Fuel Cell Power Train System Simulation of a Car SAMAND SOREN

Arash Khosravi*

School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

Abstract

Due to increasing energy crisis and environmental problems because of air pollution, fuel cell hybrid vehicles are considered as an alternative for internal combustion (IC) vehicles. Proton exchange membrane fuel cells (PEMFC) are the most proper kind of fuel cells for portable usage due to high power density and low performance temperature. In this paper, power train system of a real car, SAMAND SOREN, is modeled and simulated using a dynamic model in MATLAB/SIMULINK software. Five important subsystems in the model are: cathode air supply system, anode fuel supply system, electric motor, battery, and power transmission system. Finally, parameters like power and voltage produced by fuel cell, electric motor torque and vehicle speed are demonstrated as results.

Keyword:
Fuel Cell
Hybrid Vehicle
Modeling
Torque
Power

1. Introduction
A recent study shows that approximately 18% of the main greenhouse gas, CO2, is emitted by internal combustion engines [1]. Development of Fuel Cell Vehicle (FCV) technology is one of the major challenges in vehicle industry due to environment and economic problems. Fuel Cell (FC) is an electrochemical device that converts chemical energy of a fuel (hydrogen or methanol) and air directly into the electrical energy. Every fuel cell is consisted of three parts: cathode, anode, and electrolyte. FCs work at high efficiencies and do not generate air and sound pollution and have minimum energy loss.

PEMFC is the only fuel cell that is suitable for transportation applications. In these FCs, the electrolyte is an ion conducting polymer covered with the catalyst. These cells are suitable to be applied in vehicles because of having high power density, solid electrolyte, long cell life, less sediment, very low noise, and low performance temperature (50°C-100°C) which provides having steady conditions and less start time [1].

A vehicle with FC power train has high power density. For instance, a FC system with methanol as the fuel has 1900 W/kilogram of power density compared with 40 W/kilogram for an acid battery. FC can also be recharged in a few minutes, similarly to gasoline vehicles [2].

In FC vehicles, a compressor uses a part of the produced electricity of FC to provide compressed air. The cathode inlet air should be controlled in a way to provide the required flow and pressure. Compressor discharge air has high temperature and should be reduced in cooler to performance temperature limit of the FC. The role of cooler in FC is like radiator in vehicles with internal combustion engine. FC supply air must have the relative humidity of one. The more the relative humidity of the input air to the FC is close to one, the higher voltage is obtained, but the humidity over 100% causes water production at the cathode and accordingly causes impressive reduction in the produced voltage [2]. The stored hydrogen enters the anode passing the pressure control valve. In an efficient PEMFC, the pressure at the cathode and the anode must be close together and even equal at every moment. The unequal pressure between anode and cathode causes fuel leak or reverse ion motion through the electrolyte. Thus, the pressure control of hydrogen supply to the...
anode plays an important role in FC efficiency. The supplied hydrogen is humidified to reach the relative humidity of 100%.

**Anode:** $H_2 \rightarrow 2H^+ + 2e^-$ \hspace{1cm} (1)

**Cathode:** $0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$ \hspace{1cm} (2)

At the cathode, oxygen reacts with the obtained electrons from the electrode and $H^+$, which has been come from the membrane to the cathode environment, and produces water. This water must be removed to prevent the cell from being flooded. Transmission of $H^+$ from the anode to the cathode is done by a substance which is called the polymer membrane. The membrane only allows the proton ions to through in one path. For this reaction to proceed continuously, the electrons produced at the anode must flow through an external circuit, and the protons must flow through the PEMFC shown in figure 1.

The first vehicle with FC power train which went on road in the history was a car from General Motors which was produced in 1966. The company Daimler-Chrysler (these two companies separated in 2007) extensively started manufacturing these kinds of vehicles in the first years of 1990s. The Ford Company produced its first model of FC vehicles called Necar in 1994. Then, the company manufactured the vehicle P2000 in 1999 [3]. In 2005, Wang et al manufactured a light vehicle named Mingtao. In this car, a 5-kW polymer FC was used to supply energy. Net efficiency of the FC in this vehicle was 30% [4]. Honda R&D center presented the advances in the field of FC production by introducing its FCX Clarity in 2009. The output power of this vehicle was 100 kW and the efficiency of the FC at the optimum performance conditions was 52%. This car had the ability of starting at the temperature of $-30^\circ$C [4-6].

