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Design and Performance Analysis of Electric Vehicles Fed by Multiple Fuel Cells

Pardis Khayyer

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Electrical Engineering

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Morgantown, West Virginia
2008

Keywords: Fuel Cell Electric Vehicle, Efficiency Enhancement, Fuel Economy, Reliability

ABSTRACT

Design and Performance Analysis of Electric Vehicles Fed by Multiple Fuel Cell Power Sources

Pardis Khayyer

Recent advances in fuel cell developments have introduced them to many applications such as hybrid electric vehicles and heat/power cogenerations. They bring the advantage of clean energy and decrease the dependency on imported oil by providing fuel efficient devices in many applications such as electric vehicles. Conventional designs of hybrid fuel cell vehicles make use of a single fuel cell power source and a storage device to provide the base load and transients in various driving cycles. This thesis proposes a new configuration of multiple fuel cell power sources in hybrid fuel cell vehicles. Fuel cells are downsized in this new configuration to provide the same amount of power, which brings the advantage of a highly fuel economic design. The power control algorithm for this new configuration is presented and simulation results are studied for a case of double fuel cell power sources. Efficiency analysis for this new configuration is presented and compared with the conventional configuration. The main objective of this thesis is to achieve a higher efficiency in urban driving cycle. In conventional configurations, the fuel cell is not efficiently loaded in urban driving cycles, where small powers were required from the single fuel cell power source. Reliability analysis is also presented for this configuration.

To my Dear Parents and my Husband, Afshin

Acknowledgement:

First and foremost, I would like to thank Dr. Parviz Famouri for his scientific and financial help during my research whilst allowing me the room to work in my own way. I would like to thank my committee members, Dr. Muhammad Choudhry and Dr. Natalia Schmid for their help and constructive guidance in preparation of this thesis and all I learned from them throughout my coursework during my Master study.

I specially thank the mental support of my dear parents who gave me what I needed to accomplish this important and provided a loving environment for me. I would like to thank my gentle brother, Abbas and my lovely sister in law, Parisa, for all their kindness and encouragements. I would also like to thank my dear friend, Koushaly, for being so kind and encouraging friend for me.

Finally yet importantly, I extend heartfelt thanks to my husband “Afshin” for his support and endurance during my studies and hard work. His love and support carried me through the hard times and my work would not have been possible without his kind help.

Table of Content

Chapter 1,

Energy

Limited fossil fuel resources, increase in pollution, very high energy consumption and harmful effects of using non-renewable energy are leading the research and development toward new and renewable forms of energy to overcome the present problems in this regard. Fossil fuels and renewable energies are two main sources of energy used for different purposes such as transportation, industries, heating and cooling. These two types of energy and several main forms of renewable energy, their advantage and disadvantages are briefly explained in this chapter.

1.1 Fossil Fuels

Some examples of fossil fuel energy sources are coal, petroleum and natural gas. The organic remains of very old (e.g. hundreds of millions of years) plants and animals have formed the fossil fuel resources and that is why the name “Fossil Fuel” is selected for this type of resources. The energy in fossil fuels is simply released in the burning process.

Forming of the fossil fuel sources takes a long time, millions of years, and are being consumed much faster than formation of their new ones. That is why they are also known as non-renewable energy sources. Based on the report of Energy Information Administration, 86% of the energy consumption in the world in 2005 has been provided by fossil fuels. The rest has been provided by hydro 6.3%, nuclear 6.0% and only 0.9% from renewable energy sources. As for the USA, the percentage of fossil fuel energy consumption has been the same, which is %86 as it is shown in Figure 1.1.1 (EIA Webpage).

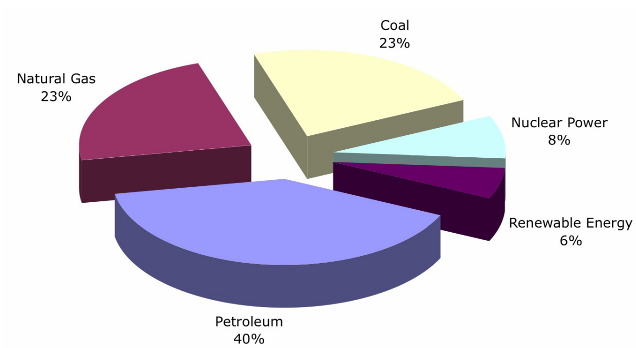


Figure 1.1.1, 86% of US energy consumption is fossil fuel (EIA Web Page)

Despite the fast consumption of fossil fuel energy sources and their limited resources, consuming fossil fuels has harmful effects to the natural environment. The main concern in this regard is the “Greenhouse Effect”.

Greenhouse gases, such as water vapor, carbon dioxide and methane, in the atmosphere, are produced from both natural sources and human activity. These gases cause a process which is called the “Greenhouse effect”. The earth absorbs some of the energy received from radiations of the sun and sends back infrared (IR) radiation of the sun to the atmosphere. Greenhouse gases re-radiate some of these emissions back to the earth while the rest goes into space. This procedure results in warming up the earth and is known as the greenhouse effect. By overusing fossil fuel energy sources and more industrial carbon dioxide emissions from the earth, the greenhouse effect has caused the “Global Warming” (Wikipedia Webpage-Greenhouse Gas), (Wikipedia Webpage-Greenhouse Effect). “Global Warming” which is the increase in the average temperature of the earth has many harmful effects. By continuing of this cycle, ices in the earth poles melt and there is a danger of covering the lands by water. As mentioned, because of limited fossil fuel resources and their harmful effects such as global warming and pollution, there is a need for another power energy source to replace fossil fuel energy sources. The best replacement is the renewable energy sources. In addition of being environmental friendly, renewable energy sources do not have limited sources. This type of power sources are explained in the next section.

1.2 Renewable Energy Sources

Renewable energy sources, such as solar, wind, fuel cell, hydroelectric, biomass and wave/ocean energy, are other types of energy sources. They are not yet widely in use, however, because of their many advantages, they have the capacity to fully replace the fossil fuel energy sources. To overcome the problems caused by fossil fuels, nowadays more attention is toward renewable energy sources. Renewable energy sources are clean and not limited in comparison with fossil fuel. However, they have some limitations such as small energy production and expensive maintenance costs which should be overcome to make renewable energy sources more common in everyday life and an alternative for fossil fuel energy. Three main types of renewable energy sources are briefly explained in this section (Thinkquest Web Page).

1.2.1 Solar Energy

Solar energy is referred to changing the energy of rays of sun into the forms of heat and electricity. To make use of solar energy, collectors or panels and storage units are required. The solar panels collect the sun rays which hit the panel's surface and transform it into heat or electric current (Brown. 1988). Collectors can generally be found as flat-plate collectors, focusing collectors and passive collectors. Depending upon the application, a collector is selected to collect the most possible sun rays and deliver it to the storage. Since the amount of energy differs during day time and night, a storage device is required to store the collected energy. Figure 1.2.1.1 shows a solar power panel.

Figure 1.2.1.1, Solar power panels at a solar power plant, California (Thinkquest Web Page)

Solar power is a clean form of energy and has no byproducts. It can be used with other renewable energy power sources for different purposes such as heating, transportation and electricity generation and is becoming more and more popular. However, some issues such as high cost of manufacturing, efficiency and geographical limitation prevented these devices to grow fast. Solar panels have efficiency as low as 40% and can generate power only in sunny geographical locations (Thinkquest Web Page).

1.2.2 Wind Energy

Clean energy of wind is another type of renewable energy resources. Harvesting the energy stored in the wind has roots in history of human being to grind their wheat, pull water from the water wells, and push their ships forward in the sea. To produce electricity, wind should turn the turbine-generator set. Like solar energy, the energy of wind varies at different locations, heights and times of year. Wind energy can be used along with other types of renewable energies to obtain and store extra energy during strong gust of winds in the storage devices. Low energy production and high maintenance costs are the main drawbacks of the wind energy. It is a very good source of energy if used as a supplement to other types of energies. Figure 1.2.2.1 shows a windmill farm in California.

Figure 1.2.2.1, a windmill farm, northern California (Thinkquest Web Page).

1.2.3 Fuel Cell

Fuel cells are electrochemical devices that change the form of chemical energy into electrical energy. Fuel cell like a battery consists of an electrolyte layer with two contacts as anode and cathode on both sides to carry on the generated current. In a fuel cell, hydrogen as a fuel is fed through anode (negative electrode) and oxygen is fed through cathode (positive electrode) to facilitate the electrochemical reactions taking place in the electrolyte membrane which produces electric current. Fuel cells can produce electrical energy as long as it is supplied by fuels and oxidants (Fuel Cell Hand Book. 2000). Figure 1.2.3.1 shows different parts of a typical fuel cell.

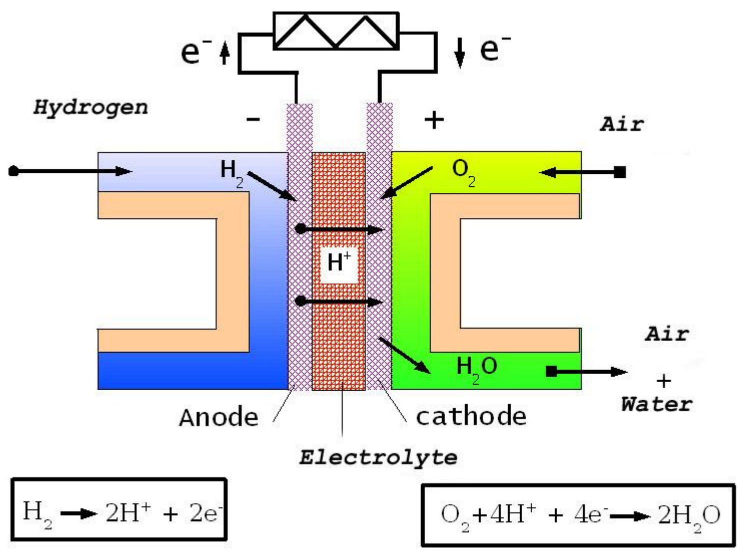


Figure 1.2.3.1, Different parts of a typical fuel cell (Wikipedia Webpage-Fuel Cell Image).

