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Design and testing of proton exchange membrane fuel cell (PEMFC) power pack for platform vehicle

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Abstract. During the last few years and in this context of constant innovation, several alternatives for internal combustion engines arose with the aim to find feasible options to fossil fuel consuming devices. As one may recall, the main alternative for internal combustion cars is without a doubt BEVs (battery electric vehicle). Those vehicles rely on electricity in order to function, storing the electricity in a battery pack and using it to feed a motor in order to give motion. However, some issues are still to solve in order to market them as appealing as internal combustion cars. Two of the most important issues to tackle are mileage range and charging time. On the other hand, fuel cell technology which began in the late sixties is beginning to take part in the automotive sector. This paper presents design evaluation and testing of 100 kW PEM fuel cell power pack for battery operated platform vehicle application developed to drive PMSM motor with requisite energy range that can be adapted by the power conditioning elements of the system under implementation to attain desired speed under Matlab/Simulink environment and the overall system dynamic performance was found to be coherent by analyzing basic operating parameters.

1. Introduction

Nowadays there are many technologies that could actually partially or even totally substitute fossil fuels in energy matters, all related in some way to electricity production such as hydro power generation, wind power, photovoltaic, solar thermal energy, etc. [1]. Just as energy industry, automotive industry which is always in a context of constant innovation has been inflicting change trying to find feasible alternatives to internal combustion engines which are the main cause of fossil fuel consumption and pollution in mobility currently [2]. Recently companies like Toyota, Hyundai, Honda or Nikola Motors have been making progress in this technology, and even launching commercial models such as the Toyota Mirai. This type of technology takes advantage of hydrogen being the most abundant element in nature and tackles the problem of autonomy range and recharge time. [3] discussed about comparative analysis of the plugin fuel cell vehicles (PFCV) regarding different topologies, drive cycles and control strategies for PFCV systems. Then the proposed strategy is able to reduce hydrogen consumption for the high-speed drive cycles with the less braking operation. As well as the on-off switching frequency of the PEMFC system to design and development in this presentation presented. An optimization strategy is proposed at first by regulating the power distribution between the battery and the PEMFC system. Then a direct multiple shooting (DMS) algorithms are used to solve this nonlinear programming problem (NLP) over the spatial domain. The PEMFC in portable applications and simulation results was presented in [4]. A detailed analysis of the model-independent tracking techniques to extract maximum power (MPP) and maximum efficiency point (MEP). PEMFC exhibits nonlinear output characteristics which may result in low efficiency and low power operation of the PEMFC. However, the output and efficiency of the PEMFC should be high for a portable application but they are low at MEP and MPP respectively in the paper. The main advantage is a portable application mobile in nature like a small vehicle truck utilizing fuel cell electric power. In [5], Stated that for vehicle applications to be qualified as high efficiency electrical system, it should consist of a fuel cell, a battery and superconductor. A precise power management unit (PMU) was discussed to propose a hybrid energy storage (HES) to improve its performance by combining various promising devices in [6-10]. These devices are used for storage purpose because of the sudden vehicle hydrogen gas will empty the power supply from the battery to run the vehicle. Here, the hybrid vehicle design consideration is predominantly energy storage. In [11-16] carried a study with an emphasis on reducing fossil fuel consumption and environmental protection. A delivery van design was proposed based on the fuel cell and battery size, to reduce emissions in vehicular trucks using world operational data and duty cycles from GPS technique. However, cost is critical to the success and adoption of these zero emissions trucks. In [17-28] studied the influence of the physical and geometrical gas flow parameters on the consumption of reagents in PEMFC and identified the performance of the fuel cell, a wider channel improve, chemical reaction in the catalyst layer, voltage drop, performance increase in saturation temperature, performance of the PEMFC rates, effect of rib/channels width which showed greatest sensitivity, activation and diffusion, highest power densities are made with speeds of flow low due to the smaller activation [29-36].

2. Motivation for using PEMFC

A fuel cell of polymer electrolyte membrane also called proton exchange membrane the fuel cells applications, including transportation and automotive industry applications, are currently the most used type of fuel cell for most of PEM as well as offering low weight and volume when put aside other types of fuel cells [7]. This type of cell is capable to deliver high power density (nowadays 0.7 Wcm^{-2}). In PEMFCs use a polymer as an electrolyte, carbon electrodes and gas diffusion layers and platinum-based catalysts. The main advantage of this type of fuel cell is that they feed from hydrogen and oxygen from the air. The typical PEMFC is presented in figure 1.

