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Simulation and optimization of hydrogen consumption in a fuel cell/battery hybrid vehicle

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ABSTRACT

This paper presents a physics-based mathematical model for a fuel cell hybrid vehicle system. The performance design of fuel cell hybrid electric vehicles (FCHEVs) is an area of interest in transportation applications. FCHEV is a combination of a proton exchange membrane fuel cell (PEMFC), with a battery and associated DC/DC and DC/AC converters. Suitable batteries are used in FCHEV acts as a backup system with efficient energy management. The battery is designed for fast power transfer during transient response and constant performance without hydrogen. The power management schemes discussed are consistent with the most common modern power management techniques used in fuel cell vehicle applications, including: the state engine control strategies, rule-based fuzzy logic strategies, classical proportional integral control strategies, frequency fuzzy logic decoupling/control minimization strategies. Therefore, we tested and evaluated the reliability of the model using the MATLAB/Simulink environment, with mixed results.

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NOMENCLATURE

T_t	: The total traction force	$V_{activatic}$	: Voltage loss due to the reaction rate at electrode surface
T_{xf}	: The traction force fronts the wheels	V^0	: Open cell voltage of the fuel cell
T_{xr}	: Traction force of the rear wheels	F	: Faraday constant
T_m	: Motor torque	T_0	: The standard temperature (25 °C)
R_a	: Force has the air resistance on the vehicle	ΔS^0	: Entropy change (considered constant = -164 J/mol. K)
f_r	: The rolling resistance coefficient	R	: Universal gas constant = 8.31 J/mol. K
R_t	: Total strength of the resistors	p_{H_2}, p_{O_2}	: The pressure of hydrogen and oxygen
R_{tr}	: Total resistance force of the Wheels on the ground	p	: The air pressure on the electrode surface
P_m	: The engine required to drive the vehicle at a speed	p_0	: Atmospheric pressure
P_g	: Strength of resistance to the slope	$P_{air-com}$	: Power needed to compress air

P_t	: Total power
n_t	: Transmission system performance
M_v	: Global mass of the vehicle
i_g	: Gear ratio of transmission
i_0	: The gear ratio of the final drive
r_d	: The effective radius of the tire
ρ_a	: Mass volume of air
η_t	: The efficiency of driveline from the power plant to the drive wheels
A_f	: The front surface of the vehicle
C_D	: Aerodynamic drag coefficient
V_0	: Basic speed of the electric motor
V_w	: Wind speed and direction of movement
V	: Vehicle speed
N	: Motor speed in revolutions per minute
ΔG	: Gibbs free energy
G_n	: Free energies in species "n" of products "a"
G_m	: Free energies in species "m" of product reactant
Z	: Number of moles of electrons exchanged for the formation of one mole of water
β	: Charge transfer coefficient
γ	: The ratio of specific heats of air (= 1.4)
V_{nth}	: The theoretical nominal voltage
$V_{concentration}$	: Voltage loss due to reduced gas concentration or delivery of large quantities of oxygen and hydrogen
V_s	: Output voltage of fuel cell
V_{ohm}	: Ohmic voltage drop due to resistance of proton flow in electrolyte
$P_{air-cir}$	: Power consumption of circulating air pump
$\dot{m}_{air}$	: Mass flow
m	: Constants in the mass transfer voltage
N_c	: Cell number
I_{fc}	: Output current density [A/cm2]
I_n	: Internal current density
I_0	: Exchange current density
I_s	: Output current fuel cell
I_{max}	: Maximum current fuel cell
r	: Internal resistance fuel cell
η_{pump}	: Efficiency of the air pump plus motor drive
η_v	: Efficiency voltage
η_f	: Faradic efficiency
η_{sys}	: Efficiency system
η_{total}	: Total efficiency of the fuel cell
Uf_{H_2}	: Use of hydrogen fuel cell
ΔH	: The reaction enthalpy at the absolute temperature T
FCHEV	: Fuel cell hybrid electric vehicles
ESS	: Electrical storage systems
PEMFC	: Proton exchange membrane fuel cell
AFC	: Alkaline fuel cell
PAFC	: Phosphoric acid fuel cell
SOFC	: Solid oxide fuel cell
MCFC	: Molten carbonate fuel cell

1. INTRODUCTION

In the ambition to deal with environmental pollution and the limited supply of fossil fuels, automotive industries have embraced the objectives outlined by international and regional agreements for environmental protection and pollution control and have shown increasing interest in fuel cell hybrid electric vehicles (FCHEVs). This orientation is evidenced by the recent agreement of the European Parliament adopted on Wednesday, June 8, 2022, which aims for a ban on combustion-powered cars and vans from 2035 within the European Union. Rapid advances in electronics technologies and the great potentials offered by fuel cell have enabled a developed future for FCHEVs [1], [2].