The only byproducts of fuel cells are water and heat. The voltage produced by one cell in the fuel cell is about 0.7 (DC) volts and therefore for high power applications several cells are connected in series in one fuel cell to produce the desired power. Fuel cells have application in generating electricity and transportation purposes. There are different types of fuel cells which will be explained in the next chapter.

1.3 Energy for stationary and mobile loads

Generally, the energy consumers can be divided into two main groups of stationary loads and mobiles. Stationary loads receive the required energy through their connecting wires, pipelines, storage tanks and etc. Whereas mobile applications which require specific characteristics of their energy generation devices and consumes almost 28% of the total energy in the USA (Figure 1.3.1). Figure 1.3.1 shows Energy consumption in the US by buildings, Industry and transportation. The source of energy should be carried on in the storage tanks to be converted into the required form during transportation. Polluting fossil fuels are required to be replaced by renewable and green energy resources. A solution to overcome problems related to using fossil fuel in vehicles is to replace older vehicles with vehicles which run on renewable energies and are clean and have the potential to be very economic. One of the clean energies is electricity which can be stored in batteries and ultra-capacitors in vehicles. Current available Battery Electric Vehicles (BEV) have some limitations in charging the batteries and providing enough power for long trips. Reasonably sized battery units cannot provide high powers and cannot run the vehicle for long time. On the other hand, BEV has high maintenance costs.

To provide green transportation, fuel cells, as one of the best electric energy resources are widely in use in fuel cell vehicles (FCV). Fuel cell vehicles have obtained increased attention due to their benefits and have taken preference over battery-powered vehicles in recent decade. Having a longer driving range is one of the several benefits of fuel cell in comparison with battery-powered vehicles. More details on fuel cell vehicles will be explained in the next chapters.

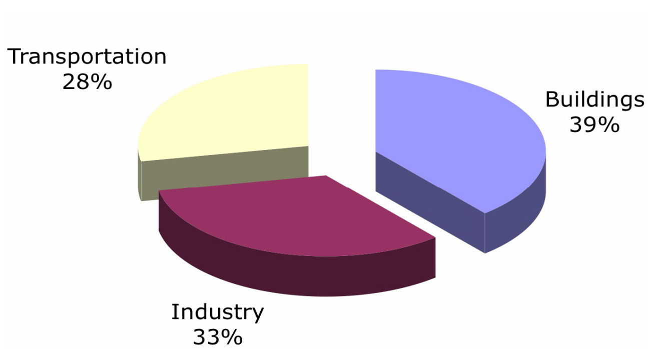


Figure 1.3.1, Energy consumption in the US by buildings, Industry and transportation (EIA Web Page)

1.4 Overview and Objective of Thesis

This research will focus on the fuel efficiency of fuel cell vehicles and provides topologies to increase the fuel economy of electric vehicles in different driving cycles. Traditional and new system configurations are illustrated and compared with each other for efficiency analysis. In the new design, multiple fuel cell systems are connected in parallel to feed the load required in different driving cycles. The size reduction and the resultant advantages of this technique are illustrated. Efficiency curves of fuel cells are demonstrated and used to base the efficiency measurements. Other factors such as reliability of operation and well-to-wheel efficiencies are introduced and used for new design approaches.

Fuel cells as source of power are illustrated and their dynamic modeling is discussed in chapter 2. Electric vehicles, their configurations and characteristics are presented in chapter 3. Current configurations of fuel cell vehicles, their characteristics, simulation results and their cost discussion are presented in chapter 4. Chapter 5 presents a new configuration with the objective of gaining higher fuel efficiency in urban driving cycle, where frequent stop-start acceleration and deceleration puts the power sources in high tension and imposes inefficient fuel economy in most vehicles. Higher system reliability is also obtained as a result of implementing the new configuration. Chapter 6 is dedicated to the conclusion and future work.

Chapter 2,

Fuel Cell

2.1 Introduction

As mentioned in previous chapter, fuel cells are electrochemical devices that change the form of energy from chemical into electrical. The technology is over 150 years old when Sir William Grove demonstrated the first fuel cell in 1839. A Schematic of a typical hydrogen fuel cell is shown in Figure 2.1.1 which shows the fuels are being fed to the anode (negative electrode) and cathode (positive electrode) of the device. Electrodes are separated with an electrolyte layer or membrane and carry Hydrogen and Oxygen as main fuels. The electrochemical reactions generate electrical current as fuels are carried through the electrodes and burnt in the membrane. This reaction can go on for long time and as long as the fuel pressure and some more conditions are maintained electrical energy is produced. Water and heat are the main byproducts of the electrochemical reactions which make fuel cells green sources of energy (Fuel Cell Handbook. 2000). Diesel and gasoline vehicles as the main air polluters, are to be considered for fuel cell future applications as the global warming and green house effects are becoming more important.

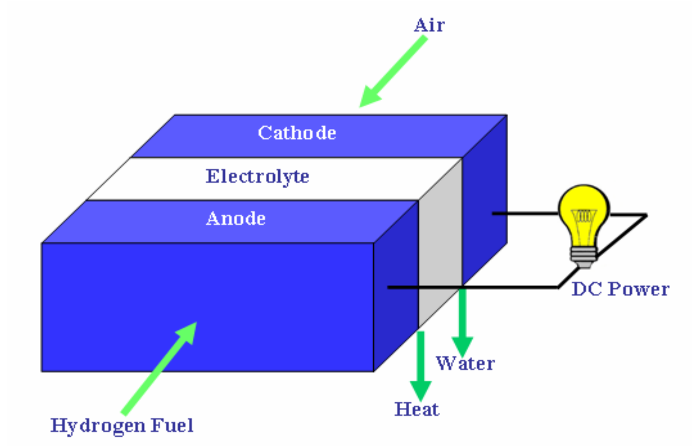


Figure 2.1.1, Schematic of a typical fuel cell

In addition to transportation, fuel cells have applications in stationary devices. Dual application of fuel cells in mobile and stationary devices makes them ideal for many new and innovative devices such as (Acharya. 2004):

- Stationary power such as power generating units, auxiliary units and distributed power generation systems.
- Transportation
- Portable electronics

The electrochemical reactions result in the governing equations of fuel cells and explain their dynamic. In the next section, electrochemical reactions are formulated for dynamical behavior explanations of the system.

2.2 Different Types of Fuel Cells

Fuel cells are categorized according to their application, operating temperature and type of electrolyte. Some types of fuel cells and their characteristics are shown in Table 2.2.1 (Greenjobs Web Page).

Table 2.2.1: Different types of fuel cells and their characteristics

Type	Acronym	Technology Characteristics			
		Electrolyte	Operating Temperature	Efficiency (HHV)	Power Density
Alkaline	AFC	Potassium Hydroxide	50-200C	45-60% up to 70 with CHP	0.7-8.1kW/m2
Polymer Electrolyte	PEM	Polymer	50-100C	35-55%	3.8-13.5.1kW/m2
Direct Methanol	DMFC	Polymer Membrane	50-200C	40-50% up to 80% with CHP	1-6kW/m2
Phosphoric Acid	PAFC	Phosphoric Acid	160-210C	40-50%	0.8-1.9 kW/m2
Molten Carbonate	MCFC	Lithium or potassium carb0nate	800-800C	50-60% up to 80% with CHP	0.1-1.5 kW/m2
Solid Oxide	SOFC	Ceramic composed of calcium or zirconium oxides	500-1000C	50-65% up to 75% with CHP	1.5-5.0 kW/m2

As the table shows, operating temperature is one of the key elements in each application. When the temperature is not important, other elements such as power density will make a significant difference in applications. Size of the device also limits its application in portable supplies. Among all different types of fuel cells, Polymer Electrolyte Membrane (PEM) has the lowest weight, operating temperature, and start-up time and therefore is suitable for vehicle applications. PEM fuel cell is explained in more details in the coming sections.

2.3 Reactions inside Hydrogen Fuel Cell

As mentioned, fuel cell is made up of two electrodes (Cathode and Anode) with an electrolyte membrane in between. When fuels pass the electrodes and react in the membrane, protons can easily pass the electrolyte membrane but electrons are blocked. This phenomenon generates current of electrons (electric current) outside of the device. Blocked by a catalyst, hydrogen fed to the anode is broken up into electrons and positive Hydrogen as:

$$2H_2 \rightarrow 4H^+ + 4e^- . \qquad (2.3.1)$$

The hydrogen protons are absorbed by cathode and delivered to the electrolyte, while electrons require external circuitry to reach to the anode. On the other hand, reaction of the positively charged hydrogen with oxygen results in water production as described in:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O\,. \qquad (2.3.2)$$

Figure 2.3.1 shows typical reaction of the fuels in the electrodes and membrane of the fuel cell (Pukrushpan, Stefanopoulou & Peng. 2004).