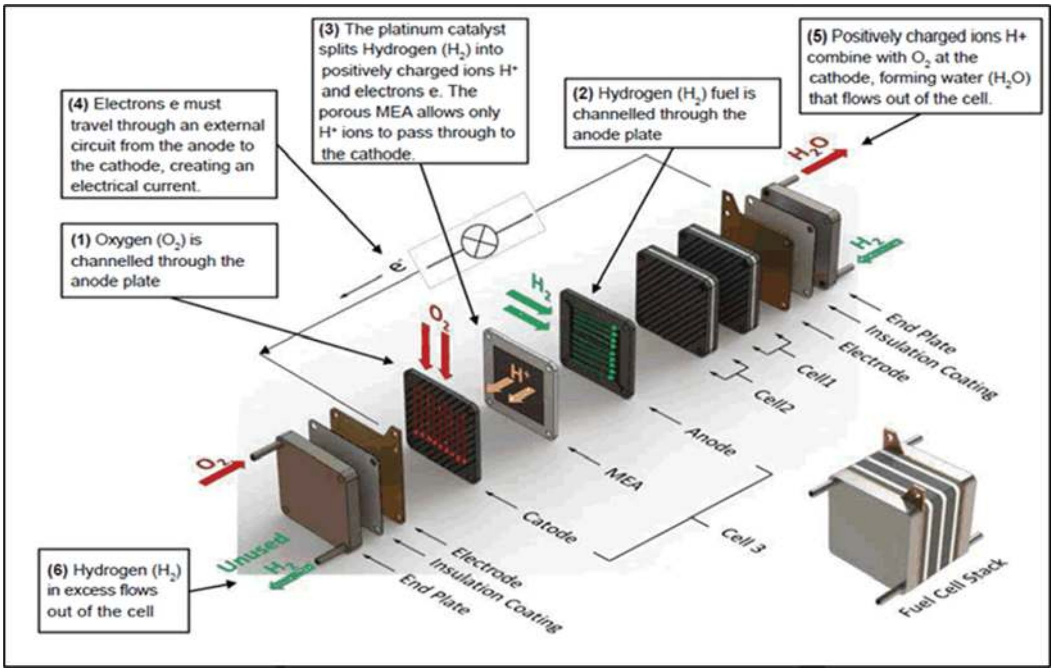

Figure 1. Layout and operation of PEMFC.

Normal operating temperature for this type of fuel cell are around 80°C (considered relatively low temperatures). However, it has been proved that cold starts for fuel cell vehicles are possible even in below 0°C situations [37]. As they are able to start in low temperatures, they have a quick start and that entail less wear of the components of the system and therefore, gives more durability to the whole set. Nevertheless, the use of platinum as catalyst increases the cost of the fuel cell stack drastically [38]. In all, PEMFCs are a very suitable and feasible alternative for mass producing hydrogen powered vehicles due to how technologically advanced and reliable they are, as well as their good power to weight ratio [39-46].

3. Modeling and testing of PEMFC power pack for platform truck

To achieve high current density optimal operating conditions, need to be identified for a fuel cell by system thickness, catalysts, and alloys particle size, catalyst quantity, catalyst layer thickness to analyze in this research. The most promising system among several different kinds of fuel cells due to their various advantages such an easy startup and operating temperature range from 30^{0}C to 80^{0}C, no liquid electrolyte, the optimal thickness of the membrane. Membranes are usually lightweight and their thickness is in microns (look like a very thin sheet around 20 microns which enables necessary ions only to pass between anode and cathode). In short it consists of a polymer electrolyte membrane along with catalyst and diffusion layers to achieve the desired purpose.

3.1 Balance of Parts in PEM Fuel Cell for Platform Truck

The following figure 2 displays fuel cell power conversion system components that are utilized in the development of PEMFC based platform truck and the following sections brief description about them. The following are the subcomponents of the fuel cell system that are used in the development of PEMFC based platform truck which are discussed as follows.