The potential of FCHEVs remains enormous in terms of cost reduction and improved durability. The implementation of a second energy storage participates to decrease significantly carbon dioxide emissions in the vehicle [3], [4]. For that reason, the hybridization process plays a major function in the rational consumption of hydrogen and reducing the greenhouse gases [5].

Typically, FCHEV is composed of two different energy sources in perspective to use their advantages to enhance the performance of the FCHEV, the storage system has proven its reliability and technical feasibility. Compared to conventional combustion engines, they provide efficient electricity, lower noise and virtually zero emissions. That's why it seems necessary to make a combination between fuel cells and other energy storage component such as lithium-ion batteries or super-capacitors. This blending can optimize the exchange of energy and extending the autonomy of the fuel cell systems by taking advantages from the battery charge. The traditional way to evaluate hybrid system performance is to create a simulated model system of the vehicle, which allows the test of many different driving cycles, the tire dynamics and breaking effects on vehicle performance haven't generally been considered.

2. METHOD

As represented in the Figure 1, the system we will use in this paper contains 4 global blocks or 4 main functions. The driver block represents the standard driving cycles in order to simplify the approach. Concerning the control system, it aims to establish an energy management system that can be adapted to the driving conditions and which will then be transmitted to the vehicle system's block for application. The speed and the energy profiles issued from the vehicle system are viewed at the result's block.

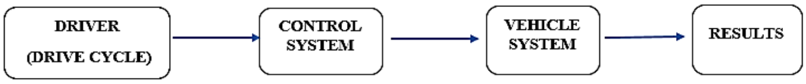

Figure 1. Representation of the fuel cell hybrid vehicle

2.1. Control system

The strategic management of Energy tries to explain how energy is distributed between batteries and fuel cells. They can optimize the fuel cell capacities and consumption depending of energy demands. When developing and evaluating energy management strategies, it is necessary to understand the ultimate limit to improving that fuel cell stack aging in relation with driving manners. Jung *et al*. [6] are proposed an energy management strategy, based on maintaining efficient fuel cell stack and cell behavior by using a hybrid controller. Cell and demand power management between fuel cells helps to guarantee a transitory behavior of the battery pack with more efficiency and a slow aging [7]. They developed a power distribution that could account for the loss of recovered energy loads.

The optimization process declined in many developed algorithms is aimed principally on reducing the power consumption of the propulsion system. In spite of that, in the future, regenerative braking energy of the electric motor must be included simultaneously with the FCS output power for recharging the battery [8]. Therefore, when considering regenerative braking energy, the power consumption of the car must take into consideration the battery consumption level. Beyond this particular problem, a control strategy developed specifically for FCHV is presented in [9]–[14].

2.2. Vehicle system

The basic principles of vehicle operation represent vehicle behavior mathematically as an interactive mechanical system. A vehicle in a complex ecosystem comprising a number of interconnected components. Complex mechanical and mathematical knowledge is required to adequately describe its behavior. As shown in Figure 2, a representation of the vehicle's resistance including tire's ones to its motion.

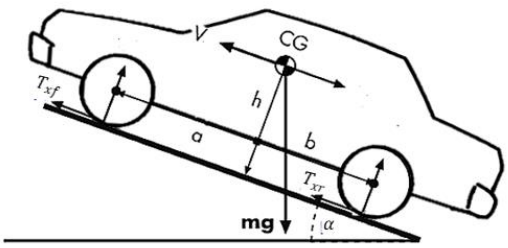

Figure 2. Vehicle body longitudinal dynamics

The formula for the mechanical power of the engine requisite to impel the vehicle at speed V:

$$P_m = \frac{VT_t}{n_t} \quad (1)$$

with T_t : the total traction force $T_t = T_{xf} + T_{xr}$. The dynamic equation of vehicle motion is expressed by Newton's second law:

$$\frac{\mathrm{dV}}{\mathrm{dt}} = \frac{T_t - R_t}{\delta M_v} \quad (2)$$

with δ : the factor of the mass.