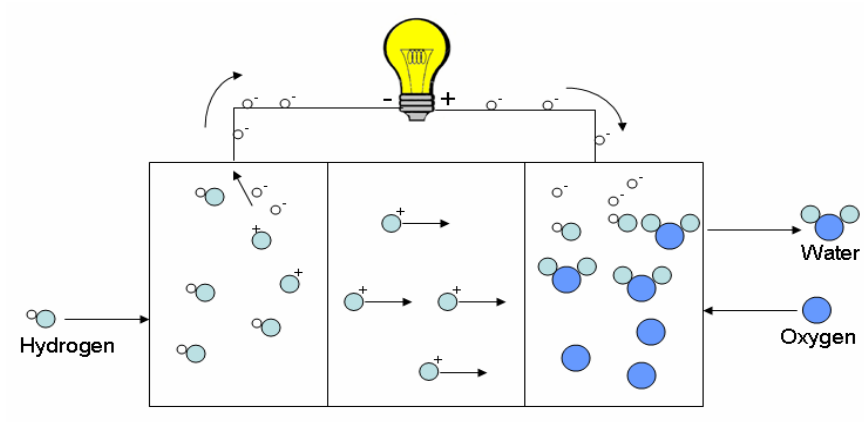


Figure 2.3.1, Schematic of reactions inside fuel cell

The reaction of hydrogen and oxygen is a heat generating process; however, heat can be increased through the electric loss in the device resistances. Different conduction paths and their losses are explained in details in this chapter.

2.4 Fuel Cell Performance

Like other power sources, the performance of the hydrogen fuel cells is measured according to some criteria such as open circuit voltage, voltage drops, ohmic and activation losses, and mass transport. In this section, variables that express the behavior of hydrogen fuel cells are defined and explained.

2.4.1 Open Circuit Voltage (OCV)

The open circuit voltage of a fuel cell is defined as

$$E = \frac{-\Delta \overline{g_f}}{2F} \quad , \tag{2.4.1.1}$$

where E is the electromotive force (EMF), F is the Faraday constant and $\Delta \overline{g_f}$ is the Gibbs energy release. By using this equation, a theoretical OCV of $1.2V$ is obtained for a device operating at temperature below $100^{\circ}C$. In actual fuel cells the theoretical OCV of $1.2V$ is not obtained due to losses in the fuel cell (Larminie & Dicks. 2003).

2.4.2 Voltage Drop

As the loading on the fuel cell increases, the output voltage drops in two different linear and nonlinear regions of the V-I characteristic curve of the fuel cell (Larminie & Dicks. 2003). The V-I characteristic curve of a typical fuel cell is shown in Figure 2.4.2.1 (Fuel Cell Handbook. 2000). In the beginning, the voltage drops rapidly to follow a linear curve down to a critical value. If the load of the cell increases, the voltage will drop rapidly again and follows a nonlinear variation.

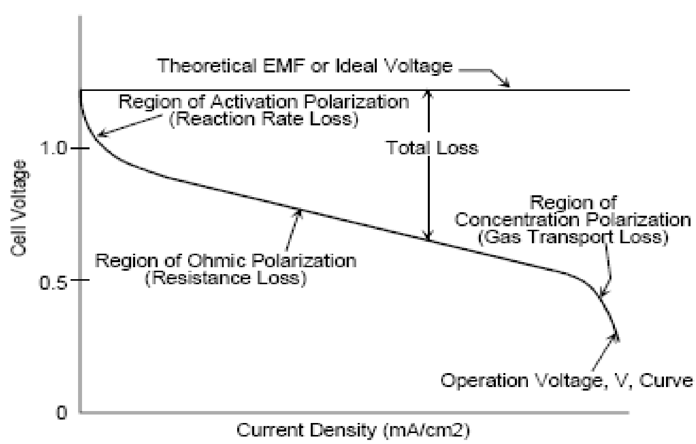


Figure 2.4.2.1, The V-I characteristic curve of a typical fuel cell, theoretical and actual (Fuel Cell Handbook. 2000)

The main causes of the voltage drops are as (Fuel Cell Handbook. 2000), (Larminie & Dicks.2003):

- Activation losses
- Ohmic losses
- Concentration losses or mass transport.

Each of these effects is described in the following subsections.

2.4.3 Activation Losses

Initial voltage drop in the fuel cell from the OCV is because of the activation loss in the cell. Figure 2.4.2.1 shows the activation loss with a significant drop on the voltage as the loading starts from zero. Activation loss is a major issue on the fuel cells operating at low and medium temperatures and mostly occurs at the cathode. The activation voltage drop follows the Tafel equation as

$$V = A_{\circ} \ln(\frac{i}{i_0}), \qquad (2.4.3.1)$$

where A_0 is a constant, i stands for the current density, i_0 is the current density where the voltage begins to drop and V is the voltage drop. Tafel equation is valid for $i > i_0$ (Larminie & Dicks.2003).

2.4.4 Ohmic Losses

The flow of electrons and ions through Ohmic resistance of electrodes and electrolyte generates Ohmic losses. The voltage drop in this region is easily obtained by the Ohm's law, $V = IR$, and is proportional to the current. Making the electrolyte membrane as thin as possible with an optimal design of electrodes with high conductivity materials will reduce the Ohmic losses.

2.4.5 Concentration Losses or Mass Transport

In many fuel cells, air is used as the source of oxygen as fuel. High oxygen consumption at heavy loads will decrease the oxygen concentration in air around the electrode. This sudden reduction of oxygen concentration around cathode depends on the quality of air compression and amount of oxygen consumption. Oxygen concentration in that region is also proportional to the partial pressure of the air in that region. A drop in oxygen concentration leads to the drop in partial pressure of the oxygen in that region. The same scenario may happen to hydrogen in the anode, based on the current taken from the fuel cell and the hydrogen flow to anode, there might be a reduction in hydrogen concentration in that region and following that a reduction in the partial pressure of hydrogen.

The concentration drop both for oxygen and hydrogen results in a voltage drop and is known as the concentration loss. The region of concentration drop in the V-I curve is shown in Figure 2.4.2.1. The voltage drop resulting from the concentration loss can be computed, considering a constant oxygen pressure and that the hydrogen pressure varies from P_1 to P_2, as (Larminie & Dicks.2003),

$$\Delta V = \frac{RT}{2F} \ln\left(\frac{P_2}{P_1}\right), \tag{2.4.5.1}$$

where R is the universal gas constant, T is the operating temperature, F is the faraday constant and P_1 and P_2 are the hydrogen pressure in two different cases.

Considering the maximum current i_1 is taken from a fuel cell and that occurs when all of the supplied hydrogen is consumed by the cell, then at i_1 pressure P_2 becomes zero. If we assume that P_1 is the pressure when current density i_1 is zero, and at the maximum current density of i_1 the pressure drops to zero, then the pressure P_2 at any current density can be obtained as

$$P_2 = P_1\left(1 - \frac{i}{i_1}\right). \tag{2.4.5.2}$$

Substituting equation (2.4.5.2) into (2.4.5.1), the voltage drop due to mass transport losses is obtained as

$$\Delta V = \frac{RT}{2F}\ln\left(1-\frac{i}{i_1}\right). \qquad (2.4.5.3)$$

If the oxygen is supplied through the air in the fuel cell, a significant amount of nitrogen is also fed to the system which surrounds the cathode and limits the oxygen from reaching to the electrode and increases the mass transport loss. In addition, high time constant of mechanical valves delays the supply of required hydrogen and increases the concentration losses (Larminie & Dicks.2003).

2.5 PEM Fuel Cell

As mentioned earlier, Polymer Electrolyte Membrane (PEM) fuel cells have advantages over their classical counterparts. They come with capabilities that best suit the vehicle industry needs; therefore, they are exclusively designed, used and modified in transportation, distributed power, heat production and back-up power systems of Electric vehicles.

Fuel cell vehicles are in much interest since they do not emit pollutants and have high power density and quick start-up (Yuvarajan & Yu. 2004), (Wang, Nehrir & Shaw. 2005). Other significant reasons for much attention to PEM fuel cells are their low working temperature, compactness, and easy and safe operational modes (Wang, Nehrir & Shaw. 2005), (Na, Gou & Diong. 2005). Figure 2.5.1, shows a schematic of a typical PEM fuel cell (Fuel Economy Web Page).

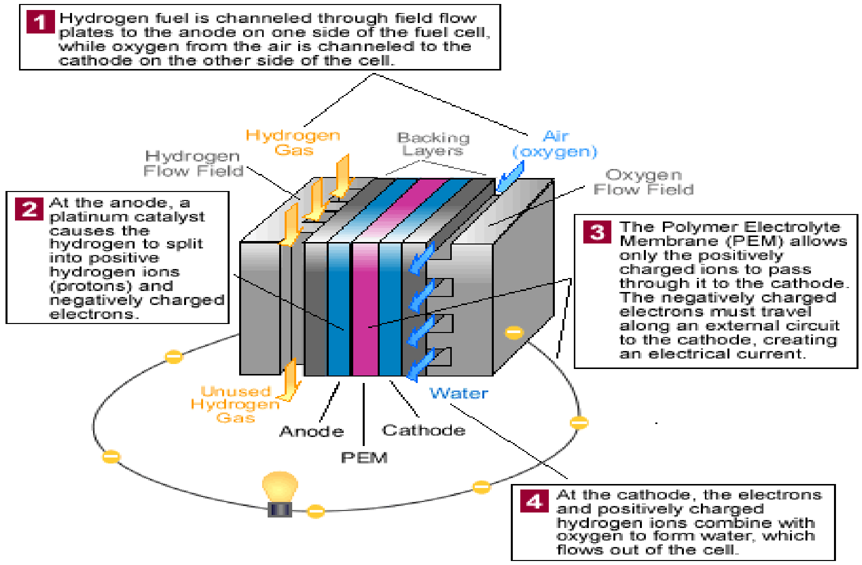


Figure 2.5.1, PEM Fuel Cell and its operating procedure (Fuel Economy Web Page).