Many car manufacturing companies are focusing on the research and development of FCVs. FCV is called as the green car because of minimum air and noise pollution. In 2011, the number of FC vehicles moving on US roads reached to 600 which most of them are in California [3].

In 2010, the Hyundai Company presented two models of FCV on Tuscan and Sportage platforms. In 2009, the Daimler Company announced that it will send ten thousand FCVs to the market. In the same year, the company manufactured two FCVs called F-CELL and F-CELL Roadster. The Peugeot Company exhibited its first car of this type in 2004 as Qurak and in 2008; it demonstrated the H2Origin-Fuelcell. The last FC vehicle model of GM is Hydrogen4 which is introduced in 2007. This car has 440 FCs with the power of 93 kW. This car consumes 1.3 kilogram of hydrogen per hundred kilometers [2].

**2. Power train System Modeling**

The overall system is divided into five subsystems that are being controlled individually in connection with each other [7]. The five subsystems are as follows:

- Reactors flow
- Temperature and heat
- Water management
2.1. Reactors flow system

This subsystem supplies the air and the hydrogen for the cathode and the anode, the compressed air flow and the electromechanical behavior of the motor are the main parameters in dynamic modeling of the air compressor. When the power demand increases, a lack of air and hydrogen is possible inside the stack. In this condition, to avoid fuel starvation on the anode surface, the amount of the hydrogen and the oxygen is modified with a valve and by making a positive pressure in air flow. Here, the aim of the control is to make an enough flow of reactants, to ensure fast and safe power transient response to minimize the axial power consumption. Direct coupling of the FC with the compressor is preferred because of high efficiency and the volumetric benefits.

2.2. Temperature and Heat Management System

This subsystem includes the cooling system of the FC body and the reactant temperature as well. When the cooling system flow rate drops due to engine demand, the heat increases inside the FC. Considering the FC size which is designed to carry passengers, the accumulated heat cannot be eliminated by the air displacement and the radiation from the outer surface. Here, an active cooling inside the stack is needed. Cooling management in a FC system is more difficult and complicated than an internal combustion engine. Because the ionized water is used instead of water for FC body cooling and the design temperature of the FC is about 80 degrees of centigrade, so the heat capacity of the outflow air is limited. A little temperature difference between the body and the cooling water is an obstacle to the effective heat transmission from the body. Heat management can be achieved by velocity change of the cooling fan and the water circulation pump. The aim of the heat management is quick heating of the system without final temperature overshoot and minimizing the consumption of pump and cooling fan.

2.3. Water Management System

The role of the water management system is to maintain the humidity of the polymer membrane and balance between water consumption and water production. The amount of reactors flow and the injected water to the cathode and the anode affects the membrane humidity. Dry membrane and over humid membrane result in increased power dissipation in the poles. When the FC flow drops, the water molecules are produced at the cathode and are transferred from the anode to the cathode by the hydrogen ions. When the water density increases in the cathode, the density gradient causes the water to penetrate from the cathode to the anode.

Disturbance in FC humidity can be induced by different factors which are: accumulated water inside the stack while load increasing, changes in relative and absolute pressure of the reactors inside the membrane, air flow changes and body temperature changes. 20 to 40 percent of power drop is due to lack of proper moisturizing [4].

2.4. Power Management System

This system controls the power of FC body. Without considering the power management, the drawn current from the system could disturb the whole FC system. The drawn current from the FC system affects directly all other subsystems. If a battery is used as another power source in the system, power management between two power sources must be in a way that gives a suitable response to the required traction of vehicle under any condition to reach the optimal efficiency condition in the FC system [5].

2.5. Fuel Processing System

Lack of infrastructure for refueling, distributing, and supplying the hydrogen makes this subsystem a vital part in the FC system. Methanol, gasoline, liquid hydrogen, and natural gas are examples of the possible fuels for the FC.