The resistances of the vehicle that oppose its motion include the rolling resistance of the tires. The expressions of F_a of air resistance force on the vehicle, with F_{tr}, the global resistance force of the wheels on the ground ($R_{tr} = R_{rav} + R_{rar}$) are the following:

$$R_a = \frac{\rho_a A_f C_D (\mathrm{V}+V_w)^2\, sgn(\mathrm{V}+V_w)}{2} \tag{3}$$

$$R_{tr} = M_v\, g\, f_r\, \cos\alpha \tag{4}$$

when the vehicle moves up (down) a hill, a force of resistance to the slope caused by its weight:

$$P_g = M_v\, g\, \sin\alpha \tag{5}$$

the total force of the resistances to movement is:

$$R_t = R_a + R_{tr} + P_g \tag{6}$$

consequently, we neglect V_w and replace in the dynamic equation of motion of the vehicle [15].

$$\frac{\mathrm{dV}}{\mathrm{dt}} = \frac{T_t - \frac{1}{2}\rho_a A_f C_D \mathrm{V}^2 + M_v\, g\, \sin\alpha + M_v\, g\, f_r\, \cos\alpha}{\delta M_v} \tag{7}$$

So, if α is small (c.-à-d. $\cos\alpha$, $\sin\alpha = \tan\alpha$):

$$T_t = \delta M_v \frac{\mathrm{dV}}{\mathrm{dt}} + \frac{1}{2}\rho_a A_f C_D \mathrm{V}^2 + M_v\, g\, (f_r + k) \tag{8}$$

with $k = \tan\alpha$. This gives the total power that requires the vehicle to accelerate from zero to that speed V in second:

$$P_t = \frac{1}{n_t}\left(\frac{2}{3} M_v\, g\, V f_r + \frac{\delta M_v}{2t}\left(\mathrm{V}^2 + {V_0}^2\right) + \frac{1}{5}\rho_a A_f C_D \mathrm{V}^3 + M_v\, g\, (f_r + k)\right) \tag{9}$$

2.3. Transmission

As modeled in Figure 3, the transmission and chassis simplified system is presented. Electric cars use a single gear, which makes acceleration and braking easier. Wheel traction (T_t) and vehicle speed (V) can be expressed using the following equations:

$$T_t = \frac{T_m i_g i_0 \eta_t}{r_d} \tag{10}$$

$$V = \frac{\pi\, N\, r_d}{30 i_g i_0} \tag{11}$$

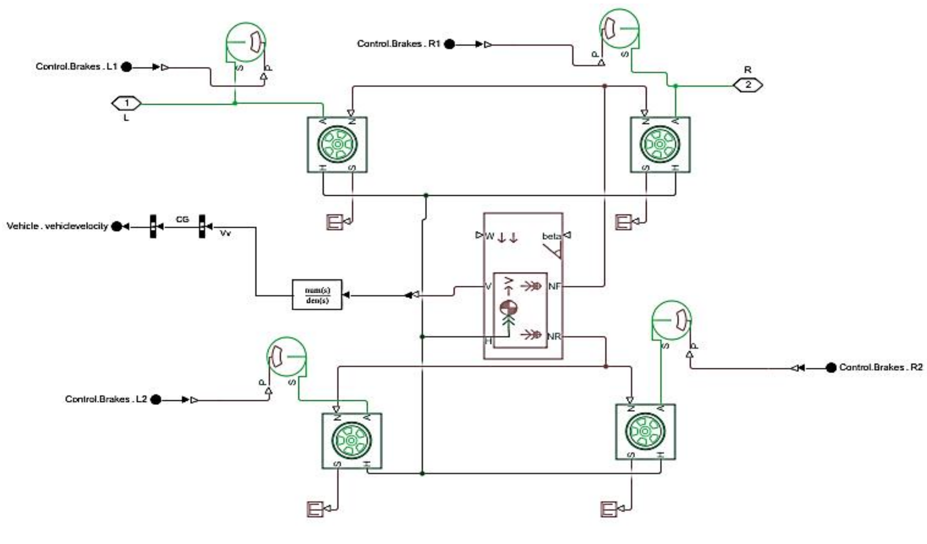

Figure 3. Model of the "Transmission and Chassis" system in Simulink SimPowerSystems

2.4. Motor

The output voltage of the suggested transformer is sent through an inverter to an electric motor for vehicle propulsion. Electric vehicles play an important role in FCHEV. The right electric vehicle can significantly reduce the size of fuel cells and its costs consequently. In the beginning, most automakers resort DC motors for electric vehicles. The brushes and rotating devices make DC motors more expensive to maintain and inefficient operating [16]. Currently, the technology using motors BLDC with a permanent magnet is the most used in FCHEV applications, like the model presented in Figure 4, due to their ease of control, high reliability and robustness.