The electrolyte used in PEM fuel cell is an ion-conducting polymer. Since the electrolyte used in PEM fuel cell is solid, this type of fuel cell is safer than the fuel cells with liquid electrolyte. Hydrogen and oxygen molecules are separated by the electrolyte membrane and therefore no combustion happens in the fuel cell. Electrodes are located on both sides of the electrolyte membrane and all are connected in series using bipolar plates in most cases. Because of low working temperatures of polymer electrolytes, the PEM fuel cell has short start-up time compare to other types. In room temperature about 50% of the maximum power of the fuel cell is available. The anode-electrolyte-cathode assembly of the PEM fuel cell is thin and therefore this property makes it possible to have very small and compact fuel cells available (Larminie & Dicks.2003), (Greenjobs Web Page).

Since membrane conducts protons, it requires a humid layer for better conductivity. Water management system in fuel cells with operating temperature less than that of boiling water such as PEM fuel cells does the humidification of the membrane layer to maintain a suitable conductivity (Mikkola. 2001). Amount of water that exist in the system is also very important. While the fuel cell should be humidified for better membrane conductivity, the water content in the system should not increase to block the pores of the electrodes. Interested readers can find more information on water management in (Larminie & Dicks.2003).

Humidity control and water management can increase the performance of PEM fuel cells and provide cost effective devices (Larminie & Dicks.2003), (Greenjobs Web Page).

2.5.1 Modeling of PEM Fuel Cells

To apply fuel cell as a part of a larger system in the real world, first it is necessary to see the modeling of the fuel cell system and its interaction with other connections such as power electronic devices, critical loads and control systems. In most fuel cell applications, fuel cell is a sub-system of a larger system; therefore, accurate electrical modeling of the fuel cell plays a significant role in studying applications of fuel cells. Previous research has highlighted the significance of dynamic and circuit modeling of PEM fuel cells based on electrochemical reactions in (Famouri & Gemmen. 2003), (Wang, Nehrir & Shaw. 2005) and, (Hernandez & Diong. 2005). Modeling of PEM fuel cells using small signal equivalent circuits are studied in (Pasricha & Shaw. 2006) and electrical circuit modeling of PEM fuel cells are presented in (Yu & Yuvarajan. 2004). Application based modeling of PEM fuel cells are presented in (Yu, Srivastava, Choe & Gao. 2006), (Grasser & Rufer. 2007) and, (Granier, Pera, Hissel, Harel, Candusso, Glandut, Diard, De Bernardinis, Kauffmann & Coquery. 2003).

To achieve the most accurate performance evaluations of the overall system in which the fuel cell is considered as a sub-system, dynamic modeling of the system is the best technique. Dynamic modeling is obtained with interpretation of the electrochemical reactions in fuel cells as mathematical equations that also express the transient conditions. Accurate transient modeling benefits the systems such as electric vehicles in which the whole design depends on the systems reaction.

The very first and most important step in modeling of the fuel cell is obtaining the equivalent circuits from the chemical equations. Furthermore, electric circuits representing these chemical reactions are carried out. This modeling approach is also used to derive the stack voltage in each cell and to illustrate its steady state and transient behavior during the load variation.

2.5.1.1 Stack Voltage

In the first step the stack voltage of a fuel cell is computed. Fuel cell open circuit voltage, based on the Nernst Equation, can be described as (Wang, Nehrir & Shaw. 2005)

$$E_{cell} = E_{0,cell} + \frac{RT}{2F}\ln\left[p_{H2}\cdot\sqrt{p_{O2}}\right] - E_{d,cell}\,, \qquad (2.5.1.1.1)$$

where E_{cell} (V) is the open circuit voltage of the fuel cell, $E_{0,cell}$ is the reference potential of the cell, $E_{d,cell}$ is the potential for the overall effect of the fuel and oxidant delay, R is the gas constant, T is the temperature (K), F is the Faraday constant, p_{H2} is hydrogen partial pressure (Pa), and p_{O2} is the oxygen partial pressure, (Pa). $E_{0,cell}$, the reference potential of the cell, is expressed as

$$E_{0,cell} = E^{o}_{0,cell} - k_E(T - 298)\,, \qquad (2.5.1.1.2)$$

where $E^{o}_{0,cell}$ is the standard reference potential at the standard state of 298 ^{0}K and 1-atm pressure. As it is shown in equations (2.5.1.1.3) and (2.5.1.1.4), at normal operating conditions, the output voltage of the fuel cell is less than the open circuit voltage of the fuel cell, E_{cell}, which is affected by the activation loss, ohmic resistance voltage drop and concentration overpotential which are represented by V_{act}, V_{ohm} and V_{conc}, respectively (all in volts). The cell and stack voltages are (Wang, Nehrir & Shaw. 2005)

$$V_{cell} = E_{cell} - V_{act,cell} - V_{ohm,cell} - V_{conc,cell}\,, \qquad (2.5.1.1.3)$$

$$V_{Stack} = N_{cell}V_{cell} = E - V_{act} - V_{ohm} - V_{conc}\,. \qquad (2.5.1.1.4)$$

Therefore, equations (2.5.1.1.1), (2.5.1.1.3) and (2.5.1.1.4) result in the output or stack voltage summarized as (Famouri & Gemmen. 2003)

$$V_{stack} = N\underbrace{\left[E_0 + \frac{RT}{nF}\ln\left(\frac{P_{H2}\sqrt{P_{O2}}}{P_{H_2O}}\right)}_{\text{Generation (Nernst Factor)}}\underbrace{-ZI - h_e - h_D}_{\text{Loss}}\right], \tag{2.5.1.1.5}$$

where V_{stack} is the stack voltage (V), N is the number of cells, E_0 is the standard state voltage (V), R is the universal gas constant, T is the operating temperature (K), n is the molar flow rate (gm-mol/sec), F is the Faraday constant, P_{H2} is Hydrogen partial pressure (Pa), P_{H2O} is water vapor partial pressure (Pa), P_{O2} is the Oxygen partial pressure (Pa), Z is the cell impedance (ohm), I is the cell current (A), h_e is the electrochemical overpotential (V) and h_D is the diffusion overpotential (V).

2.5.1.2 Oxygen and Hydrogen Conservation

The next step toward fuel cell modeling is calculating the conservation of oxygen and hydrogen. Anode's mole conservation is expressed as

$$\left(\frac{V_a}{RT}\right)\frac{dP_{H2}}{dt} = \dot{m}_{H2\_in} - (\rho_{H2}UA)_{out} - \frac{I}{2F}, \tag{2.5.1.2.1}$$

and Cathode's mole conservation as

$$\left(\frac{V_c}{RT}\right)\frac{dP_{O2}}{dt} = \dot{m}_{O2\_in} - (\rho_{O2}UA) - \frac{I}{4F}, \tag{2.5.1.2.2}$$

where V_a is the anode fuel cell volume (m^3), V_c is the cathode fuel cell volume (m^3), R is the universal gas constant, T is the operating temperature (K), P_{H2} is the hydrogen partial pressure (Pa), P_{O2} is the oxygen partial pressure (Pa), $\dot{m}_{H2\_in}$ is the input hydrogen mole flow rate, $\dot{m}_{O2\_in}$ is the input oxygen mole flow rate, ρ_{H2} is the hydrogen gas density, ρ_{O2} is the oxygen gas density (gm-mol/m^3), U is the velocity (m/sec), A is the channel flow area (m^2), I is the cell current (A) and F is the Faraday constant (Famouri & Gemmen. 2003).

2.5.1.3 Input Gas Flow Rate

The input gas flows of the fuel cell are determined as

$$\dot{m}_{in} = \rho K \Delta P = \rho U A \,, \qquad (2.5.1.3.1)$$

where ΔP is the pressure difference between humidifier and stack. Following equation can be used to determine the humidifier pressures in the anode and cathode.

$$\frac{dP_h}{dt} = \frac{RT_h}{V_h}(\dot{m}_{ih} - \dot{m}_{oh}), \qquad (2.5.1.3.2)$$

Now that the basics of the circuits are obtained, the equivalent electric circuits are presented in the next section.

2.5.2 Circuit Modeling

In equivalent circuit modeling, shown in Figure 2.5.2.1, voltage represents the pressure and current represents the mole flow. The capacitor C_1 shows the effect of the constant $\frac{V}{RT}$.

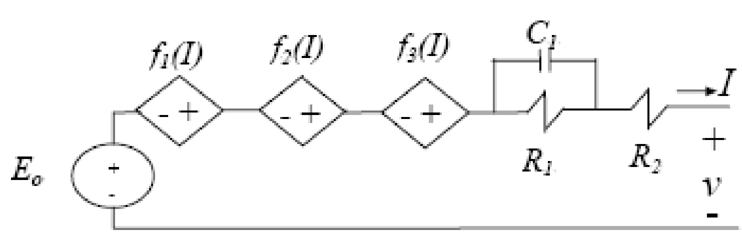


Figure 2.5.2.1, The main circuit model for fuel cell (Famouri & Gemmen. 2003).

