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Review

Energy management and fault tolerant control strategies for fuel cell/ultra-capacitor hybrid electric vehicles to enhance autonomy, efficiency and life time of the fuel cell system

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ABSTRACT

The hybridization of the fuel cell (FC) hybrid electric vehicle (HEV) by an auxiliary energy source has the benefit of improving the system's dynamic response and efficiency. Indeed, an ultra-capacitor (UC) used as an energy storage device to permit the FC lowest dynamics during fast power changes and recovers the braking energy to enhance the HEV autonomy.

In FC/UC HEV, an adequate power management approach is one essential objective of the researches in this area. In this paper, an advanced control strategy managing the power distribution among the two energy sources is elaborated using state-flow bloc of Matlab/Simulink. The UC control power is realized indirectly through the DC bus voltage regulation. For the FC power demand, an algorithm with filtering power vibrations is developed. This algorithm, depending on the UC state of charge (SOC) and the vehicle speed to minimize the FC power demand transitions and enhance its life time. The traction power is provided utilizing two five-phase permanent magnetic synchronous machines (PMSM) in each rear wheels of the vehicle to reduce clutter caused by mechanical part. A fault tolerant strategy is added to eliminate all faults appeared in the tractions machines in aims to reduce torque ripples and power vibrations for more stability and length life time of the HEV systems. The models of the HEV and the control strategy are produced employing Matlab/Simulink. Simulation results indicate the desirability of the proposed system and its energy management strategy for HEV.

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Introduction

Air pollution caused mainly by conventional combustion vehicle and the employment of battery as the only source of energy for electric vehicles is still restricted because of its low autonomy, life time and charging time problems [1]. In support, the FC is as a good alternative source to its high autonomy and its zero emission of polluting gas [2,3]. Between the different FC technologies, the Proton Exchange Membrane (PEMFC) is very useful for the transportation area [4–9]. PEMFC offers a lot benefits such as the working at a low temperature compared to other types of FC, low cost which is very important point, quick start up and high efficiency. Only, the FC cannot respond to fast transient peak power demand [10–12]. The vehicle speed and power fluctuations may lead to pressure oscillation and oxygen starvation in the FC membrane which can affect the cell life time [3,6,11,13]. To solve this problem, a hybridization with another source as UC was the most excellent solution to assist the FC source [5,13–15]. This system was used not only to cover the peak power demand, but also recover the braking energy. Therefore, such configuration decreased the hydrogen consumption considerably, improved efficiency and satisfied the power drive demands in all drive conditions.

The problem of the use of more than one energy source is the power management strategy. In the literature, different strategies have been appeared to solve this problem. For example in Ref. [11], the FC supplied power to UC source to maintain them charged but this strategy is not economic in terms of hydrogen consumption and there are not more benefit in braking energy recuperation. A power management strategy and structure of HEV enveloping operation modes using a battery as secondary source depending on the power demand and the SOC of the battery was developed in Ref. [16] but the use of the battery as a second source return to same problem such as the recharging in braking mode and it does not support abrupt power variations. Also, an others type of control strategies and HEV structures was regrouped by authors of [4] and [17] to reduce the hydrogen consumption. Others used a fuzzy logic control to supervise the power exchange between the FC and the UC in FC/UC HEV. This control was simply presented in Ref. [18], cascaded with wavelet strategy in Ref. [19] and combined with the flatness control technique in Ref. [20]. A several fuzzy supervisor developed by authors of [21] to an online controller in order to reduce power losses. The problem of management with fuzzy logic is the necessity of a great numerical memory for calculations of fuzzification and deffuzification of the data. In Ref. [22], the energy management strategy is based on neural network and wavelet transform here it pose the same problem cited before, all strategies with artificial intelligence need more and high electronic equipments which increase the cost of the HEV.

This work proposes a strategy of management that, in addition of the SOC of UC, the speed of vehicle as second parameter in control strategy and a few of the strategies mentioned above took into consideration the vehicle speed. This control using State-flow do not need more time or memory for calculation and it give the control in few time. The case of a fault in the machines or inverters will generate a great variation in the power demand [23]. A fault tolerant strategy is added to protect the FC when a fault is detected in traction machines.

This paper is decomposed as follows. First, the FC, the UC and the HEV system models were presented. After, the control of the converters, speed regulation, the fault tolerant strategy and the proposed energy management was explained. Before finishing, the simulation results were showed. Finally, discussions and conclusions were given.

FC/UC hybrid electric vehicle

The power system of the FC is represented in Fig. 1. The two energy sources (FC and UC) exchange power with a DC bus.

For the FC, a boost converter unidirectional in current is utilized to connect the FC to the DC bus; although, the UC requires DC/DC converter bidirectional in current to supply power and to recover the breaking energy. The two inductances added as filters and to respect sources alternation. The DC bus which is a capacitor supplies the both traction machines with employing a five phase inverter for each one to convert the DC power into AC power. This system gives the torque control of each wheel in dependently with a significantly high accuracy, which can enhance the stability of the HEV, reduce clutter caused by the mechanical part such as mechanical differential and transmission shafts and give more frees space in the vehicle for UC and hydrogen tank. The motors are five-phase permanent magnetic synchronous machine type which is frequently used in the transportation field due to its good power, high efficiency, weight ratio machines and it can still continue to run using the remaining phases without any external intervention in faults open phases [23]. The Fig. 1 shows the model of FC/UC HEV used in this work.

Dynamic modeling of the FC

The PEMFC is the main energy source for the vehicle. Its cell voltage and its total power are defined by the following equations [4,24]:

$$V_{FC} = N_0 V_{FC,cell} \tag{1}$$

$$V_{FC,cell} = E_{Nernst} - U_{act} - U_{ohm} - U_{conc} \tag{2}$$

$$U_{ohm} = R_{FC}\, I_{FC} \tag{3}$$

$$U_{act} = b_1 + b_2\, T_{FC} + b_3\, T_{FC} \ln\left(I\, 5.2\, 10^{-3}\right) \tag{4}$$

$$U_{act} = B_{FC} \ln(0.0136\, I_{FC}) \tag{5}$$

The expression of the Nernst equation according to JC Amphlett is given by [25]:

$$E_{Nernst} = 1.229 + 0.85\, 10^{-3} \\ (T_{FC} - 298.15)\, 4.3085\, 10^{-5}\ T_{FC}\, 0.5 \ln\left(p_{H_2}\right) \ln\left(p_{O_2}\right) \tag{6}$$

The FC should be able to provide the power demand of the vehicle P_v by taking into account the FC efficiency η_{FC} [26].