The additional control components and regulators which should be considered with the fuel processing system make the control system more complicated. In addition to the FCs variables, the fuel processing variables need to be controlled which consist of the reaction temperature and the density of hydrogen and carbon monoxide in the gas flow.

FC power train system requires an electric motor driven compressor to reach the required pressure and air flow. The main parameters that should be adopted are: flow rate of the reactors, overall pressure of the cathode and the anode, the partial pressure of the reactors and temperature and humidity of the electrolyte. Considering these parameters following aims could be achieved:
The main components of control system are the compressor voltage to regulate the pressure and the input air flow, partial pressure at control valve on the input hydrogen line of the FC, the velocity of water pump or radiator fan to regulate the temperature and the moisturizer to control the humidity. These parameters are not independent and have effect on each other. FC modeling includes four parts: the FC voltage model, the anode flow model, the cathode flow model and the membrane hydration model, figure 2.

Figure 2. Main components of the subsystems in a typical PEM fuel cell system

3. Power Train System Modeling

The produced voltage in the FC and the supplied voltage in the battery are used to move the FC vehicle. In hybrid vehicles, the FC uses an ultra capacitor to make the vehicle hybrid [3]. The power train system consists of the electric motor, the gearbox, and the differential. A DC/DC convertor is used to produce the proper current for the electric motor.

3.1. Electric Motor Modeling

The specification of an electric motor used in the car FORD P2000 given in table 1 is used to model the electric motor.

The amount of the current in a DC motor equals to the difference between the supplied voltage (the produced voltage of the FC) and the anti-traction voltage divided to armchair resistance. Equation (3) is used to calculate the current.

\[ I_{motor} = \frac{V_{sup}}{R_n} - \frac{k_w \phi_{motor} \omega_{motor}}{R_n \omega_{motor}} \]  

(3)

| Motor Type       | 3 Phase, 4 Pole |
|------------------|-----------------|
| Maximum Power    | kW 67           |
| Maximum Torque   | N.m 190         |
| Nominal Efficiency| 91%             |
| Maximum Revolution | 12500 RPM     |
Where \( R_a \) is the resistance of the armchair, \( k_m \) is the motor coefficient, \( \phi_{motor} \) is the magnetic flow passing the armchair core in terms of Weber and \( \omega_{motor} \) is the rotational speed of the rotor in terms of rad/s. The amount of the engine’s produced torque as a function of the motor current is as equation (4).

\[
Tor_{motor} = k_m \phi_{motor} I_{motor}
\]  

(4)

As it is obvious from the equations (3) and (4), when the rotational speed of the rotor is zero, due to the lack of anti-traction voltage, the amount of the torque and the motor current will be maximum. The motor torque can be demonstrated by the equation (5).

\[
Tor_{motor} = \frac{k_m \phi_{motor}}{R_a} V_{at} - \left(\frac{k_m \phi_{motor}}{R_a}\right)^2 \omega_{rotor}
\]  

(5)

\( q \) is defined as the characteristic parameter of the motor as follows:

\[
q = \frac{k_m \phi_{motor}}{R_a}
\]  

(6)

In this study, \( q \) is considered 1.1018 for the electric motor [11]. Using the obtained equations for the current and the electric motor torque, the produced power of the electric motor is achieved as in equation (7).

\[
p = \eta_{motor} I_{motor} V_{at}
\]  

(7)

The produced torque of the electric motor is calculated from the equation (8).

\[
Tor_{motor} = qV_{at} - (q)^2 \omega_{rotor}
\]  

(8)

A schematic of the power train system is shown in figure 3.