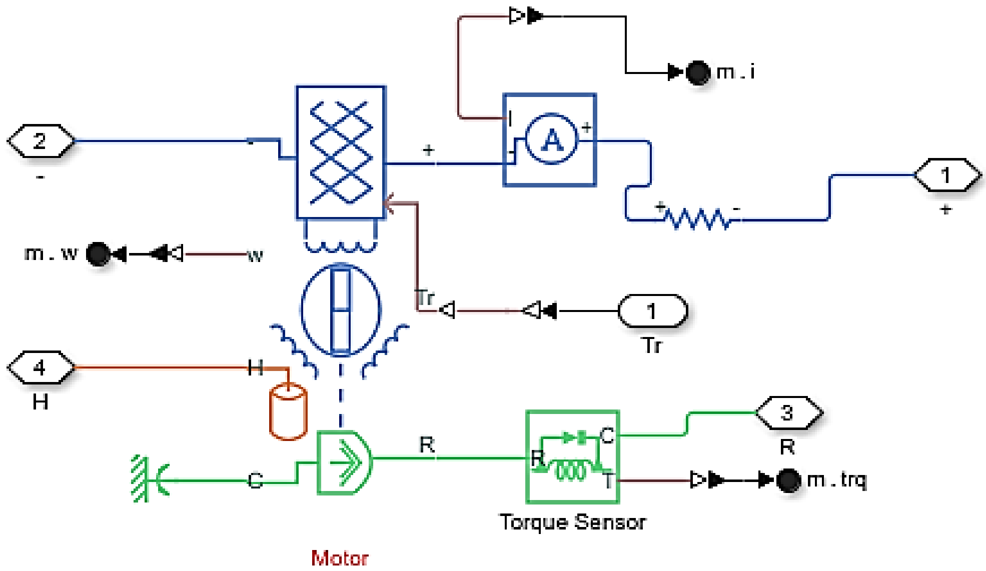

Figure 4. Model of the electric motor in Simulink SimPowerSystems

2.5. Fuel cell

Fuel cells are supposed to be low-emission generators for stationary and mobile applications. There are different types of fuel cells using different electrolytes, the operating temperature, and most importantly, the field of application. They can be divided into four categories, details in Table 1: solid oxide fuel cells (SOFC), (MCFC) molten carbonate fuel cells, phosphoric acid fuel cells (PAFC) and (PEMFC) polymer electrolyte membrane fuel cells. All these systems, PEMFC dominates the automotive industry with its minimized operating temperature and fast start-up time [17].

PEMFC use a perfluoro sulfonic acid membrane (usually Nafion) as an electrolyte; their performance is highly dependent on their hydration state [18], [19]. They are the famous fuel cells integrated in automotive applications. This is greatly because they work at the low temperature so by a quick start the full load can be achieved easily.

$$\Delta G = \sum_{product} G_n - \sum_{reactants} G_m \tag{12}$$

Where G_n and G_m are the free energies of product species n and reactant species m.

As shown in the Figure 5, ion exchange membrane fuel cells use a reaction between hydrogen (or a hydrogen-rich fuel) and oxygen (or air) to create an electricity energy based on two redox reduction reactions:

$$anode \quad H_2 \rightarrow 2H^+ + 2e^-$$

$$cathode \quad 2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O$$

Table 1. Table representing several fuel cells

Type of FC	Electrolyte	Operating temperature	Chemical reaction
Polymer electrolyte membrane fuel cells (PEMFC)	Solid organic poly perfluoro sulfonic acid	60-100	$Anode: H_2 \rightarrow 2H^+ + 2e^-$ $Cathode: \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ $Cell: H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
Phosphoric acid fuel cells (PAFC)	Liquid phosphoric acid soaked in a matrix	175-200	$Anode: H_2 \rightarrow 2H^+ + 2e^-$ $Cathode: \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ $Cell: H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
Molten carbonate fuel cells (MCFC)	Liquid solution of Li, Na, K carbonates soaked in a matrix	600-1000	$Anode: H_2 + CO_2 \rightarrow H_2O + CO_2 + 2e^-$ $Cathode: \frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_2$ $Cell: H_2 + \frac{1}{2}O_2 + CO_2 \rightarrow H_2O + CO_2$
Solid oxide fuel cells (SOFC)	Solid zirconium oxide with small amount of yttria added	600-1000	$Anode: H_2 + O_2^- \rightarrow H_2O + 2e^-$ $Cathode: \frac{1}{2}O_2 + 2e^- \rightarrow O_2^-$ $Cell: H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