In the circuit, Nernst factor, electrochemical overpotential and concentration (diffusion) overpotential are represented by three nonlinear current controlled voltage sources, $f_1(I), f_2(I)$ and $f_3(I)$ respectively and are expressed as

$$f_1(I) = \frac{RT}{2F}\ln\left(\frac{P_{H2}\sqrt{P_{O2}}}{P_{H2O}}\right), \tag{2.5.2.1}$$

$$f_2(I) = \frac{-RT}{2F}\ln\left(\frac{I}{I_O}\right), \tag{2.5.2.2}$$

$$f_3(I) = \frac{RT}{2F}\ln\left(1 - \frac{I}{I_{\max}}\right). \tag{2.5.2.3}$$

Figure 2.5.2.2 represents the humidifier's equivalent circuit model where the output of the circuit is the voltage of the fuel cell stack.

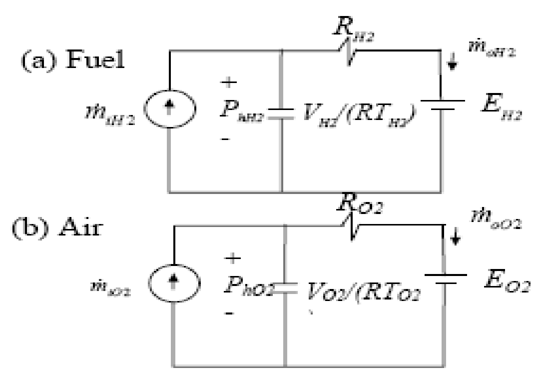


Figure 2.5.2.2, Humidifier circuit models (Famouri & Gemmen. 2003).

The input fuel and air mole rates are represented by the independent currents sources in the circuit, Figure 2.5.2.2. Figure 2.5.2.3 shows the circuit modeling for mole conservation for oxygen, hydrogen and water.

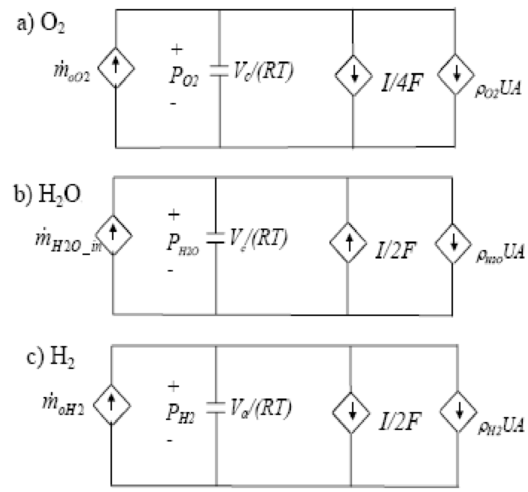


Figure 2.5.2.3, Circuit modeling for mole conservation for oxygen, hydrogen and water (Famouri & Gemmen. 2003).

Now that the equations of the modeled fuel cell system are derived and the relative circuits are obtained, the whole model of the fuel cell can be simulated. In the next section, the fuel cell model is simulated using MATLAB/Simulink, and the results are discussed.

2.5.3 PEM Fuel Cell Simulation in MATLAB/Simulink

The circuit model obtained in previous section is completely modeled in this part using MATLAB/Simulink. The input hydrogen and oxygen mole flow rate is presented by a 0-5 volts input in the model. Number of cells in the model is $N = 60$ and the channel flow area is $19.4\,cm^2$. The output is the fuel cell stack voltage which is connected to a load where in the simulation the load is considered purely resistive. The V-I characteristic curve of this fuel cell is shown in Figure 2.5.3.1. As it can be seen in this figure, the V-I characteristic of the fuel cell model is as expected and similar to that of a real fuel cell. The activation, ohmic and concentration losses can be seen in the V-I characteristic of the fuel cell model.

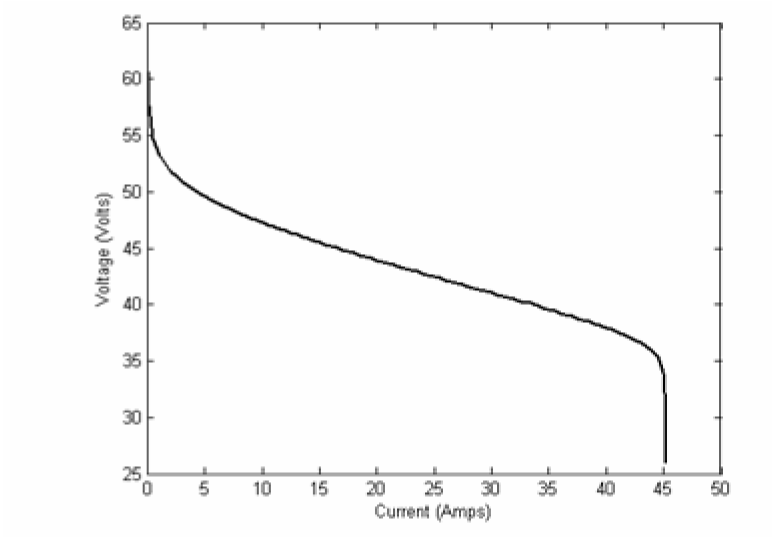


Figure 2.5.3.1, V-I characteristic curve of the fuel cell model in Matlab

The output of the fuel cell (the stack voltage) variation at full input flow rate is shown in Figure 2.5.3.2.

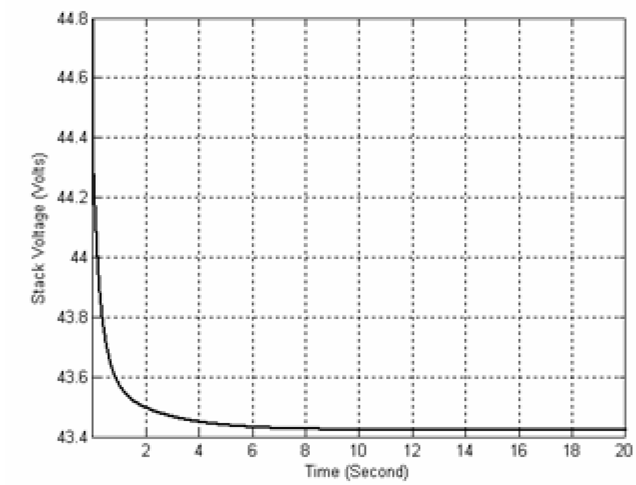


Figure 2.5.3.2, The output of the fuel cell at 100% input flow rate

The size of the fuel cell, which is defined by the output power of the fuel cell, is proportional to the channel flow area and the fuel inlet capacity of the fuel cell. Another parameter which affects the output power of the fuel cell is the number of the cells.

The V-I characteristic curve of a fuel cell with a double increase in size than that of the first fuel cell is shown in Figure 2.5.3.3.

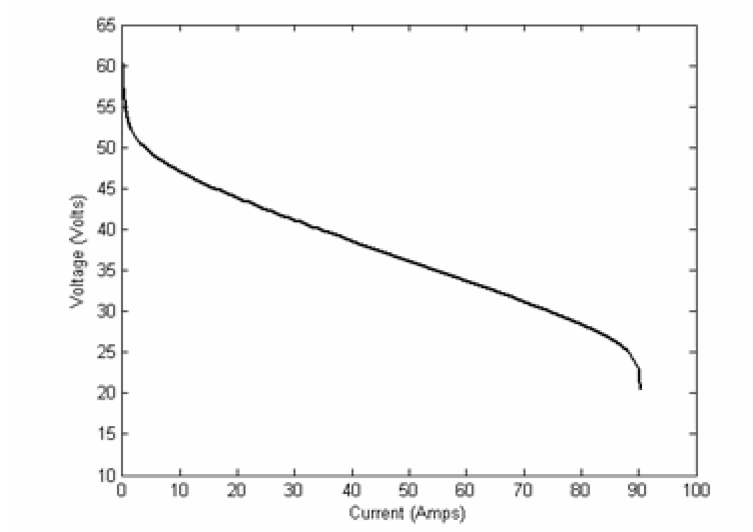


Figure 2.5.3.3, V-I characteristic curve of the larger fuel cell model in Matlab

Figure 2.5.3.4 shows the V-I characteristic curve of both fuel cells in one graph.

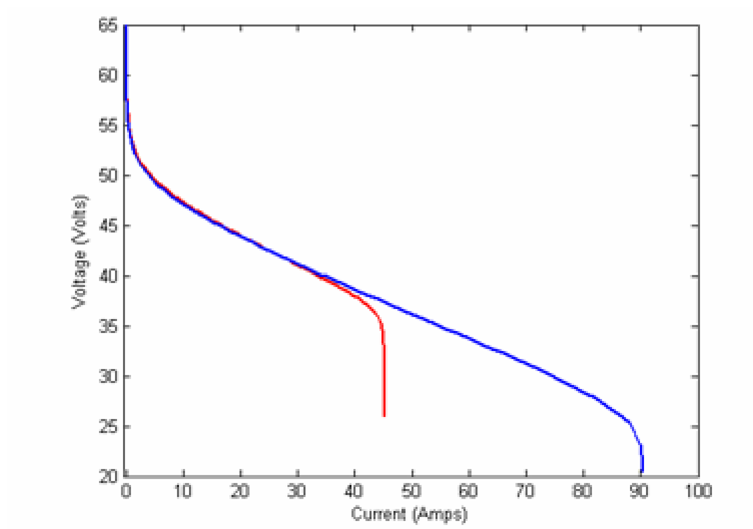


Figure 2.5.3.4, V-I characteristic curve of the large and small fuel cell models

Dynamic modeling of PEM fuel cells considers more details such as power and design parameters in application based analysis of these devices.