![Figure 3. Schematic of the vehicle power train](image)

### 3.2. Modeling of the Vehicle and Power Train Forces

This model calculates the forces acting on the vehicle during a limited acceleration cycle, rotational speed of the electric motor and the vehicle velocity. In this model, the balance of the forces acting on the vehicle is as follows.

\[
F_v = m_v \cdot a_v + F_a + F_f + F_g
\]  

(9)

Where, \( F_v \) is the vehicle traction force (N), \( m_v \) is the vehicle mass, \( F_a \) is air resistance, \( F_f \) is the friction force and \( F_g \) is the gravity force. The equations (10) to (12) are used to calculate the vehicle forces.

\[
F_a = 0.5 \rho_v A_f C_d V_{vehicle}^2
\]  

(10)

\[
F_c = V_{vehicle} C_{m_c} m g \cos \theta
\]  

(11)
\[ F_x = m \cdot g \cdot \sin \theta \]  

Where, \( A_f \) is the vehicle effective area \((m^2)\), \( C_d \) is the aerodynamic coefficient between the air and the vehicle surface, \( V_{\text{vehicle}} \) is the vehicle velocity \((m/s)\), \( C_f \) is the friction coefficient between the road surface and the tire and \( \theta \) is the road slope \((\text{rad})\). Equations (13) and (14) are used to calculate the traction torque of the vehicle and the rotational speed of the tires.

\[ Tor_v = F_t \cdot r_w \]  
\[ \omega_v = \frac{V_{\text{vehicle}}}{r_w} \]  

Where, \( r_w \) is the dynamic radius and \( \omega_v \) is the wheel rotational speed. In this vehicle, the power train system includes only one set of gears with the ratio of 10:1.

\[ \omega_m = \frac{V_{\text{vehicle}}}{r_w} \cdot i_G \]  

Where, \( \omega_m \) is the rotor rotational speed and \( i_G \) is the gear ratio.

\[ Tor_m = \frac{Tor_v}{i_G} \]  

The vehicle technical data used in the simulation is shown in table 2.

| Table 2. Technical data of SAMAN SOREN for vehicle simulation |
|---------------------------------------------------------------|
| Differencial Ratio | 1 | Fuel Cell | 320 Cells 80 kiloWatts |
| Gearbox Ratio      | 8 | Electric Motor | 80 kiloWatts 288 Volts |
| Vehicle Track      | 1720 mm | Battery | 13.0 Amper 25 kiloWatts |
| Wheelbase          | 2671 mm | Drag Coefficient | 0.22 |
| Vehicle Lenghth    | 4527 mm | Tire | 185/65 R15 |
| Vehicle Height     | 1460 mm | Vehicle Mass | 1220 (kg) |

4. Detailed model for FC stack

The detailed model represents a fuel cell stack when the parameters such as pressures, temperature, compositions and flow rates of fuel and air vary. These parameters can be selected to vary on the Signal variation pane on the block dialog box.

5. Motion Simulation of the FC Vehicle

To simulate a vehicle motion with the FC power train, an acceleration profile which is shown in the figure 4 is applied to the system as input. This motion is done on a zero-slope road. The technical data used in the simulation is demonstrated in table 2.
The vehicle speed under the acceleration profile shown in figure 4 is demonstrated in figure 5. Due to having less mass, the vehicle has the ability of fast accelerating and safe braking. In this vehicle, the power train system is designed in a way that there is enough capability of producing power for fast acceleration or moving on a hard slope at any moment.

Figure 6 shows the produced power of the electric motor, the power transferred to the vehicle differential and the power flow in the battery. In the first 6 seconds of the motion, to overcome the vehicle stationary inertia, the battery, and the electric motor produce power for the vehicle motion and then some of the produced power is supplied permanently in the battery (the negative power of the battery in the figure shows the power transmission to the battery). The supplied power in the battery helps the FC power train system during quick accelerations and slope motion.
The electric motor rpm of the vehicle which depends on the amount of the required torque from the electric motor is shown if figure 7. The amount of the needed torque at the wheels for the vehicle motion and the transmitted torque to the wheels are demonstrated in figure 8. As it is seen, the transmitted torque equals to the required torque with minimum error. During sudden accelerations, the needed time to achieve the required torque is very short.

Figure 9 exhibits the vehicle speed under the same acceleration pattern (the only difference of the acceleration pattern is that in a 10 seconds interval of the motion start, the motion acceleration is 0.1 \((m/s^2)\) and the braking acceleration is...
-0.1 (\(m/s^2\)) and on a slope of 3 degrees. Due to using battery in any moment, there is more power available for the electric motor. In comparison to the car FORD analyzed before, this vehicle has more FCs with fewer cells but has the ability of producing more power in any moment.