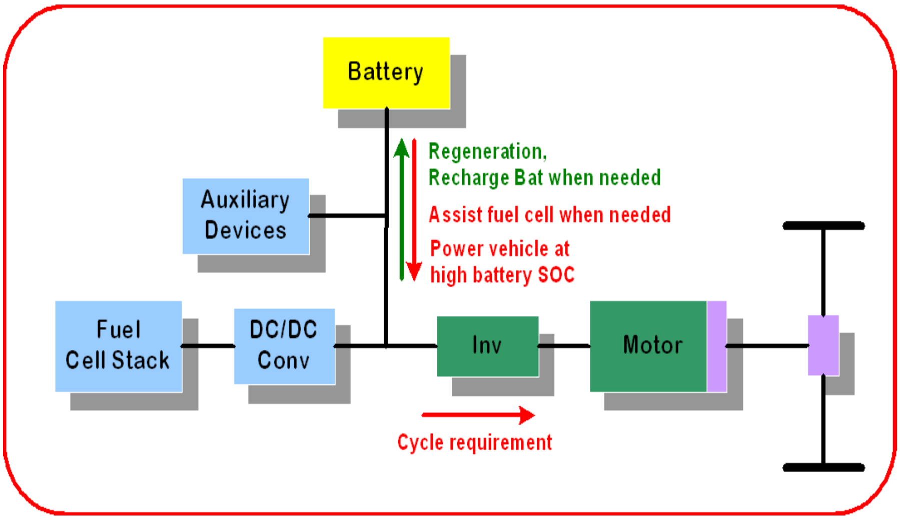

Figure 2. Fuel cell power conversion system components.

3.1.1 Fuel cell stack

A single fuel cell consists of membrane electrode assembly (MEA), flow fields for reactant gas flow delivering the cell voltage about 0.7-0.9 V. The output of the fuel cell depends upon the size of the stack. Increasing the number of cells increases the voltage. To obtain the maximum power of 3 kW (2.5 kW net power), 75 cells are used and assembled, called a stack. Considering stack reference parameters, it is intended to develop a new stack in Matlab/Simulink environment, to achieve 100 kW by increasing area as well as number of cells along with their dimensions.

3.1.2 Power Conditioners

According to the polarization curve [7], unregulated DC voltage generated in fuel cell drops down when the current increases. As a tradeoff, power is usually conditioned before supplying to load with the use of DC/DC regulators and/or inverter regulators to raise the voltage between battery and inverter.

3.1.3 DC/DC converter

It should be ensured that overall fuel cell stack output voltage must be equal to the grid voltage while designing the number of cells and their output interconnections either in series or parallel. If for some reason the number of cells is chosen differently, a DC/DC converter can be used to achieve the right output voltage level. The voltage over the stack is normally not constant and when the current increases there will be a voltage drop. In fuel cells this voltage drop is greater than in normal electrical power generators. In this case there is also need for a DC/DC converter to solve this problem [9]. This problem can be rectified by developing the new fuel cell stack in Matlab environment by modifying (either by increasing or decreasing the number of cells) to achieve the desired voltage (ex: 400 cells for 400 V assuming 1 V output from each fuel cell).

3.1.4 DC/AC inverter

The inverter or DC/AC converter is the device responsible for transforming the DC current obtained in the boost converter after the fuel cell stack to AC inverter current in order to feed the electric motor in the drive train system. In order to do those parameters such as output voltage, output frequency, and total delivered power have to be specified, and the final design of the converter will vary if those parameters vary. When decelerating, the inverter has to be capable to obtain the AC current generated in the motor and transform it in DC current in order to feed the battery. For that reason, it is needed a three-phase inverter, scheme of which is shown below.

3.1.5 Battery

Demand for extra power during driving tasks for longer periods of time should be available at high speeds such as towing a load up an incline. This extra energy required for a hard acceleration can generally be provided by batteries for less cost and mass. Further, it is also useful when the vehicle is operating in a very low-efficiency region. During low-power demands, the control method adopted by battery management system can be used to improve the overall efficiency of the vehicle [10][11].

3.1.6 Motor

As seen before, fuel cell vehicles obtain electricity to feed an electric motor. Electric motors are divided in two types according to whether they work with direct (PMDC) or alternating current (PMAC). For PMAC motors we can find two different types; Brushless DC Motors (BLDCM) and Permanent Magnet Synchronous Motor (PMSM). But the most used type of motor in automotive solutions due to power/weight ratio, durability and technology knowledge is the Permanent Magnets Synchronous Motor (working with alternate current). While brushless DC motors generate a trapezoidal counter electromotive force when the rotor spins, PMSM generate a sinusoidal force.

