Energy Management for a Hybrid Fuel cell/SC for Four-Wheel Drive Electric Vehicle

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Abstract

This work presents the using of Hybrid power source for electric vehicle four wheels drive, composed of a proton electrolyte membrane fuel cell (PEMFC) as the main energy source, and a supercapacitor (SC) as an auxiliary power source. The fuel cell PEMFC has a main weak point it is slow dynamics, because to prevent fuel starvation problems must limited the fuel cell current slope in order, to ameliorate its performance and lifetime. The supercapacitor can complement the slow output power of the main source, to produce the compatibility and performance characteristics needed in a propulsion system, because it has a very fast response and high specific. DC-DC boost converter connected to the fuel cell source to ensure the input voltage of four electric induction motors controlled by the direct torque control based space vector modulation (DTC-SVM), and a supercapacitor connected via bidirectional dc converter to the output voltage of the boost converter, to give the overshoot power and the fast response power. The simulation results of powers behaviour of fuel cell, SC and the demanded power by electric vehicle are given and interpreted, then simulation results of speed, electromagnetic torque and current in different phases.

Keywords: Fuel cell, Energy management, DC-DC converter, Electric vehicle, DTC-SVM

Received: January 31, 2019

To cite this article:
Soumeur M., Gasbaoui B., Abdelkhalek O., Hartani M., Hafsi O., "Energy Management for a Hybrid Fuel cell/SC for Four-Wheel Drive Electric Vehicle", in *Electrotehnica, Electronica, Automatica (EEA)*, 2019, vol. 67, no. 3, pp. 58-64, ISSN 1582-5175

1. Introduction

The fuel cells are one of the most promising candidates for vehicle power generation as an alternative to the internal combustion engine.in the frame of emission reduction policies. The proton exchange membrane fuel cells (PEMFCs) are the most interesting for this purpose due to their compactness and low operation temperature [1].

So, automobile manufacturers are developing direct hydrogen, polymer-electrolyte fuel cell systems to provide traction power for vehicle because of their zero emissions [2].

At the same, the use of hydrogen in the electric vehicle has opened the window of opportunity for other different fuels natural and biomass. However, the fuel cell has a very slow dynamic response respect to the load transition, because the output characteristic of PEMFC is limited by the mechanical devices which are used for maintaining the air pressure, temperature and the humidity in the cell. It will take about several seconds for the fuel cell to build another new steady state once there is a load transition [3].

This process will shorten the operating life of the fuel cell because of suffering temperature excess or over-air-pressure.

To solve the problem, the fuel cell/battery or fuel cell/super-capacitor hybrid systems have been proposed [1], [3], [4], [5], [6].

One motivation for hybridizing power is to improve its fuel economy by recovering a portion of the braking energy and sustains the operation life of fuel cell.

Simultaneously, use the advantage of both technologies and reducing their disadvantages by combining the high energy density of fuel cells and the high power density of batteries.

However, this complex fuel cell hybrid power system requires more elaborate studies for component configuration and system-level control strategy development to fully explore the potential benefits of this advanced technology, In this paper, a general configuration of hybrid 4WDEV is proposed which is described in Figure 1.

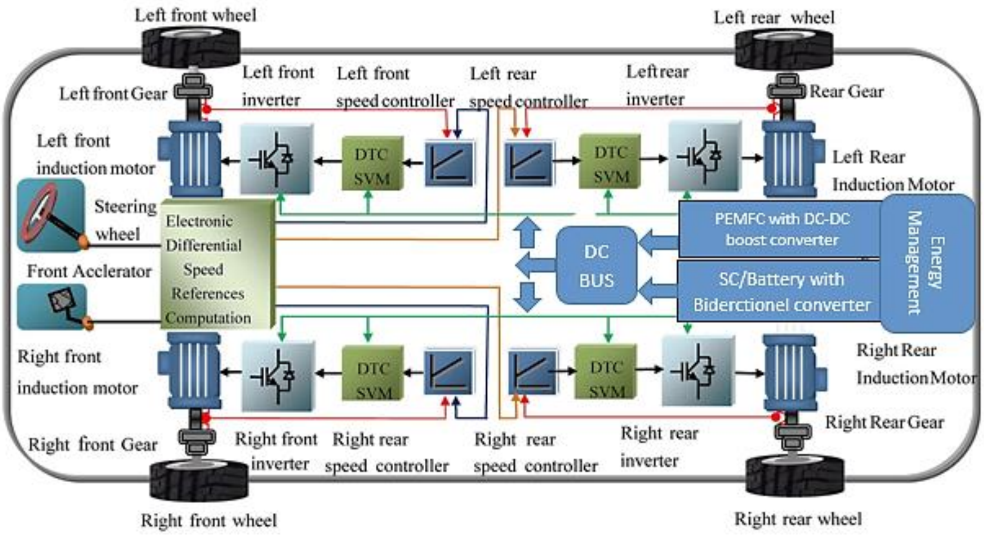

Figure 1. Proposed 4WDEV configuration of hybrid fuel cell/SC powertrains system

A hybrid fuel cell powertrains system is given, as shown in Figure 2.