As it was shown, the fuel cell model demonstrates very similar results to the actual fuel cell system. Interested readers can find more information on the fuel cell model in Simulink in appendix A.

2.6 Drawbacks of Fuel Cell Power Sources

High prices of fuel cells can be lowered in mass productions; however, there are problems in their application and fueling which are described in this section.

The hydrogen fuel is produced from fossil fuels, mostly from natural gas, which is one of the main issues in hydrogen production which itself still demands for more hydrocarbons. Hydrogen can be easily obtained from electrolyzing of water in the solar energy converters.

Another drawback of hydrogen fuel cell is the hydrogen storage. Hydrogen gas is very explosive and dangerous; therefore, safe storage and operations should be carefully scrutinized. Any hydrogen leakage should be prevented in the design. To store only 3 kg of pressurized hydrogen in a safe tank, the tank itself would weight 400 kg which makes it very heavy and not economic. On the other hand, liquidizing hydrogen in low temperatures requires high tech facilities and is costly. The technology should overcome these hurdles to see fuel cell vehicles on roads (Columbia University Web Page) & (Masstech Web Page).

Chapter 3,

Electric & Hybrid Electric Vehicles

3.1 Introduction

Nowadays, imagining life without transportation apparatus of all kinds such as cargo trucks, trains, planes, and personal vehicles is almost impossible. Personal vehicles made short and long trips possible for summer vacations, daily shopping and work trips. Most of these vehicles made use of internal combustion engines to make fast-start and ease of processing fuels. The main questions remaining for today are, how efficient these engines are and what environmental impacts these engines can have. Certainly, today's problems that the earth is struggling with have been caused by excessive and inefficient consumption of fossil fuels. Therefore, the need for an alternative fuel in lieu to the fossil versions is heavily sensed. Electricity can be generated from new and renewable energy resources and can be somewhat independent from hydrocarbons. If this source of energy is accessible enough to be used in vehicles, that can reduce a high percentage of air pollutant fossil energy consumed in vehicles every day. The first electric vehicle was built in 1881 with the help of electric motor propulsion. The source of energy was a battery unit equipped in the vehicle and could only provide enough energy for short distance trips. Brake Energy harvesting technique could provide more regenerative power for the vehicle and longer the trips since 1897. This technique becomes even more efficient if the driving cycle includes frequent stop-starts such as urban driving cycle.

More acceleration power, flexibility and ease of use made gasoline vehicles popular compared to electric vehicles. Electric vehicles, on the other hand, are clean, vibrate less, generate low noise pollution and are manufactured mechanically simple. However, their driving range is limited for the same given energy content. Batteries in electric vehicle weigh more than the liquid fuel in traditional vehicles. The main hurdle in fast development of electric vehicles is the battery storage technology. Almost all different types of batteries have lower energy density than liquid fuels. High performance batteries are required in electric vehicles to meet the fast acceleration power demands.

This chapter describes the application and benefits of electric vehicles, their dynamics and road behavior. Different configurations of series and parallel hybrid systems are described.

3.2 Vehicle Fundamentals

Based on Newton's second law, the equation for vehicle acceleration can be written as

$$\frac{dV}{dt} = \frac{\Sigma F_t - \Sigma F_{tr}}{\delta M}, \tag{3.2.1}$$

where V is the speed of vehicle, ΣF_t is the total tractive effort of vehicle, ΣF_{tr} is the total resistance, M is the total mass of the vehicle and δ is the mass factor which includes the effect of the rotating components in the power train. Therefore, considering the Newton's second law, the maximum power required (power command) for the vehicle to reach to a certain speed and maintain that speed considering the rolling resistance is obtained as

$$P_{\max} = \frac{v}{\eta 1000}\left(Mg\mu\cos(\theta) + 0.5\rho_a C_D A_f v^2 + Mg\sin(\theta) + M\frac{dv}{dt}\right), \tag{3.2.2}$$

where v is the velocity of the vehicle $\left(\frac{m}{s}\right)$, η is the motor efficiency, M is the vehicle's mass (kg), g is the gravity acceleration $\left(9.81\frac{m}{s^2}\right)$, μ is the coefficient of rolling resistance, ρ_a is the air mass density $\left(1.202\frac{Kg}{m^3}\right)$, C_D is the aerodynamic drag coefficient of the vehicle, A_f is the front area of the vehicle $\left(m^2\right)$, θ is the grade of the road and P is the power in Kw.

The total resistance, ΣF_{tr}, for the vehicle is composed of tire rolling resistance, aerodynamic drag and uphill resistance to stop the vehicle from movement. In (3.2.2), $\left(0.5\rho_a C_D A_f v^2\right)$ represents the aerodynamic drag, $(Mg\mu\cos(\theta))$ represents the rolling resistance, $(Mg\sin(\theta))$ represents the grading resistance and $\left(M\frac{dv}{dt}\right)$ represents the vehicle's acceleration (Ehsani, Gao, Gay, Emadi. 2005). Figure 3.2.1 shows the forces entered to a vehicle on the road with angle α. Each of these forces is described in details in the following sections.

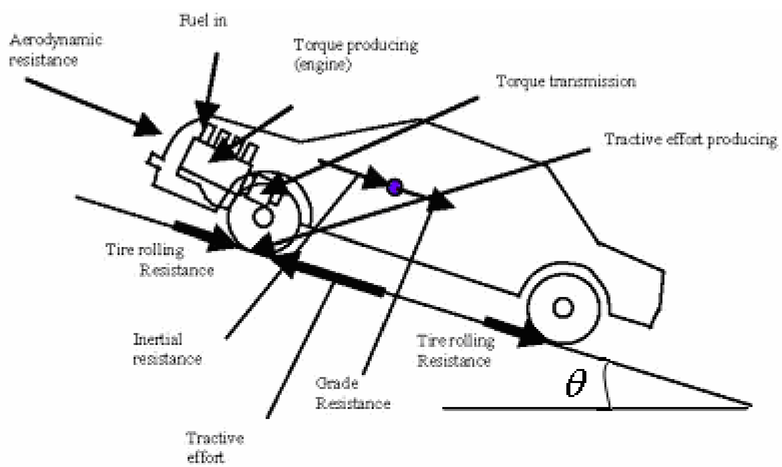


Figure 3.2.1, Forces acting on a vehicle (Abedini & Nasiri. 2006)

3.2.1 Rolling Resistance

The deformations of the wheel or tire in addition to the deformation of the ground are the main reasons of the rolling resistance. The primary cause of rolling resistance is the hysteresis effect in tire materials, which varies while rolling on different roads. Table 3.2.1.1 shows examples of rolling resistance coefficients on various roads (Wikipedia Web Page-Rolling Resistance). The effects of rolling resistance on the vehicle are heat and sound.

Table 3.2.1.1, examples of rolling resistance coefficients on various roads

Rolling resistance coefficient	Description
0.001 to 0.0025	Train steel on steel with tatz-mounted electric traction. 0.001 is considered to be the theoretical limit achievable.
0.0015 to 0.0025	Low resistance tubeless radial tire used for solar cars/eco marathon cars as specially made by Michelin
0.005	Tram-rails standard dirty with straights and curves
0.0055	Typical BMX bicycle tire used for solar cars
0.006 to 0.01	Low rolling resistance car tire on a smooth road and truck tires on a smooth road
0.010 to 0.015	Ordinary car tires on concrete
0.020	Car on stone plates
0.030	Car/bus on tar/asphalt

3.2.2 Aerodynamic Drag

The resistance to the movement of the vehicle caused by the surrounding air is called the aerodynamic drag. Aerodynamic drag is a function of the vehicle speed, vehicle frontal area, shape of the vehicle and air density. In equation 3.2.2, aerodynamic drag is shown by term $\left(0.5\rho_a C_D A_f v^2\right)$. Table 3.2.2.1 shows the aerodynamic coefficient, C_D, for a few types of vehicle body shapes (Ehsani, Gao, Gay, Emadi. 2005).

