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Modelling and Frequency Separation Energy Management of Fuel Cell-Battery Hybrid Sources System for Hybrid Electric Vehicle

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Abstract **– This paper presents a hybrid system of fuel cell-battery power sources for electric vehicle.**
Because fuel cell (FC) and battery have advantages and disadvantages of their own, it should be beneficial to have hybrid sources, in which FC supplies the base energy while battery supplies peak power for fast acceleration and captures the braking energy regeneration.
In this paper a state space model for the Fuel Cell-Battery Hybrid Electric Vehicle (FCEV) power system is given and an energy management based on frequencies separation is discussed and validated by Matlab simulation.

Keywords – FC, Hybrid power system, DC-DC Boost converter, State space modelling, Frequency separation energy management.

I. Introduction

Vehicles equipped with conventional internal combustion engines (ICE) exist for over 100 years. With the increase of the world population, the demand for vehicles for personal transportation has increased dramatically since the past decade. This trend of increase will only intensify with the catching up of developing countries; the demand for oil has increased significantly.

Another problem associated with the ever-increasing use of personal vehicles is the gas emissions. The greenhouse effect, also known as global warming, is a serious issue that needs to be addressed. There have been increased tensions in part of the world due to the energy crisis.

Government agencies and organizations have developed more stringent standards for the fuel consumption and emissions. Nevertheless, with the ICE technology being matured over the past 100 years, although it will continue to improve with the aid of automotive electronic technology, it will mainly rely on alternative approaches evolution to significantly improve the fuel consumption and reduce emissions [1].

Battery-powered electric vehicles (EVs) were one of the solutions proposed to tackle the energy crisis and global warming. However, the high initial cost, short driving range, long charging (refueling) time, and reduced passenger and cargo space have proved the limitation of battery-powered EVs.

The hybrid electric vehicle (HEV) was developed to overcome the disadvantages of both ICE vehicles and the pure battery-powered EV. The HEV uses the onboard ICE to convert energy from the onboard gasoline or diesel to mechanical energy, which is used to drive the onboard electric motor in the case of a series HEV, or to drive the wheels together with an electric motor in the case of parallel or complex HEV [2].

The onboard electric motor(s) serves as a device to optimize the efficiency of the ICE, as well as to recover the kinetic energy during braking or coasting of the vehicle. The ICE can also be stopped if the vehicle is at a stop, or if vehicle speed is lower than a preset threshold and the electric motor is used to drive the vehicle along. The ICE operation is optimized by adjusting the speed and torque of the engine. The electric motor uses the excess power of the engine to charge battery if the engine generates more power than the driver demands, or to provide additional power to assist the driving if the engine cannot provide the power required by the driver.

Due to the optimized operation of the ICE, the maintenance of the vehicle can be significantly reduced, such as oil changes, exhaust repairs, and brake replacement. In addition, the onboard electric motor provides more flexibility and controllability to the vehicle control. Although, HEVs possess many advantages; they also have certain limitations. The main concerns include increased cost due to the introduction of electric motors, energy storage system and power converters with little gas emissions (not zero emission) [1].

Fuel cell vehicles (FCVs) use FCs to generate electricity from hydrogen. The electricity is either used to drive the vehicle or stored in an energy storage device, such as battery pack. Since FCs generates electricity from chemical reaction, they do not burn fuel and therefore do not produce pollutants. The byproduct of a hydrogen FC is water and heat. FCVs provide quiet operation and more comfort with zero emissions. These vehicles are efficient, reliable, optimum, and long lasting at reasonable cost. They have greater efficiency compared to heat engines; FCVs could be a long-term solution [3].

II. FUEL CELLS

The developments leading to an operational FC can be traced back to the early 1800's with Sir William Grove recognized as the discoverer in1839. A FC is an energy conversion device that converts the chemical energy of a fuel directly into electricity. Energy is released whenever a fuel (hydrogen) reacts chemically with the oxygen of air. The reaction occurs electrochemically and the energy is released as a combination of electrical energy (low-voltage DC) and heat [4].

FC consists of an electrolyte sandwiched between two electrodes. The electrolyte has a special property that allows positive ions (protons) to pass through while blocking electrons. Hydrogen gas passes over one electrode, called an anode, and with the help of a catalyst, separates into electrons and hydrogen protons [5] (Fig.1).

