, public satisfaction, reliability, durability, and performance during transient periods are necessary elements to improve fuel cell electric vehicles that can compete with ICE-based vehicles. Many organizations are calling for price reductions to encourage climate protection by: Reducing the cost of hydrogen as the cost of hydrogen must be competitive with conventional fuels, Developing hydrogen storage technology. In addition, Reduce the cost of fuel cells and improve their life span so that the cost of fuel cell power systems is suitable to compete with conventional technologies [46, 47].

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