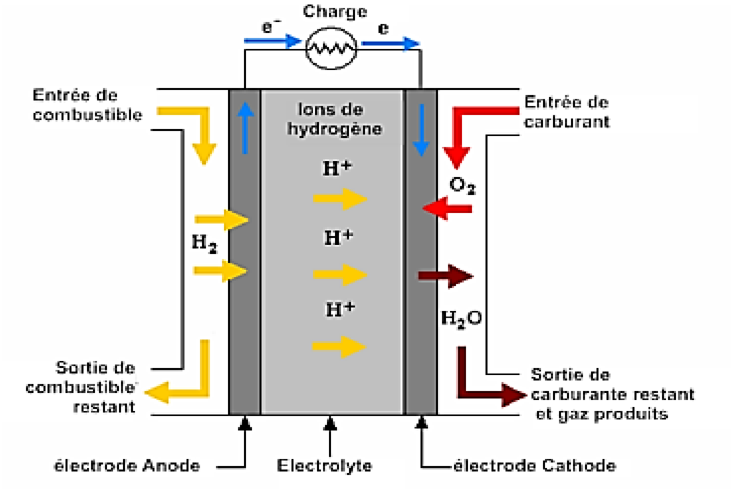

Figure 5. The reaction in a fuel cell with an exchange membrane

The overall chemical reaction is described by the equation [20]:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

This reaction is spontaneous (it does not require energy to do so). The energy delivered in reaction to form water, called the Gibbs free energy (ΔG), conditioning by temperature, the operating pressure of the cell, and the state of the water at the outlet (which may be in liquid or gas form) [21]. Therefore, the theoretical nominal voltage was established from the Nernst equation:

$$V_{nth} = -\frac{\Delta G}{z\,F} = V^0 + (T + T_0)\left(\frac{\Delta S^0}{zF}\right) - \frac{RT}{zF}\ln\frac{1}{p_{H_2}\sqrt{p_{O_2}}} \quad (13)$$

The output voltage of the PEMFC Vs is defined as an outcome combination of the cell current, the pressures of the reactants, the ambient temperature of the fuel cell and the humidity of the membrane, represented by these equations:

$$V_s = V_{nth} - V_{activation} - V_{ohm} - V_{concentration} \quad (14)$$

with:

$$V_{activation} = N_c \frac{RT}{2\beta F}\ln\frac{I_{fc}+I_n}{I_0} \quad (15)$$

$$V_{ohm} = N_c\, I_{fc} r \tag{16}$$

$$V_{concentration} = N_c\, m \exp nI_{fc} \tag{17}$$

In fact, fuel cells require auxiliary materials to function. Auxiliary equipment is mainly composed of air circulation pump, coolant circulation, pump, fan, oil pump and the electrical control component. In auxiliary units, airflow pumps are the biggest energy consumers' power consumption of the circulating air pump including its drive motor can reach 10% of the total fuel cell output.

Auxiliary equipment is considered less energy consumers comparing to the circulating air pumps [22]. In fuel cells, the gas pressure p at electrode surface is often above atmospheric pressure p_0 to reduce the voltage drop. From thermodynamics, the power required to upgrade the air pressure from compress p_0 to another pressure p value with $\dot{m}_{air}$ mass flow can be presented as (18):

$$P_{air-comp} = \frac{\gamma}{\gamma-1}\dot{m}_{air} R.T\left(\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{18}$$

with T: the compressor inlet temperature in Kelvin.

In the calculation of the power consumption of the circulating air pump, the total power consumed is presented as (taken into consideration the energy losses in the air pump and the motor drive):

$$P_{air-cir} = \frac{P_{air-comp}}{\eta_{pump}} \tag{19}$$

– Fuel cell efficiency

The voltage efficiency, is the ratio between the real voltage of the fuel cell and V_{nth} battery (given by the Nernst equation):

$$\eta_v = \frac{V_s}{V_{nth}}) \tag{20}$$

The faradic efficiency η_f, is the ratio between the output current of the CAP and the maximum current:

$$\eta_f = \frac{I_s}{I_{max}} \tag{21}$$

the system efficiency η_{sys}, is the ratio of the net power delivered by the fuel cell generator (the system) to the power generated by the fuel cell:

$$\eta_{sys} = \frac{P_{net}}{P_{gross}} \tag{22}$$

Total system efficiency η_{totale}, given by the (23):

$$\eta_{total} = -\frac{z\,\eta_{sys}\,F\,Uf_{H_2}V_s}{\Delta H} \tag{23}$$

with large currents cause inefficiencies due to large stack voltage drops, while very small currents cause inefficiencies due to the increased percentage of power dissipation in auxiliary power dissipation [23].