![Figure 9. Vehicle velocity on a slope](image1)

Figure 9. Vehicle velocity on a slope

Figure 10 demonstrates the produced power during slope motion. Since more power is required during moving up a slope, the battery charge is done only during braking in this motion and in other conditions all the produced power is used to move the vehicle. In the 16 and 25 seconds which the vehicle accelerates suddenly, the supplied power in the battery is used to supply the vehicle power.

![Figure 10. The produced power in the vehicle during motion on a slope](image2)

Figure 10. The produced power in the vehicle during motion on a slope

6. Conclusions

The world leading car manufacturing companies are planning the mass production of FCVs until 2020. Hence, much effort has been done during recent years to make progress in producing these cars. In this paper, using the information of the car SAMAND SOREN, a car manufactured in Iran, the modeling and the simulation is done and from the achieved results it can be seen that this car has the capability of assembling the FC equipment and moving with this energy source.

In hybrid vehicles with FC power train, some of the required power is supplied by the battery during acceleration, and this makes the system apart from high current. The system response to the acceleration changes is maximum 0.45 seconds which is a proper time for a vehicle.

References

[1] Laramie J, Dicks A, “Fuel cell systems explained”, John Wiley and Sons, New York. 2003.
[2] Pukrushpan JT, Stefanopoulou AG, Peng H. “Control of fuel cell breathing. IEEE Control Systems”, 2004;24(2):30-46. Doi:10.1109/MCS.2004.1275430.
[3] http://en.wikipedia.org/wiki/Fuelcellvehicle.
[4] Hwang J, Wang D, Shih N. “Development of a lightweight fuel cell vehicle”, Journal of Power Sources. 2005;141(1):108-15. doi:10.1016/j.jpowsour.2004.08.056.

[5] Yamaguchi N, Iwai A, Fukushima T, Shinoki H. “New Drive Motor for Fuel Cell Vehicle FCX Clarity”. SAE Technical Paper; 2009. Report No.: 0148-7191. doi:10.4271/2009-01-1001.

[6] Morikawa H, Kikuchi H, Saito N. “Development and advances of a V-flow FC stack for FCX clarity”. SAE International Journal of Engines. 2009;2(2009-01-1010):955-9. doi:10.4271/2009-01-1010.

[7] Matsunaga M, Fukushima T, Ojima K. “Advances in the power train system of Honda FCX clarity fuel cell vehicle”. SAE Technical Paper; 2009. Report No.: 0148-7191. doi:10.4271/2009-01-1012.

[8] Yamaguchi N, Iwai A, Fukushima T, Shinoki H. “New Drive Motor for Fuel Cell Vehicle FCX Clarity”. SAE Technical Paper; 2009. Report No.: 0148-7191. doi:10.4271/2009-01-1001.

[9] Schell A, Peng H, Tran D, Stamos E, Lin C-C, Kim MJ. “Modelling and control strategy development for fuel cell electric vehicles”. Annual Reviews in Control. 2005;29(1):159-68. doi:10.1016/j.arcontrol.2005.02.001.

[10] Marshall J, Kazerani M, editors. “Design of an efficient fuel cell vehicle drivetrain, featuring a novel boost converter”. Industrial Electronics Society, 2005 IECON 2005 31st Annual Conference of IEEE; 2005: IEEE. Doi:10.1109/IECON.2005.1569080.

[11] Yalcinez T, Alam M. “Improved dynamic performance of hybrid PEM fuel cells and ultracapacitors for portable applications”. International Journal of Hydrogen Energy. 2008;33(7):1932-40. doi:10.1016/j.ijhydene.2008.01.027.

[12] Adams JA, Yang W-c, Oglesby KA, Osborne KD. “The development of Ford’s P2000 fuel cell vehicle”. SAE Technical Paper; 2000. Report No.: 0148-7191. doi:10.4271/2000-01-1061.