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4. Configuration of the proposed PEMFC vehicle system

The configuration of an entire driving system formed by the fuel cell stack, the DC/DC boost converter, DC/AC converter and PMSM motor has been chosen. The Matlab/Simulink tool is used to implement an integrated design level sub system structures such as energy management, electrical and fuel cell vehicle (FCV) dynamics to model complex systems to analyze the desired scenario as shown in figure 3.

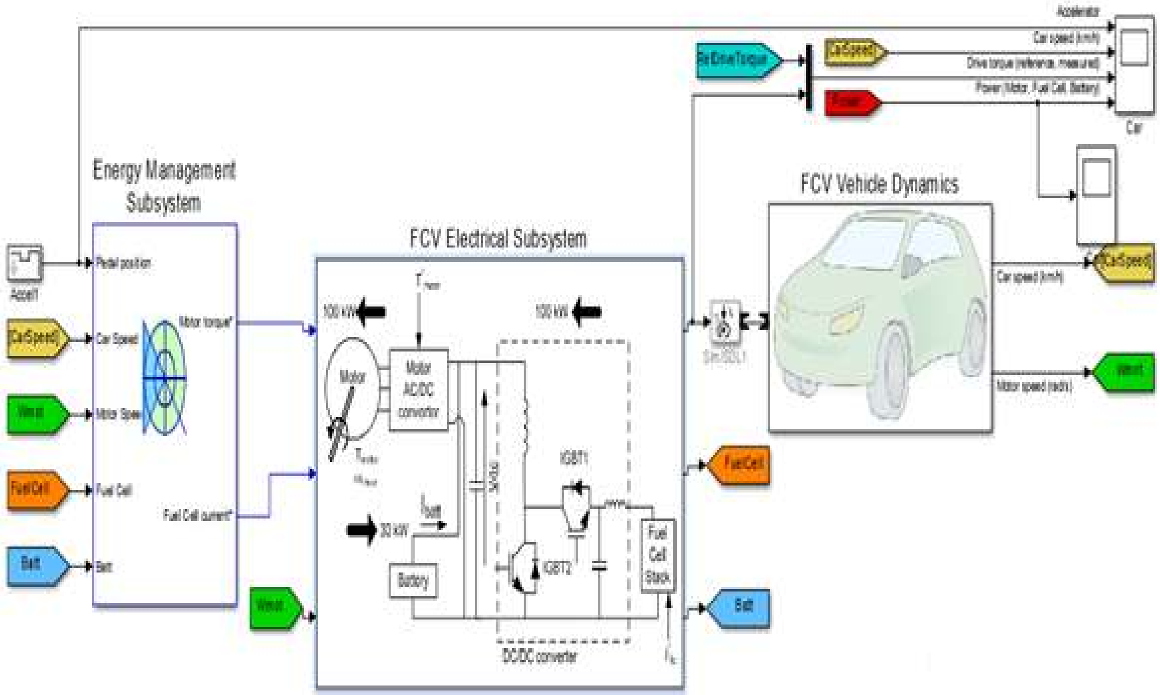

Figure 3. Proposed system of the 100-kW fuel cell vehicle.

4.1 Energy management subsystem

It is essential to implement energy management strategy to ensure dynamic response as well as reliable operation of a PEM fuel cell generator to enhance its lifetime. The following figure 3 shows the integration of energy management, electrical and fuel cell dynamics simulation subsystems with its ancillaries connected via DC electrical network.

For a conventional PEMFC fuel cell, the output voltage can obtain through the Nernst equation in order to attain reversible potential of the fuel cell [12]. This equation only corresponds to the behavior for one single fuel cell. Every fuel cell within the fuel cell stack is driven by this same equation. The corresponding equation in a proper electrical model for a fuel cell can be designed. However, this model will depend on the inputs of both temperature and current to work properly.

$$\Delta G = nFE \tag{1}$$

Where ΔG = Gibbs free energy, n is the number of electrons transferred in the reaction (from balanced reaction), F is the Faraday constant (96,500 C/mol), and E is potential difference.

Figure 3 exhibits the simplified electrical modelling diagram of fuel cell system and its energy management strategy using Simulink platform. The proposed energy management strategy must be able to respond to dynamics requested by fuel cell electrical quantities. The cooling circuit must maintain fuel cell temperature in its operating range and the fuel cell voltage must be monitored to avoid gas diffusion limitation problems. The fuel cell Stack is supplied with hydrogen by high pressure cylinders (From 300 to 700 bars) aboard vehicle and its flow is regulated by pressure reducing valve. The determination of air flow reference depends on fuel cell voltage. Indeed, by increasing air flow over its real consumption in the stack, partial pressure of oxygen will increase in cathode compartment. This overpressure will then increase requisite fuel cell voltage. The following table 1 shows the list of simulation parameters along with their specification that are considered for project execution.