A model of the fuel cell system was created in MATLAB/Simulink using the SimPowerSystems as presented in the Figure 6. The PEMFC stack produces a low unregulated DC output voltage. Traditional boost converters are used as the power electronic interface, and boost converters may not be compatible with high power applications due to their low current and thermal management systems [24]. To deal with these difficulties, various high voltage gain DC/DC converters have been adopted [25], [26].

2.6. Battery

Electric vehicles have the advantage of being quiet, extremely low or even zero-emission. Nowadays, battery technology is the principal serious issue in electric vehicle development. Vehicles with internal combustion engines. To enhance a fast and a sure development of electric vehicles, one effective way is to get effective solutions for battery issues, and also to solve the battery problem.

Today, fuel cell hybrid electric vehicles (FCHEVs) are taking more importance in the automotive industry. Generally, in a fuel cell hybrid vehicle, a battery is made for use in parallel to the fuel cell. The battery is responsible for starting, cold cranking, electrical braking surges and energy storage ministry of electricity [27].

The batteries, studies and chosen in this paper are lithium-ion batteries because of their higher energy density and better efficiency than other battery types such as lead-acid, nickel-cadmium, or nickel-metal hydride [28]–[30]. This presents certainly a great potential for automotive or aerospace applications. Lithium-ion batteries are electrochemical energy stores and the source of electrical energy. Lithium-ion battery cells can be presented using the equal circuit according to [31]. This model of battery is characterized by sensible accuracy, simple parameter determination and short service life.