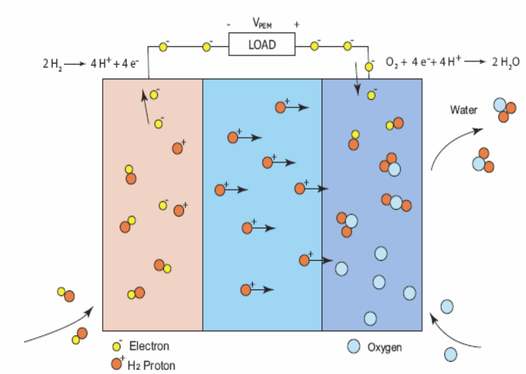

Fig. 1 Fuel cell reaction [5]

$$2H_2 \Rightarrow 4H^+ + 4e^- \quad (1)$$

The protons flow to the other electrode, called a cathode, through the electrolyte while the electrons flow through an external circuit, thus creating electricity. The hydrogen protons and electrons combine with oxygen through the cathode, and produce water.

$$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O \quad (2)$$

The overall reaction of the fuel cell is therefore

$$2H_2 + O_2 \Rightarrow 2H_2O \quad (3)$$

Hydrogen oxidation and oxygen reduction are separated by the membrane (20-200 μm) which carries protons from the anode to the cathode and is impermeable to electrons (Fig.2). This protons flow drags water molecules as gradient of humidity, leads to water diffusion according to the local humidity of the membrane. Water molecules can then go in both directions inside the membrane, according to the side where the gases are humidified and the current density, which is directly related to the protons flow through the membrane and the water produced on the cathode side. Electrons which appear on the anode side cannot cross the membrane, so, they pass through the external circuit before reaching the cathode [6].

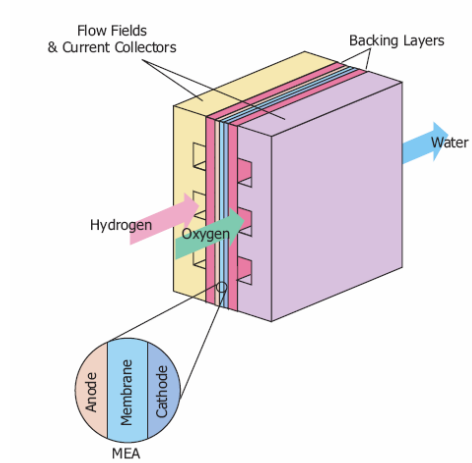

Fig. 2 Fuel cell structure [5]

As the gases are supplied in excess to ensure a good cell operating, the non-consumed gases leave the FC carrying with them the produced water [6].

Generally, a water circuit is used to impose the FC operating temperature (around 60- 80 °*C*). At start up, the FC is warmed and later cooled, as at the rated current nearly, the same amount of energy is produced under heat form than under electrical form [6].

Types of FCs differ principally according the type of electrolyte they utilize [6]. The type of electrolyte, which is a substance that conducts ions, determines the operating temperature, which varies widely between types. Proton Exchange Membrane Fuel Cells (PEMFCs) are presently the most promising type of FC for automotive use and have been used in the majority of prototypes built to date [6].

III. BATTERIES OF FCV

Batteries have widely been adopted in ground vehicles due to their characteristics in terms of high energy density, compact size, and reliability [7]. The internal resistance is the major factor for the limited discharging and charging current capability. The internal equivalent series resistance has different values under charging and discharging operating conditions. The charging and discharging efficiency are nonlinear functions of current and state of charge (SOC). The battery can be modeled as an equivalent circuit such as a voltage source and an internal resistor [6].

A. Lead-Acid Batteries

The spongy lead works as the negative active material of the battery, lead oxide is the positive active material, and diluted sulfuric acid is the electrolyte. For discharging, both positive and negative materials are transformed into lead sulfate [8]. The lead–acid battery presents several advantages for HEV applications. They are available in production volumes today, yielding a comparatively low-cost power source. In addition, lead–acid battery technology is a mature technique due to its wide use over the past 50 years [9]. However, the lead–acid battery is not suitable for discharges over 20% of its rated capacity. When operated at a deep rate of SOC, the battery would have a limited life cycle. The battery energy and power density are low due to the weight of lead collectors. Research efforts have found that energy density can be improved by using lighter noncorrosive collectors.