Table 1. System parameters and specifications.

Parameter	**Specifications**
Power of Stack	
Nominal of stack power	85500 W
Maximal of stack power	100022.4 W
Resistance of FC	1.1 Ω
Voltage (En)	1.1 V
Utilization of nominal	
Nominal of Hydrogen (H_2)	95.24%
Nominal of Oxidant (O_2)	50.03%
Consumption of nominal	
Nominal of fuel flow	794 LPM
Nominal of air flow	1891 LPM
Current (i_o)of exchange	0.024152 A
Coefficient of exchange	1.1912
FC signal variation parameter	
Composition Fuel (x_H_2)	99.95%
Composition Oxidant (y_O_2)	21%
At nominal hydrogen fuel flow rate utilization	
Nominal of litre per minute (LPM)	374.8 LPM
Maximum of litre per minute	456.77 LPM
At nominal oxidant utilization: Air flow rate	
Nominal	1698 LPM
Maximum	2069 LPM
Temperature (T)	368 K
Pressure of fuel supply	3 bars
Pressure of air supply	3 bars

4.2 FCV electrical system

The power systems of a fuel cell vehicle are the battery (Li-ion), the inverter and the motor. The battery is set after the boost converter in order to take advantage of the risen voltage, and manage energy charge and discharge of the system. Therefore, the battery is set in parallel between the boost converter and the inverter. Nominal voltage of the battery is set as the value obtained in the converter of output boost. Battery capacity set this nominal voltage and the power that is to be needed. When implementing the motor-inverter structure, a motor model is selected.

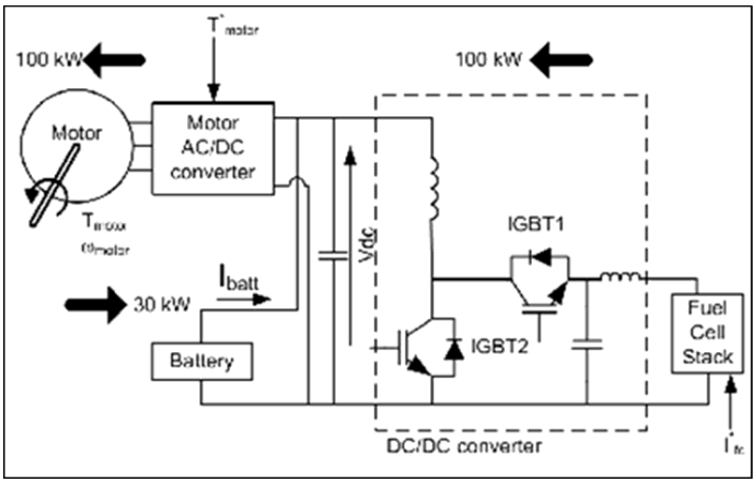

Figure 4. FCV electrical subsystem.

In this case just a 100-kW peak power motor is required and motor parameters can be subtracted. These parameters such as stator resistance, motor inductances and flux linkage can be set into the inverter model in order to link those two elements. However, these elements need to be controlled and for that, a speed and current control has to be implemented. As a speed and vector controller is implemented, taking the motor speed, obtaining the required torque and then obtaining the current control in order to drive the inverter.

4.3 FCV vehicle dynamics

In order to test the system in real conditions once it has all been modelled, it has been decided to put this system through a driving cycle consisting in an acceleration ramp, a velocity maintaining phase and a deceleration ramp between 0 and 25 km/h, as the object of study is a vehicle with small power output, such a scooter or a truck. In order to do that, several equations have to be implemented in what is called the dynamic model of the vehicle. That means that the force balance is implemented in order to get the force required by the wheel and eventually, both torque and angular speed in order to be able to control the electrical system of the vehicle.

When implementing the dynamic model of the vehicle, several assumptions have been made, such as considering the vehicle a rigid body with only one axis affected by the forces that intervene in the system. Hence, the which the model will be based is law of motion which says that the acceleration of an object as produced by a net force is mass times proportional in the same direction to this same force. In the case of the system in study, the resulting force can be written as the forces that help the vehicle accelerate (tractive forces) and the forces that make the vehicle decelerate (resistive forces) [13]. Several forces can be described as resistive, in which the aerodynamic drag, the rolling force and the grading force can be included. The following table 2 list out the dynamic model parameters that are considered for the execution of this project.