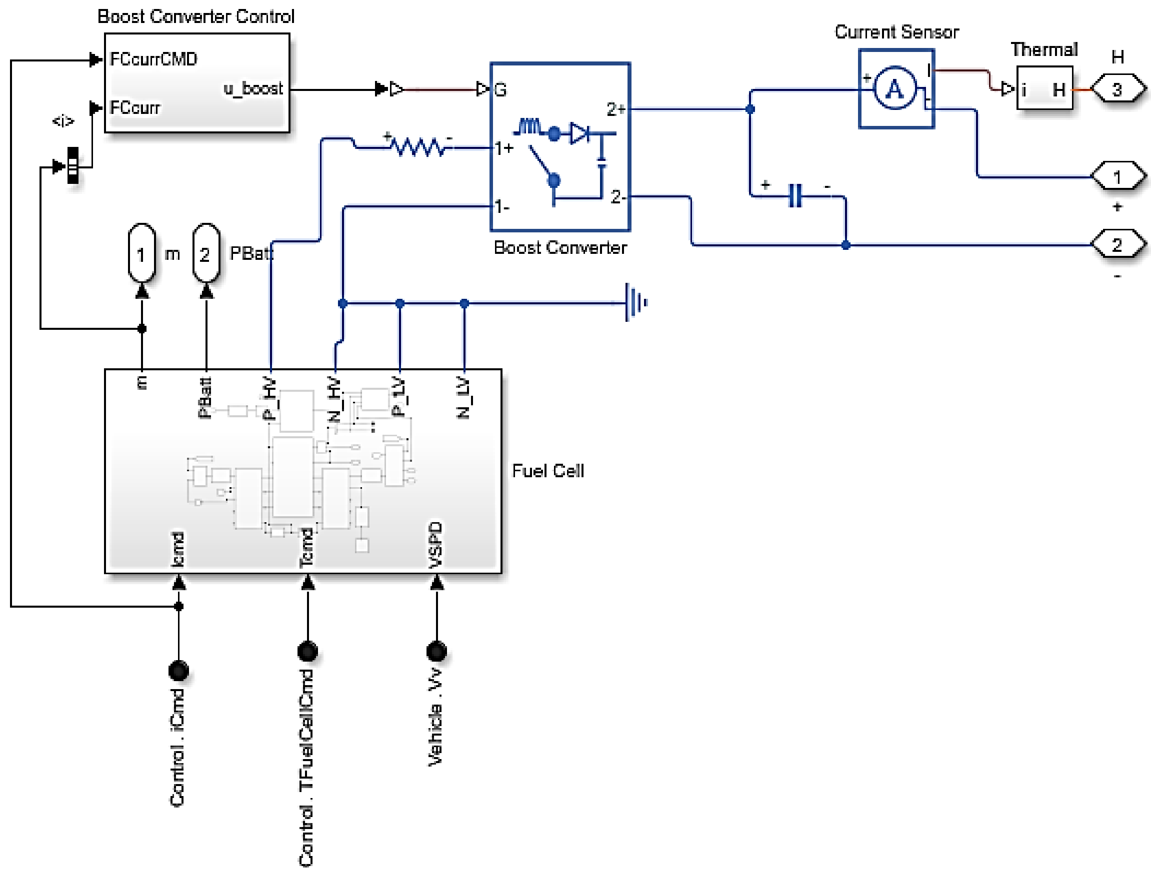

Figure 6. The fuel cell system created in Simulink using the SimPowerSystems

3. RESULTS AND DISCUSSION

To highlight the performance of the suggested model of the hybrid vehicle, Figures 7 and 8 show the results of the simulation in the NEDC and the FTP driver cycle: These figures show the hydrogen consumption every 100 km, the power is communal between the battery and the fuel cell in the step of storing negative power recovery in the battery. Depending on the load of the driving cycle described in the Figures 7 and 8. The energy losses reach a global optimum based on the reference power profile.

The simulation results show that after the peak hydrogen consumption reaches 24 L/100 km in the starting phase of the vehicle, the hydrogen consumption drops significantly and gradually stabilizes at the value of 2.5 L/100 km, as show in Figure 8 which is very meaningful. Driving cycles aims to normalize the simulation and the illustration. Additionally, it appears clear that the impact of tire wear on powertrain performance and energy efficiency cannot be ignored during severe acceleration and braking. Also, vehicle control objectives were identified in maximizing the enormous benefits associated with the functional integration either of fuel cell and battery technologies.