B. Nickel–Metal Hydride (NiMH) Batteries

The NiMH battery uses an alkaline solution as the electrolyte. The NiMH battery is composed of nickel hydroxide on the positive electrode, and the negative electrode consists of an engineered alloy of vanadium, titanium, nickel, and other metals. The energy density of the NiMH battery is twice that of the lead–acid battery. The components of NiMH are harmless to the environment; moreover, the batteries can be recycled. The NiMH battery is safe to operate at high voltage and has distinct advantages, such as storing volumetric energy and power, long cycle life, wide operation temperature ranges, and a resistance to cover charge and discharge. On the other hand, if repeatedly discharged at high load currents, the life of NiMH is reduced to about 200–300 cycles. The best operating performance is achieved when discharged 20% to 50% of the rated capacity. The memory effect in NiMH battery systems reduces the usable power for the HEV, which reduces the usable SOC of the battery to a value smaller than 100% [10].

C. Lithium-Ion Batteries

The lithium-ion battery has been proven to have excellent performance in portable electronics and medical devices. The lithium-ion battery has high energy density, has good high temperature performance, and is recyclable. The positive electrode is made of an oxidized cobalt material, and the negative electrode is made of a carbon material. The lithium salt in an organic solvent is used as the electrolyte. The promising aspects of the Li-ion batteries include low memory effect, high specific power of 300 W/kg, high specific energy of 100 Wh/kg, and long battery life of 1000 cycles [10]. These excellent characteristics give the lithium-ion battery a high possibility of replacing NiMH as next-generation batteries for vehicles. Since the price of nickel is increasing, the potential cost reduction of NiMH batteries is not promising. Li-ion batteries have twice energy density of NiMH batteries, which are low expensive. Table I demonstrates the characteristics of commercially available lead-acid, NiMH, and Li-ion batteries for vehicles [11].

D. Nickel–Zinc (Ni–Zn) Batteries

Nickel–Zinc batteries have high energy and power density, low-cost materials, and deep cycle capability and are environmentally friendly. The operation temperature of Ni–Zn batteries ranges from −10 ◦C to 50 ◦C, which means that they can be used under severe working circumstances. However, they suffer from poor life cycles due to the fast growth of dendrites, which prevents the development of Ni–Zn batteries in vehicular applications [10].

TABLE I
CHARACTERISTICS OF COMMERCIAL BATTERIES FOR HEV APPLICATIONS [10]

	Capacity (AH)	Volt-age (V)	Resistance (mΩ)	W/kg 95% eff	Usable SOC
NiMH	12	12	10	195	30%
Li-ion	4.0	4.0	3.4	745	18%
Lead-acid	25	12	7.8	77	28%

E. Nickel–Cadmium (Ni–Cd) Batteries

Nickel–cadmium batteries have a long lifetime and can be fully discharged without damage. The specific energy of Ni–Cd batteries is around 55 Wh/kg. These batteries can be recycled, but cadmium is a kind of heavy metal that could cause environmental pollution if not properly disposed of. Another drawback of Ni-Cd batteries is the cost that usually is too high to install these batteries in vehicles.

Table.1 shows a comparison between different batteries Characteristics.

As shown in Table.1, the Li-Ion battery has the best Characteristics compromise. Currently, all available HEVs, such as the Toyota Prius (2012), use Li-Ion as the energy source. Ni–Zn and Li-ion batteries show considerable potential but still need much work to make them suitable for HEV use [10].

IV. MODELLING OF HYBRID DC SOURCES

A. Structure of the hybrid source

As shown in Fig. 3, the studied system comprises a DC link supplied by a FC and a no reversible DC-DC Boost converter which maintains the DC voltage V_{DC} to its reference value $\overline{V_{DC}}$ and a battery storage device which is connected to the DC link through a current reversible DC-DC converter. The function of FC is to supply the mean power to the load, whereas the storage device is used as a power source: it supplies peak loads required during acceleration and braking [6].

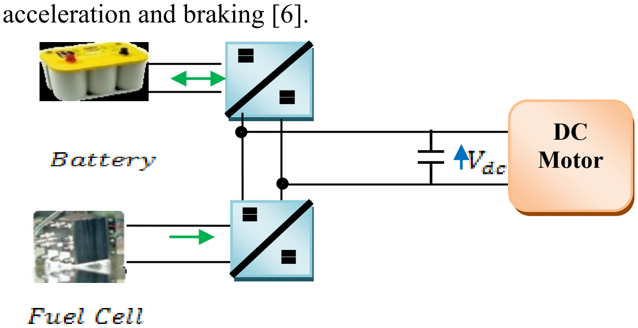

Fig. 3 Hybrid sources structure

B. Dynamic modeling

The hybrid structure is given by Fig.4. It is composed of a FC as a main source associated to a DC-DC Boost converter, a battery source connected to a current bidirectional DC-DC converter, a DC Bus and a RL load.