Table 2. dynamic model parameters.

Parameter	Specifications
Mass (kg)	1625 kg
Ground from the system height	0.5 m
Front axle from horizontal distance	1.4 m
Area of frontal	2.711 m^2
Atmospheric density	1.2 kgm^{-3}

Drag coefficient (C_d)	0.26
Effective rolling radius	0.25 m
Load vertical rated	3000 N
Rated load longitudinal peak force rated	3500 N
Rated load (%) slip at peak force	10%

5. Results and discussion

To ensure proper functioning of every part of the proposed PEM fuel cell system, the simulation results are carried out on completion of the desired system modelling. Simulation of each component and their relevant functional testing results are outlined in the figure 4.

Figure 4 shows the simulation results obtained by integrating the above discussed subsystems. From figure 4 one can clearly examine time in seconds on x-axis and parameters of concern such as acceleration, vehicle speed, driving torque and power delivered on y-axis. A discussion related to the analysis of these four important parameters with respect to time is presented below. Figure 4 shows the simulation results of dynamically modelled fuel cell vehicle exhibiting system characteristics for a time duration of 16s under four different operation modes i.e. acceleration, cruising, fast acceleration and deceleration.

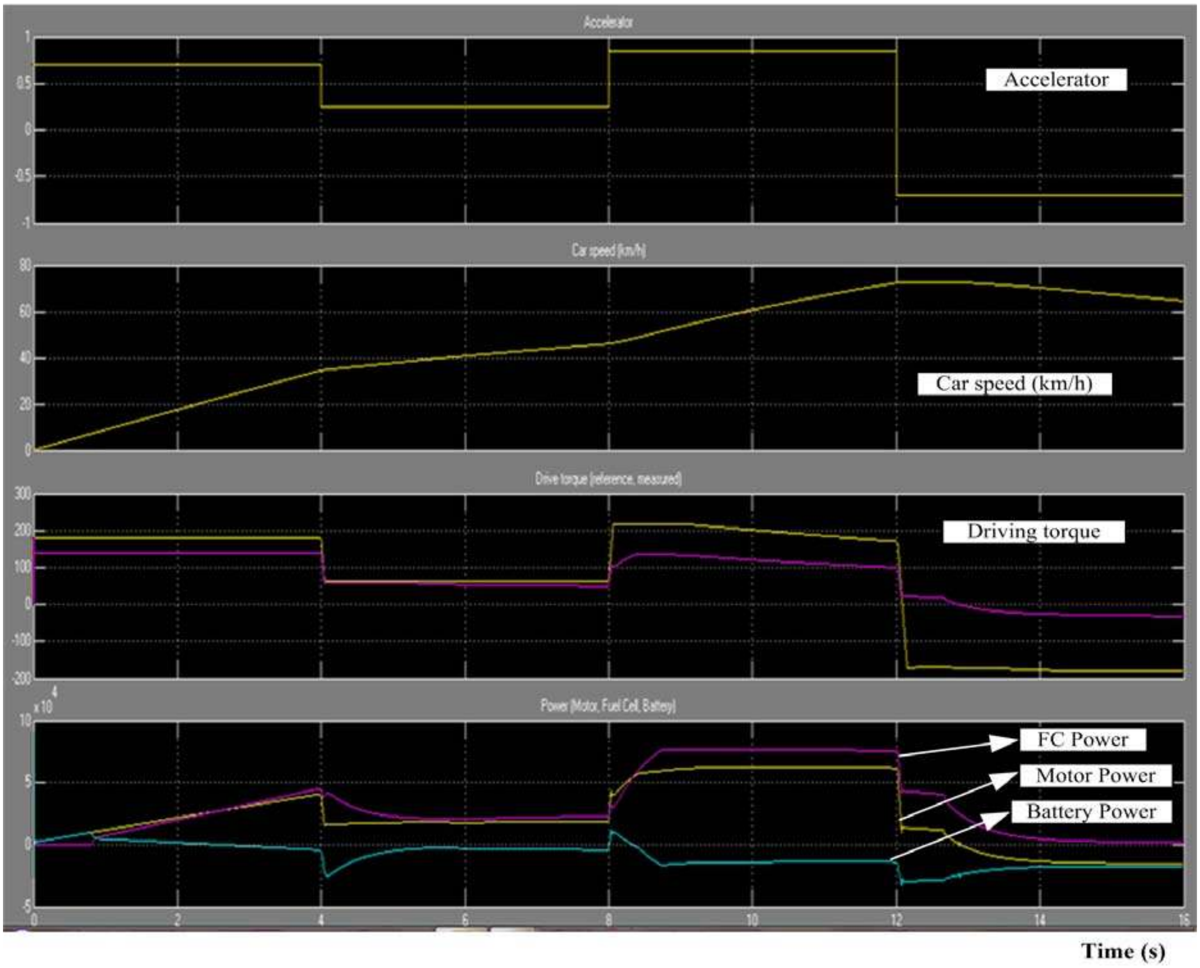

Figure 5. Simulation results and power outputs throughout the full driving cycle.

At t = 0s, the FCV is stopped and pushes the accelerator pedal to 60%. Since the fuel cell cannot start as quickly as required, the battery provides the motor power until the fuel cell starts. In fact, in real operating conditions, this is mainly due to the inertia exhibited by fuel cell stack to attain required chemical reaction rate between hydrogen and oxygen.

At t = 0.7s, the fuel cell begins to provide power but is not able to reach the reference power due to its large time constant. Therefore, the battery continues to provide electrical power to the motor.

In real operation condition, the fuel cell stack initially starts up small power will be required because of the auxiliary power systems operates fuel cell staring initial condition. Like pressure gauge and safety valves temperature controller operating at the initial stage. So that power is taken from the battery. Therefore, the battery continues to provide electrical power to the motor. Real operation of the fuel cell stack therefore the battery continues to provide electrical power to the motor. because of continuous hydrogen react with a membrane so unwanted particle enters into the pipeline reaction rate will be suddenly reduced at the stack power produces also decrease so suddenly the speed of car will slow that problem will be rectified. Therefore, the battery continues to provide electrical power to the motor.

At t = 4s, the accelerator pedal is released to 25%. The fuel cell cannot decrease its power instantaneously. Therefore, the battery absorbs excess of the fuel cell power in order to maintain the required power.