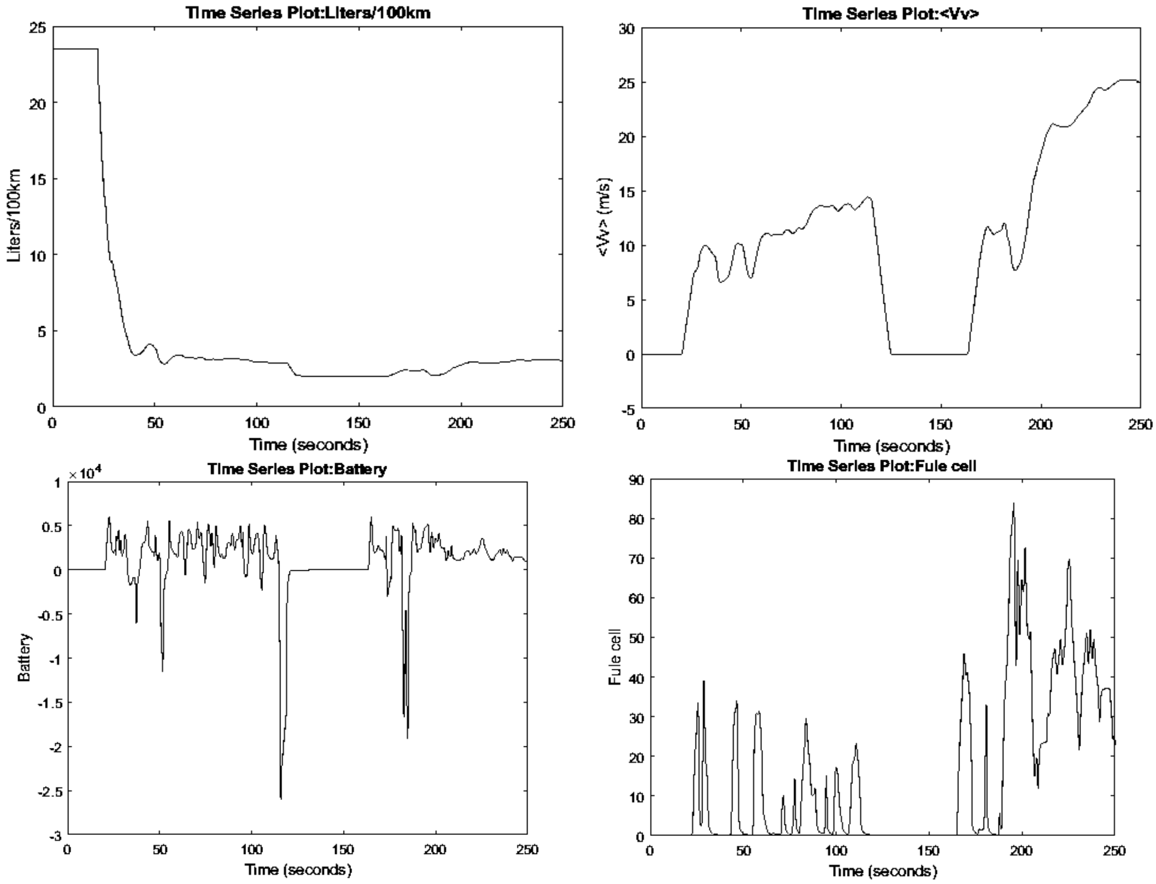

Figure 7. The results of FTP driver cycle

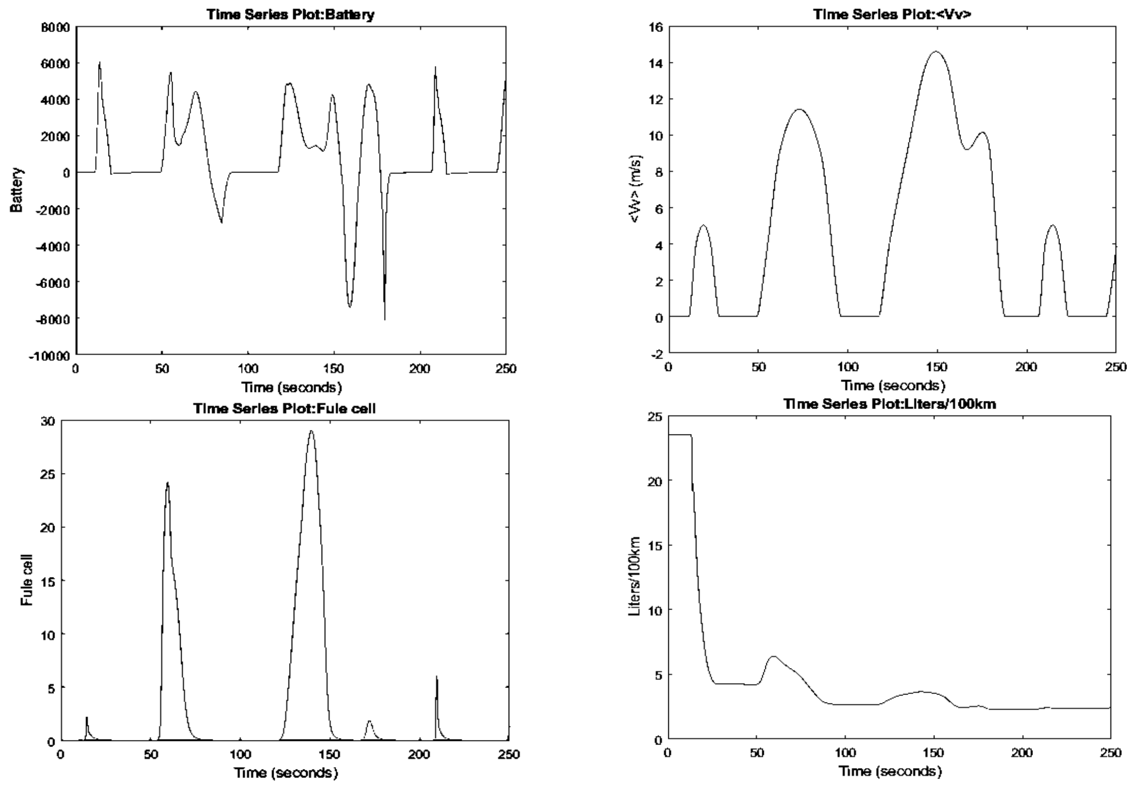

Figure 8. The results of NEDC driver cycle

4. CONCLUSION

Detailed mathematical and physical models of battery-equipped FCHVs have been presented in this paper. This model is suitable for studying the behavior and the dynamic performance of the propulsion system during heavy acceleration and regenerative braking. It contributes to a better understanding of the achievable efficiency of the vehicle in the "real world". Powertrain transient and steady-state losses are quantified in predefined test cycles containing higher accelerations, travel and braking values than conventional legal driving cycles. Simulation results show that the impact of losses on powertrain performance and fuel efficiency cannot be ignored during rapid acceleration and braking.

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