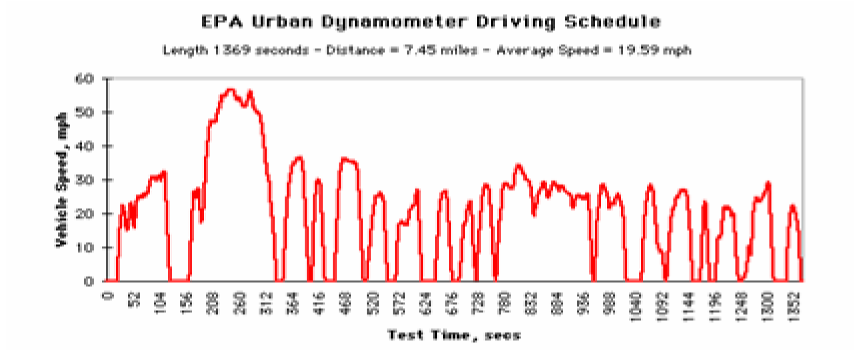
Table 3.2.2.1: Aerodynamic coefficient for different vehicle body shapes

Vehicle type	Aerodynamic coefficient
Open convertible	0.5-0.7
Van body	0.5-0.7
Ponton body	0.4-0.55
Wedge-shaped body; headlamp and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3-0.4
K-shaped (small breakway section)	0.23
Optimum streamlined design	0.15-0.20
Trucks, road trains	0.8-1.5
Buses	0.6-0.7
Streamlined buses	0.3-0.4
Motorcycles	0.6-0.7

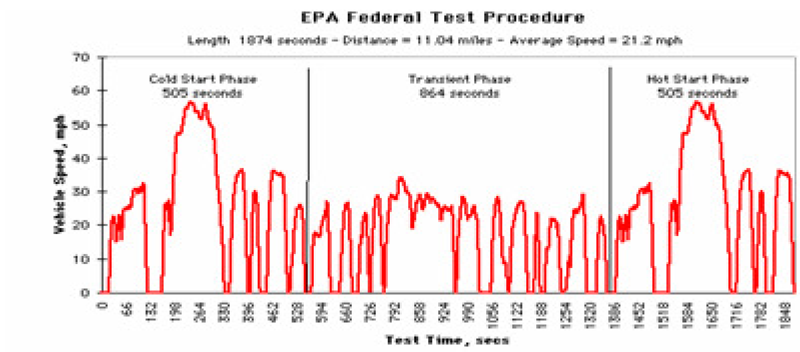
3.3 Driving Cycle

A series of data representing the speed of a vehicle versus time is called a "Driving Cycle". Different countries have published and produced driving cycles in order to evaluate the performance of their vehicles in different aspects. For instance, emission test is performed on dynamometer. Driving cycles are also used for vehicle simulations. Driving cycles of the FTP (federal Test Procedure Revisions) are shown below (Wikipedia Web Page-Driving Cycle), (EPA Web Page).

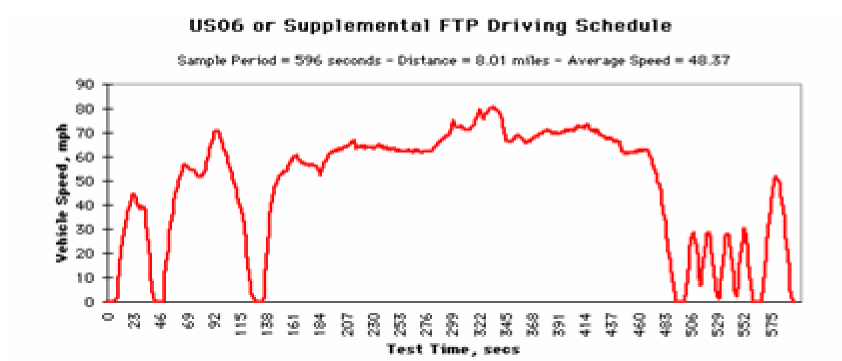
City or Urban driving Test (FTP75) represents urban driving conditions in which a vehicle is started with the engine cold and driven in stop-and-go rush hour traffic. The driving cycle for the test includes idling, and the vehicle averages about 20 mph. Figure 3.3.1 shows different driving cycles and their speed profile requirement. Figure 3.3.1.a shows the urban driving cycle which is also used in this research for test of the electric vehicles. Figure 3.3.1.b is the actual test of the vehicle in urban driving cycle which includes cold and hot start conditions. 3.3.1.c is the supplement of the urban driving condition to simulate the highway driving conditions.



(3.3.1.a), EPA Urban Dynamometer Driving Schedule (FTP-75)



(3.3.1.b), EPA Federal Test Procedure



(3.3.1.c), US06 or Supplemental FTP Driving Schedule

Figure (3.3.1), a. Urban Driving Cycle, b. Actual test of Urban Driving Cycle, c. Highway Driving Cycle

3.4 Electric Vehicle

Electric vehicles, as mentioned earlier, make use of electric energy to provide enough traction for the vehicle. Different types of electric sources such as chemical batteries, ultracapacitors, fuel cells and flywheels are used as energy sources in electric vehicles. Electric vehicles also make use of an electric motor which has different designs depending upon the application. As mentioned before, electric vehicles have many advantages over the internal combustion engine vehicle. For instance, they do not consume fossil fuel, operate quietly, do not emit pollutants and are efficient (Ehsani, Gao, Gay, Emadi. 2005), (Wikipedia Web Page-Electric Vehicle).

First designs of electric vehicles just removed the gas engine and fuel tanks and replaced them with electric motors and battery units. This configuration is heavy and inefficient in general. The single type power storage provides limited power to the vehicle and limits the driving distance. Battery unit should provide all the energy which increases the size of the battery and consequently the weight. Figure 3.4.1 shows this type of electric vehicle configuration.

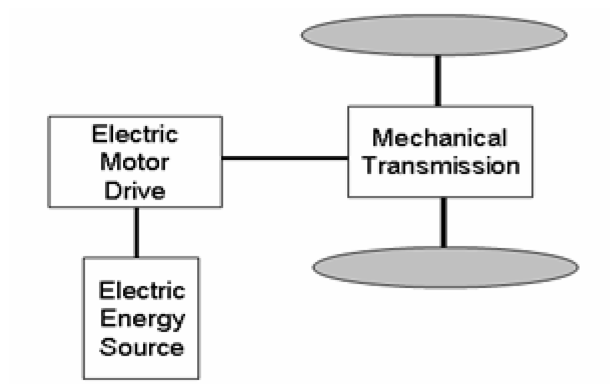


Figure 3.4.1, Old electric vehicle power train

As the figure shows, the power train system contains one source of energy (battery in this case), electric motor and mechanical transmission. In order to improve the efficiency of the system several configurations have been introduced. Figure 3.4.2 shows the general configuration for a modern electric vehicle, (EV). The power train generally consists of three units namely as:

i. Electric propulsion unit
ii. Energy source unit
iii. Auxiliary unit

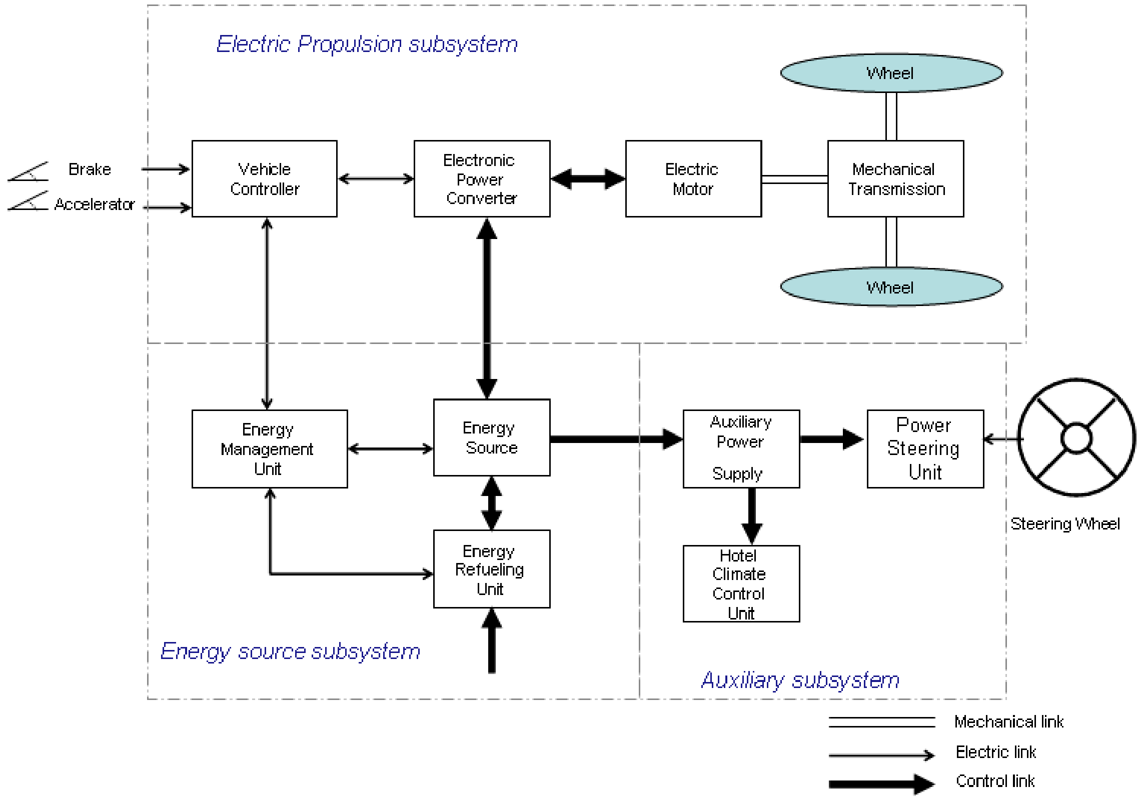


Figure 3.4.2, General EV configuration (Ehsani, Gao, Gay, Emadi. 2005)

The electric propulsion unit consists of the vehicle controller, power electronic converter, electric motor, mechanical transmission and wheels. The power converter receives the interfaced control signals from the brake and accelerator. The controller manages the power flow to the electric motor from the energy source and allows power regeneration from the brake conditions. This can boost the stored energy in the battery units and extends the battery charge while driving. Higher efficiency operations are obtained in this case.

The energy source unit contains a source of energy, energy refueling unit and energy management unit. The energy management unit and vehicle controller are both involved with the process of regenerative braking.

The auxiliary unit contains the power steering unit, auxiliary power supply and hotel climate control unit. The auxiliary units in electric vehicles are fed by the auxiliary power unit.