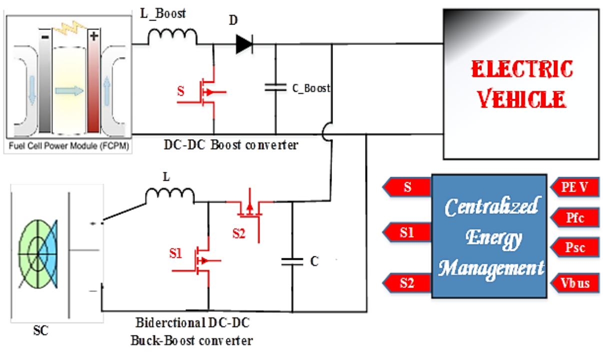

Figure 2. Proposed 4WDEV model a fuel cell/SC powertrains system

The power system is composed of a fuel cell connected through the appropriate DC-DC boost converter, and a supercapacitor connected via a bidirectional buck-boost converter to the same DC bus.

This proposed hybrid system has some advantages:

- During the start period of the system, the supercapacitor will power this system to make the fuel cell operates in an easy way.
- When the load transits, the load steps up or down, due to the fuel cell can't respond quickly, the SC will provide or absorb the unbalanced energy while the fuel cell is only exporting a slow varying power, which improved the dynamic characteristic of the whole system.
- Reducing the total cost, that can explain by, the power rating of the fuel cell can be decreased due to the SC can provide peak power.

In the hybrid system, the fuel cell is the main power source and the SC is the auxiliary source. Therefore, the control strategy needs to determine the power split between the fuel cell and the energy storage component. Which aims to make the whole system operates with high efficiency and high reliability.

In this work, the Matlab Simulink is used to simulate the proposed energy management of the hybrid Fuel cell/SC four wheels drive electric vehicle, then the results of simulation is given and interpreted.

2. Electric Vehicle Description

The electric vehicle is influenced by many opposing forces ,these forces are; the rolling resistance force F_{tire} due to the friction of the vehicle tires on the road; the aerodynamic drag force F_{aero} caused by the friction on the body moving through the air ; and the climbing force F_{slope} that depends on the road slope [7-8].

Firstly, we can define the rolling resistance force by:

$$F_{tire} = mgf_r \tag{1}$$

Secondly, the aerodynamic resistance torque is given by the relation follow:

$$F_{aero} = \frac{1}{2}\rho_{air} A_f C_d v^2 \tag{2}$$

Thirdly, the rolling resistance force is usually modelled as:

$$F_{tire} = mgf_r . \tag{3}$$

And finally, the total resistive force is equal to the sum of all the resistance forces, as shown by the relation below:

$$F_r = F_{tire} + F_{aero} + F_{slope} \quad (4)$$

where r is the tire radius, m is the vehicle total mass, fr is the rolling resistance force constant, g the gravity acceleration, F_{aero} is air density ,Cd is the aerodynamic drag coefficient, A_f is the frontal surface area of the vehicle, v is the vehicle speed, ρ is the road slope angle. Values for these parameters are shown in Table 1.

Table 1. Parameter of the electric vehicle model

r	0.32 m	Af	2.61 m^2
m	1400 Kg	Cd	0.32
fr	0.0133	pair	1.109 Kg/m^3

In this paper, a four-wheel drive electric vehicle is studied, composed of four induction motors controlled by DTC-SVM. The PEMFC/Supercapacitor hybrid system is the energy source of these motors.

The control of this system is by energy management via DC-DC boost converter and Bidirectional buck-boost converter, by using a PI controller.

3. PEM Fuel Cell Modelling

Fuel cells convert chemical energy into electrical energy directly by oxidizing hydrogen without mechanical process. PEMFCs are usually preferred in automotive applications in comparison with the others. This is because the PEMFCs are efficient and compact, and they have a quick start because they work at about 353K [9], [10], [12], [13], [14].