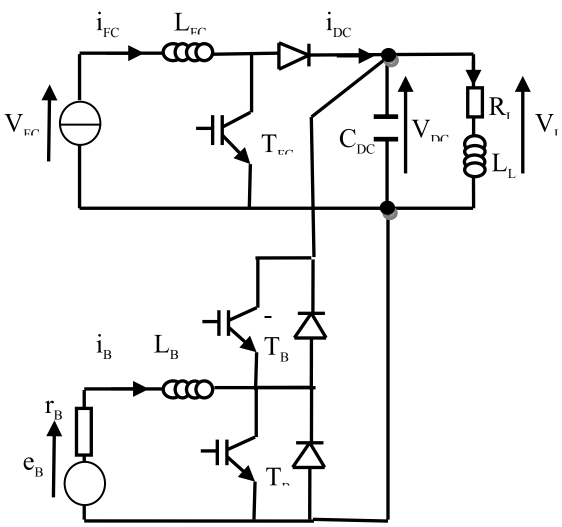

Fig. 4 Hybrid sources electrical model

Where V_{FC} , i_{FC} ,L_{FC} and T_{FC} are successively the FC voltage, current, inductance and transistor, and e_B , i_B , r_B , L_B and T_B are successively the battery voltage, current, resistance, inductance and transistor, and V_{DC} , i_{DC} and C_{DC} are the DC bus voltage, DC bus current and DC bus capacitor and R_L, L_L are the load resistance and inductance.

B.1 PEMFC model (static model)

The characteristic of the voltage versus current of the FC is presented in Fig. 5. The obtained curve is composed of three main regions corresponding to the electrochemical activation phenomena (region 1), a linear part (region 2) where the voltage drop is due to electronic and ionic internal resistances, and the last region where the diffusion kinetics of gases through the electrodes becomes the limiting factor (region 3). This last zone is characterized by a brutal voltage fall.

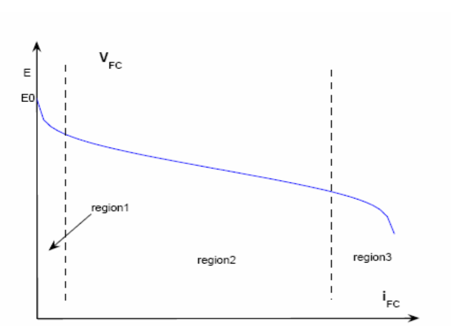

Fig. 5 Static FC characteristic [6]

$$V_{FC} = E - A*\log\left(\frac{i_{FC}+i_n}{i_0}\right) - R_m(i_{FC}+i_n) + B\log\left(1-\frac{i_{FC}+i_n}{i_{Lim}}\right) \quad (4)$$

Hence $V_{FC} = f(i_{FC})$, where E is the reversible no loss voltage of the FC, E_0 is the measured open circuit voltage, i_{FC} is the delivered current, i_o is the exchange current, A is the slope of the Tafel line, i_{Lim} is the limiting current, B is the constant in the mass transfer, i_n is the internal current and R_m is the membrane and contact resistances [6].

B.2 PEMFC and FC Boost converter model

$$\frac{di_{FC}}{dt} = \frac{1}{L_{FC}}\left[V_{FC} - (1-\mu_{FC})V_{DC}\right] \quad (5)$$

Where if $\mu_{FC} = 1 \Leftrightarrow T_{FC}$ is closed

B.3 DC bus model

$$\frac{dV_{DC}}{dt} = \frac{1}{C_{DC}}\left[(1-\mu_{FC})i_{FC} - i_L - (1-\mu_B)i_B\right] \quad (6)$$

Where if $\mu_B = 1 \Leftrightarrow T_B$ is closed and $\overline{T_B} = 0$

B.4 Battery + Battery DC-DC converter model

$$V_B = e_B - r_B i_B$$
$$\frac{di_B}{dt} = \frac{1}{L_B}\left[V_B - (1-\mu_B)V_{DC}\right] \quad (7)$$

B.5 R,L load model

$$\frac{di_L}{dt} = \frac{1}{L_L}\left[V_L - R_L i_L\right]$$
$$V_L = V_{DC} \quad (8)$$