At t = 6s, the fuel cell power is equal to the reference power. The battery is no more needed. Once the fuel cell generates the electrical power, the battery is no more needed.

At t = 8s, the accelerator pedal is pushed to 85%. The battery helps the fuel cell by providing an extra power of 50 kW.

At t = 12s, the accelerator pedal is set to -25%, corresponding to a regenerative power of 50 kW. The motor acts as a generator driven by the vehicle's wheels. The kinetic energy of the FCV is transformed into electrical energy which is stored in the battery. For this pedal position, the battery absorbs the regenerative power and the residual fuel cell power.

The improvement of the EMS as well as the dimensioning of the components can be obtained when the simulation is done with great exactitude. For example, so as not to exceed the maximum power of the battery, it is possible to directly control the electric motor in order to limit its current. These current peaks can be determined with precision through dynamic simulation. This model is thus the central point of the electric vehicular components since all other systems depend on the battery behavior. A systematic approach has to be followed while switching ON and OFF of the system to ensure reliable operation of the above-mentioned fuel cell system. During ON condition, the battery should be turned ON at first followed by fuel cell, DC/DC converter and inverter in a sequential manner otherwise due to current and voltage fluctuations, inverter leads to failure operation. During OFF state, initially the inverter has to be switched OFF followed by DC/DC converter, fuel cell and then the battery to curtail current and voltage fluctuations.

6. Conclusion

Regarding fuel cell technologies, it is clear from that PEMFC is the technology offering better performance when it comes to applying those to the automotive sector. Other technologies might be better when it comes to stationary energy procurement purposes. Nevertheless, PEM fuel cells still have a long way in terms of material improvement and cost. The major breakthrough in this type of technology will come when manufacturing is cheap enough to compete with conventional modes of transportation, as other characteristics have been already matched, such as autonomy range and recharge time. In the proposed system, it can be seen that the results of the overall system are coherent and that the system responds as it should in the proposed situation. The stack of cells is able to deliver the range of energy for which it was conceived and the power conditioning elements are able to adapt and control this power in order to give the electric motor the power to move the vehicle to the desired speed and much improvement can be done in order to perfect this model.

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