The fuel cell stack parameters have been selected as Table 2.

Table 2. Fuel stack parameters

Open circuit voltage	400 V
Nominal operating point	I=200 A, V=250 V
Maximum operating point	Imax=300, Vmax=200 V
Number of cells	334
Nominal stack efficiency(%)	55
Nominal air flow rate (lpm)	2100
Nominal supply pressure	H2:1.5 bar, Air: 1 bar
Operating temperature	65
Nominal composition (%)	H2:99.95,O2:21, H2O(Air):1

The cell potential is calculated using the Eq.(5):

$$E = 1.229 - [(\frac{RT}{nF})\ln(\frac{P_{H2O}}{P_{H2} * \sqrt{P_{O2}}})] \quad (5)$$

The number of stack voltage has been calculated assuming a nominal operating voltage of 0.72 V for one cell.

The fuel stack system includes H_2 controller and O_2 controller, which regulate the flow rate of H_2 and the flow rate of O_2, respectively.

4. Super-capacitor Modelling

The used of the supercapacitors in the hybrid electric vehicle is very important, due to the fast response, so if use it as the energy storage device in an HEV, it is necessary to connect many cells (series/parallel) to obtain a high level of voltage and current because SC has a low voltage [15], [16]. Supercapacitor model is presented in equation (6).

$$\begin{cases} V_U = V_{U_1} - R_U * I_U \\ I_U = \pm \frac{dQ_u}{dt} \\ C_U = C_0 + \beta * V_{U_1} \\ \frac{dV_{U_1}}{dt} = K * \frac{I_U}{(C_0 + 2 * \beta * V_{U_1}} \end{cases} \quad (6)$$

5. Direct Torque Control Strategy Based Space Vector Modulation

The DTC-SVM strategies operate at a constant switching frequency, this type of control strategy depends on the applied flux and torque control algorithm. Basically, the controllers calculate the required stator voltage vector and then it is realized by space vector modulation technique,[17], [18], [19].

This strategy is built by two PI controller, to regulate the torque and the magnitude of the flux. Refereeing to Figure 3, two proportional integral (PI) type controllers regulate the flux amplitude and the torque, respectively.

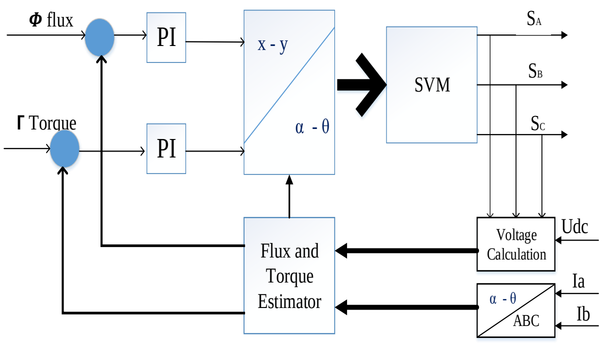

Figure 3. General diagram of DTC-SVM strategy

Therefore, both the torque and the magnitude of flux are under control, thereby generating the voltage command for inverter control. Noting that no decoupling mechanism is required as the flux magnitude and the torque can be regulated by the PI controllers.

Due to the structure of the inverter, the DC bus voltage is fixed, therefore the speed of voltage space vectors is not controllable, but we can adjust the speed by means of inserting the zero voltage vectors to control the electromagnetic torque generated by the induction motor. The selection of vectors is also changed. It is not based on the region of the flux linkage, but on the error vector between the expected and the estimated flux linkage [20], [21].

6. DC-DC Converter, Motor Inverter and Motor

The DC/DC converter includes a bus DC controller, In which the bus DC controller adjusts the current and voltage of fuel cell stack according to the calculated reference value, by a PI controller. The parameters of these converters are listed in Table 3.

Table 3. DC/DC Parameters

Type	Bi-directional converter	Boost converter
Input voltage	250 V	250 V
Output voltage	400 V	400 V
Inductance	4.2 mH	3.1 mH
Capacitor Power	0.05 mF 60 kWatt	1.2 mF 60 kWatt

The motor inverter provides the required voltage for the motor in order to maintain the motor normal operation. Their parameters are shown in Table 4.