The overall model of the hybrid system can be written in a state space model by choosing the following state space vector:

$$x = [x_1, x_2, x_3, x_4]^T = [i_{FC}, V_{DC}, i_B, i_L]^T \quad (9)$$

The control vector is

$$\mu = [\mu_1, \mu_2]^T = [(1-u_{FC}), (1-u_B)]^T \quad (10)$$

Or

$$u = [u_{FC}, u_B]^T \quad (11)$$

The 4th order overall state space model is then:

$$\dot{x}_1 = \frac{1}{L_{FC}}\left[-\mu_1 x_2 + V_{FC}\right]$$
$$\dot{x}_2 = \frac{1}{C_{DC}}\left[\mu_1 x_1 + \mu_2 x_3 - x_4\right]$$
$$\dot{x}_3 = \frac{1}{L_B}\left[-\mu_2 x_2 + e_B - r_B x_3\right] \quad (12)$$
$$\dot{x}_4 = \frac{1}{L_L}\left[-R_L x_4 + x_2\right]$$
$$y = x_2$$

With $V_{FC} = V_{FC}(x_1)$ given by (5). V_{FC} is considered as a measured disturbance, and from physical consideration, it comes that $V_{FC} \in [0, V_d]$ where V_d is the desired DC bus voltage.

V. SIMULATION RESULTS OF ENERGY MANAGEMENT

An implicit purpose of the proposed structure (Fig.4) is to use the battery as a power source supplying the transient peak power. Our simulation shows an energy management based on frequencies separation [12], [13], [14], where a PI regulator is used to regulate the DC bus voltage (V_{DC}) (Fig.8) and to give the DC bus current reference (i_{DCref}), this reference is filtered with low-pass filter to obtain the FC reference current (i_{FCref}) (Fig.9), the cut-off frequency of the filter is chosen so that the FC current is very smooth ($\tau = 0.8s$). A PI controller of the FC current gives the control voltage of the boost converter; the control pulses sent to the IGBT of the boost chopper are obtained by applying the PWM on this control voltage. The battery reference current (i_B) is calculated by the difference between the DC bus reference current and the FC reference current (Fig.9).

At first, a step of load current was applied at 0.5 s (Fig.7) in order to evaluate the sources responses to peaks of current.