Table 4. Motor inverter and motor parameters

Inverter induction motor	Motor
Input voltage: 400 V	Maximum output power: 15 kW for one motor
Control mode: DTC-SVM	Output torque: (100~+100) Nm

7. Energy Management

In this paper, the energy management algorithm used is based on the required power of electric vehicle and state of charge of the supercapacitor. The object is to minimize hydrogen consumption of fuel cell. The difference power between the fuel cell power and the required power by the electric vehicle is provided by supercapacitor in the case acceleration or deceleration. The control strategy decides the required power sharing between fuel cell and SC. During the operating process, the fuel cell acts as primary power source and the SC represents the auxiliary power source.

This energy management algorithm is divided into operating modes:

Mode 1: The load composed, of four induction motors (electric vehicle) receives the power from the storage system (Acceleration phase).

Mode 2: This mode is characterized by the activation of the fuel cell. At this moment, the PEM fuel cell supplies the 4WDEV (steady speed)

Mode 3: This mode is characterized by the activation of the Storage system. The supercapacitor recovers the energy braking (deceleration phase).

Figure 4 describes this proposed energy management algorithm.

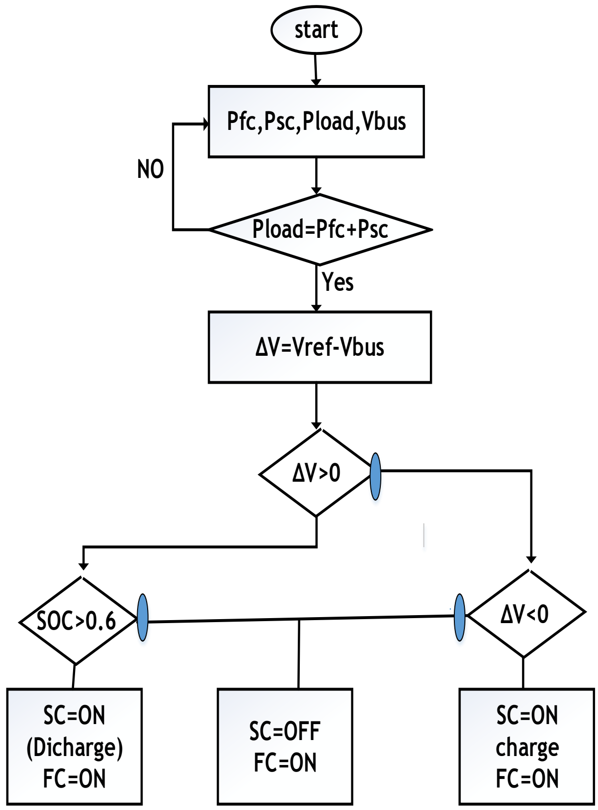

Figure 4. Energy management algorithm

BDC used to connect between the supercapacitor and DC bus can operate in three modes: Buck, Boost or Shut-Down (SD). According to the condition of SC and the fuel cell, BDC should work at one mode of three modes.

Table 5 reported the BDC operation mode. Therefore, how to control the BDC is the main issue of the power management.

Table 5. BDC operation mode

	Vbus<Vref	Vbus=Vref	Vbus>Vref
SOC<0.6	SD	SD	Buck
0.6<SOC<0.95	Boost	boost	Buck
SOC>0.95	Boost	boost	SD

In order to characterize the behaviour of EV system and energy of this system, we have made trajectory of Electric vehicle, this trajectory is divided into four phases:

1. At 0 to 1 s The car is traveling at 40 km/h
2. At 1 s to 2 s Increased speed of the car up to 121 km/h
3. At 2 s to 2.8 s At this interval, the car crosses a ramp of 10 degrees with a speed of 121 km/h

4. At 2.8 s to 3.5 s The end of the slope with speed of the EV is 121 km/h
5. At 3.5 s to 5 s At this stage, the speed of the car drops directly at 15 km/h

All these phases are shown in simulations results by using MATLAB / SIMULINK, which allowed us to see a performance of 4WDEV controlled by DTC-SVM in various speed and difference, then showed us the behaviour of energy demand by EV, Power fuel cell and power of SC, and The DC bus voltage of this system.

8. Discussion

In Figure 5, the speed cycle of electric vehicle is shown, which we have noted that the speed follows reference in four phases, and this shows a good reaction of control DTC-SVM.

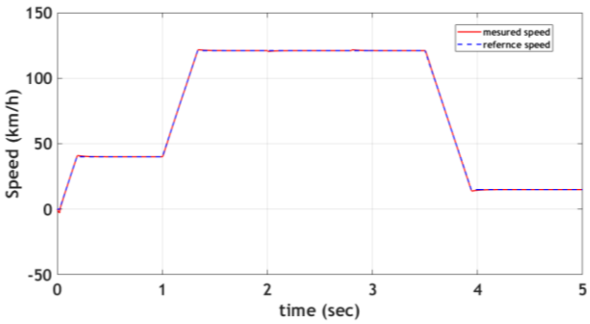

Figure 5. Electric vehicle speeds cycle

The behaviour of different power are presented in Figure 6, which it is the power demanded by the electric vehicle (PLoad), power given by fuel cell (Pfuel cell) and the power of supercapacitor (PSC) after see these results we have noted a great demand of power by the electric vehicle at the start that explain the couple of start of the four machines, so the supercapacitor give this demand, because it has a very fast response time, reverse a fuel cell has a slow response time, then after 0.4 s the fuel cell power increasing for powered EV and charged SC, at 1 s to 1.3 s in this phase the EV speed change fast than 21 km to 121 km, this variation make an overshoot in demand PEV thus the supercapacitor discharge to give this demand fast, at 1.3 s to 3.5 s in this interval the power of fuel cell is increasing to power the 4 WDEV and to charge SC, but at 2 s EV crosses a ramp of 10 degrees with a speed of 121 km/h, so SC give fast the required power of EV. At 3.5 s in this part direct drop in the required power of the vehicle because, EV decrease directly the speed to 15 km/h, so the slow response time of fuel cell make SC feed on the remaining energy of the PEMFC, thus the SC begin to charge to 4.5 s, at 4.5 s to 5 s just the fuel cell powered 4WDEV.

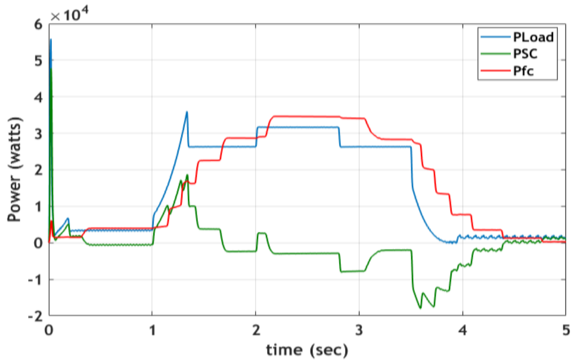

Figure 6. Power variation of fuel cell /Supercapacitor /PEV sources in all EV trajectory

The DC bus voltage is shown in Figure 7, we have noted, the dc bus follows the reference 400 V with a negligible ripple, also we noted in the case increasing or decreasing the required power of the electric vehicle, the dc bus voltage deviate a small deviation on the reference path but the supercapacitor provide or absorb this deviation to make the dc bus follow the reference 400 V.

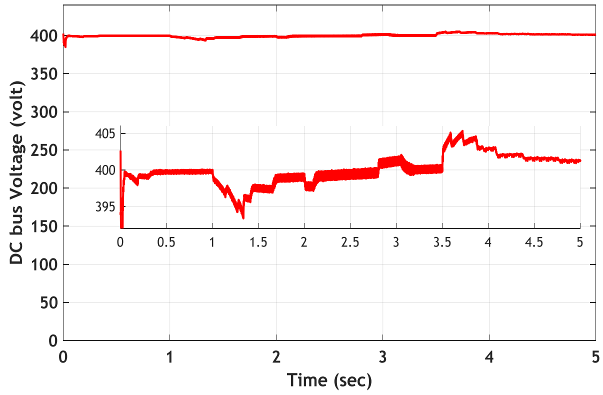

Figure 7. DC bus voltage of the hybrid system in all phases

9. Conclusions

A 4WDEV simulator provided power with fuel cell and a supercapacitor has been developed in Matlab/Simulink. In order to get well fuel economy and final supercapacitor SOC, we give a fair control strategy, where the fuel cell stack operates in good condition and the SC is used as a buffer system. The efficiency ranges about 55 %, and the minimum battery SOC is 45 % or so.

With the control of the energy management system, the minimum power rating of the fuel cell system for this type of hybrid vehicle is determined by the vehicle power demand under sustained driving conditions. At the same time, with the help of the energy management module, the fuel cell stack output current can be increasing or decreasing with the requirement of the rapid response of the vehicle fulfilling by the buffer SC. Thus, the safe operating condition can be gain for the fuel cell.

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Funding Sources

The authors wish to thank the Smart Grid and Renewable Energy at Tahri Mohamed University Bechar in Algeria. The authors would also like to thank the editors and the anonymous refeers for their constructive comments, which were helpful in the improvement of the manuscript.

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