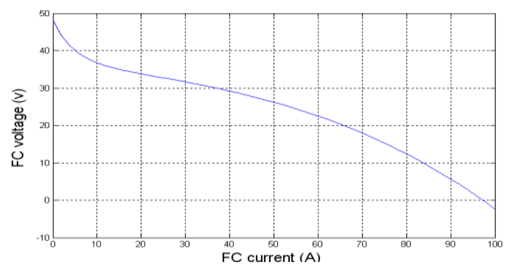

Fig. 6 FC characteristic

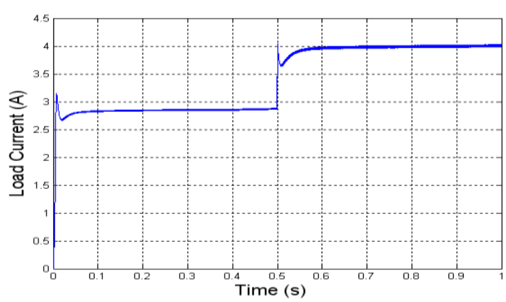

Fig. 7 Load current

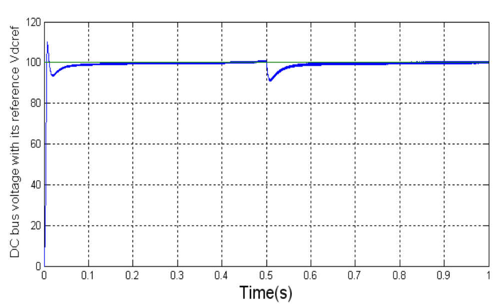

Fig. 8 DC Bus voltage with reference value 100V

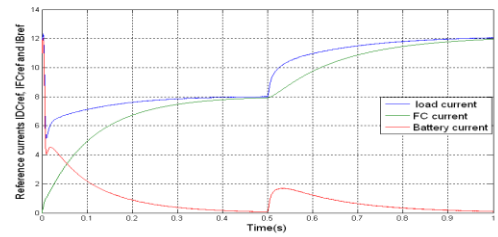

Fig. 9 References values of load current, FC current and battery current

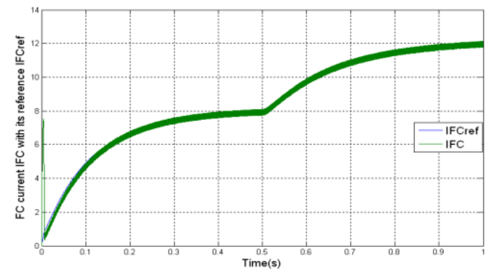

Fig. 10 FC Current with its reference

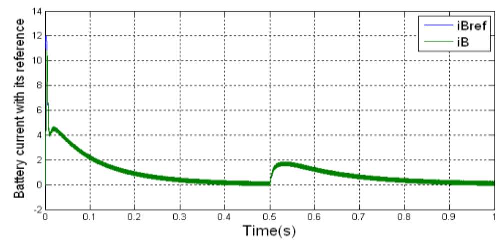

Fig. 11 Battery current with its reference

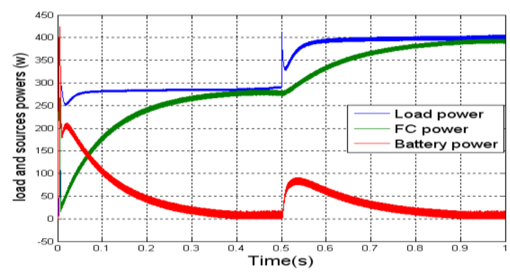

Fig. 12 Load and sources powers

Figure 8 shows the response of the DC bus voltage V_{DC} to load current change (at t=0.5s), The DC Bus voltage tracks well the reference V_{DCref}=100V.

Figure 10 shows the FC current i_{FC}. It tracks well the reference and a smooth behavior of the FC current is observed regarding the change in the load current, this is because the battery supplies the transient current. Figure 11 shows the battery current i_B response in presence of load current change. The battery supplies power to the load in the start-up and transients. It tracks its reference i_{Bref} and the current ripples due to PWM. Figure 12 shows the load power with sources powers.

In order to evaluate our energy management at real time driving conditions, typical urban driving cycle ECE15 (Fig.13) was applied with a vehicle dynamic model.

The DC machine of the vehicle is fed by the previous hybrid sources, where the DC bus is regulated to the rated machine voltage (400V) (Fig.14).

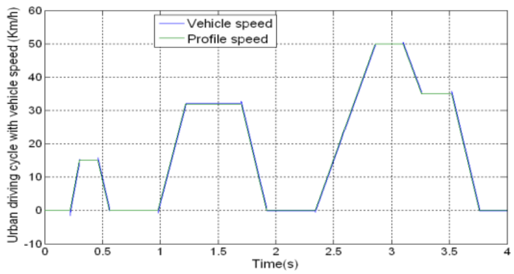

Fig.13 Urban European driving cycle with the vehicle speed

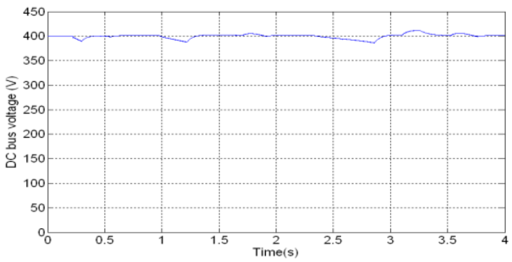

Fig. 14 DC bus voltage

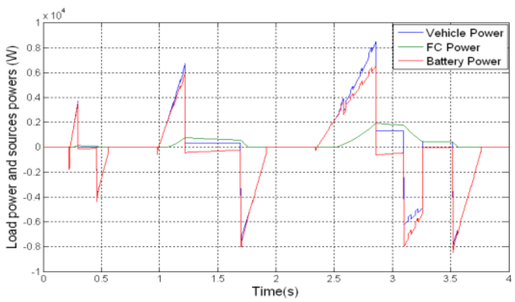

Fig. 15 Vehicle and sources powers

Figure 15 shows the vehicle power with FC power and battery power, it is observed that FC supplies the main energy while battery supplies peak power, which is the desired purpose.

VI. CONCLUSION

A dynamic modeling of a hybrid sources system composed of a FC and a battery sources is presented (with a static model of the FC).

A simple control method of power sources based on a physical constraint of FC which is the low current response time is presented in this paper in order to increase FC life time. For that, the DC bus reference current is filtered by a low-pass filter to obtain the FC reference current.

Encouraging simulation results have been obtained and discussed exhibiting the robustness of the proposed control towards load current sudden changes, and real time driving conditions using the urban driving European cycle.

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