These units can connect together in numerous topologies and provide a rich system configuration in electric vehicles (Ehsani, Gao, Gay, Emadi. 2005).

Battery powered electric vehicles (EV) provide some advantages to protect the environment; however, their inefficient design, poor performance of batteries and low energy content required new designs to overcome these problems.

3.5 Hybrid Electric Vehicle

As mentioned earlier, relying upon one single source of power, mainly battery pack, has made the design inefficient. To overcome this problem, other sources of energy are required to provide enough energy to the system in different driving conditions. Hybrid vehicles in this regard make use of two or more power sources, one as the primary power source and the others as the secondary power sources. If a hybrid vehicle makes use of electric power sources and energy converters (electric power train) it is called Hybrid Electric Vehicle (HEV). Hybrid electric vehicles not only possess the advantages of electric vehicles but also they can overcome the poor characteristics of the electric vehicles. They have shown a definite better fuel economy and lower emissions compare to internal combustion engines. Brake power regenerative system can also contribute to the efficiency increment of the vehicle.

In a hybrid vehicle, the drive train usually consists of at most two power trains. Each of these power trains can either provide tractions to the vehicle or be used to harvest the brake power or both. Therefore, several combinations of these power trains can provide various system topologies with different performances. For instance they can both provide traction power or switch alternatively to harvest the regenerative energy (Ehsani, Gao, Gay, Emadi. 2005). The main topologies in hybrid electric vehicles are explained in following sections.

3.5.1 Series Hybrid Electric Drive Trains

In a series hybrid electric drive train, there exist two power sources and an electric traction motor. Battery unit is one of the power sources while another source can be provided by the main engine which can be an internal combustion engine. This engine drives an electric generator which can charge the battery unit and power up an electric motor at the same time. In case of heavy loads, the electric motor is fed electrically both from the batteries and the generator. Figure 3.5.1.1 shows the common configuration of hybrid series drive train (Wikipedia Web Page-Hybrid Vehicle Drivetrain).

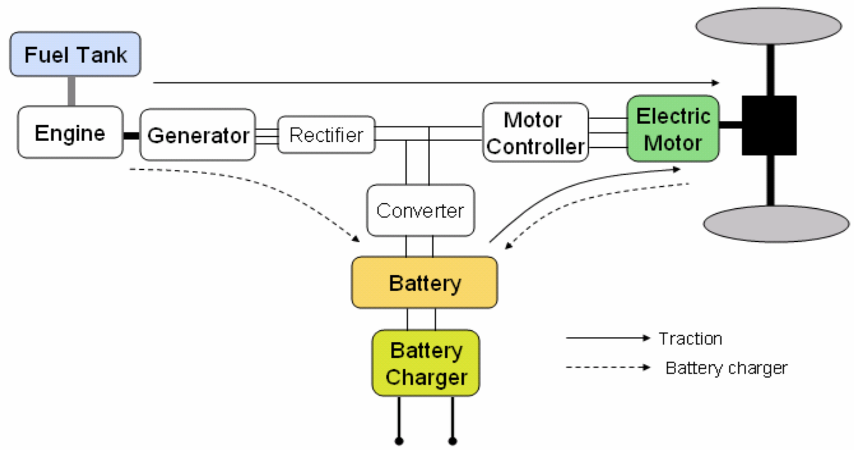


Figure 3.5.1.1, Common topology of hybrid series electric drive train (Wikipedia Web Page-Hybrid Vehicle Drivetrain)

In this configuration, there is no direct mechanical connection between the internal combustion engine and the wheels. The engine runs at its optimal point all the time, feeding the motor and charging the battery and therefore, low fuel consumption and high efficiency are main advantages of this method.

In series hybrid electric drive configuration the engine is decoupled from the traction system, therefore, it can be tuned to operate at the maximum efficiency all the time and it reduces the control system's complexity. In addition, since the speed of electric motors can be controlled continuously, there is no need to have a complex multi-gear transmission system.

In this configuration, since the energy is converted from mechanical engine to electrical and to mechanical the resultant system might have low efficiency and this will increase the loss in the system. The vehicle requires a powerful traction motor to provide enough acceleration and power to the vehicle.

3.5.2 Parallel Hybrid Electric Drive Trains

As mentioned earlier, the power trains can join together and provide a parallel source of power for the traction system. This allows a direct connection of the engine to the traction system which was avoided in series configuration. The electric motor can also contribute to the power traction system in several configurations, all of which require accurate control systems to provide an efficient overall system. These combinations provide torque-coupling, speed-coupling, and torque and speed coupling in parallel hybrid electric drive trains.

At low speeds, where Internal Combustion Engine (ICE) is not efficient, the electric motor can solely provide enough traction for the vehicle. The internal combustion engine is connected to the traction system while the electric motor can be used as a generator to charge the batteries at high speeds, noting that ICE is more efficient at high speeds. In other power/speed combinations both ICE and electric motor can be used to provide an efficient energy for the vehicle (Wallén. 2004). Figure 3.5.2.1 shows the common topology of a hybrid parallel electric drive train.

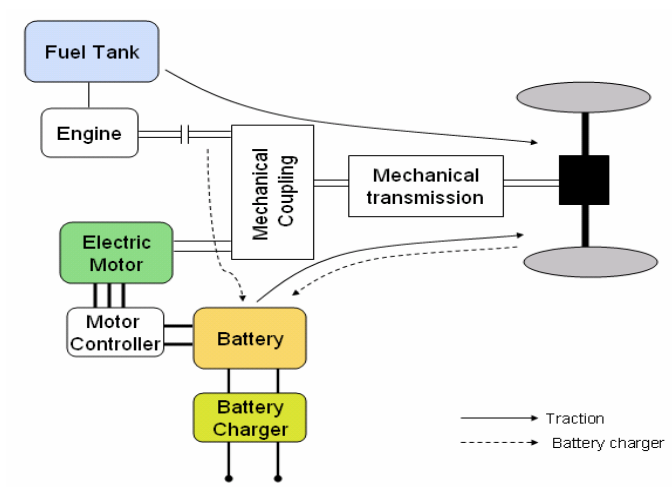


Figure 3.5.2.1, Common topology of hybrid parallel electric drive train (Ehsani, Gao, Gay, Emadi. 2005), (Wikipedia Web Page-Hybrid Vehicle Drivetrain)

In parallel hybrid power train, at each time instant, the most efficient operating point of ICE and electric motor can be selected so that the whole system is in the best operating condition. Parallel configuration for hybrid electric vehicle has the lowest loss in comparison with other topologies of hybrid electric vehicles (Wallén. 2004).

3.5.3 Series-Parallel Hybrid Electric Drive Trains

In previous sections, distinctive designs of series and parallel were explained. A possible combination of these techniques together provides a powerful and efficient design for hybrid electric vehicles called series-parallel hybrid electric vehicle. Figure 3.5.3.1 shows the common topology of hybrid parallel-series electric drive train. This configuration has the potential of having the advantages of both series and parallel configurations. However, it is relatively more expensive than the former configurations (Emadi, Rajashekara, Williamson & Lukic. 2005) In the parallel-series power train, two main configurations, among different possible configurations of electric motor and internal combustion engine, are electric-heavy and engine-heavy configurations. In electric-heavy configuration, the electric motor is more active for propulsion in comparison with the internal combustion engine. The same concept is true for the engine-heavy configuration whereas the internal combustion engine is more active than electric motor for propulsion. In both electric-heavy and engine-heavy groups, the electric motor is used at the start while the engine is off. For the engine-heavy group, during the normal driving cycles, the engine propels the vehicle while in same case for the electric-heavy group the electric motor propels the vehicle. During acceleration both electric motor and the engine are used to provide the required power for the vehicle in either groups. In case of braking, the electric motor acts as a generator to charge the battery in regenerative braking conditions (Wallén. 2004).

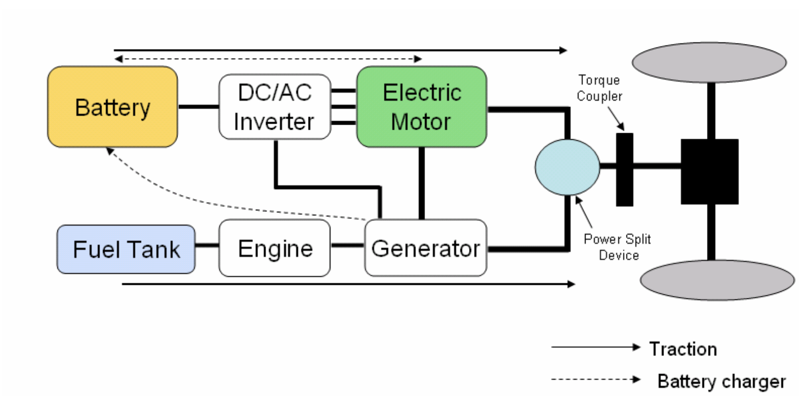


Figure 3.5.3.1, Common topology of hybrid parallel-series electric drive train (Emadi, Rajashekara, Williamson & Lukic. 2005).

3.6 Conclusion

As mentioned earlier in this chapter, the electric vehicles are a strong alternative for internal combustion engine vehicles. They bring the advantage of clean energy consumption and result in higher efficiency applications. They require additional source of power to produce electricity in the system and run electric motors. The electric energy sources are mainly battery units, on board generators and motor/generators. Other sources of energy can be found that provide cleaner energy and do not weight as much as batteries. Fuel cells are a good replacement of heavy generators and battery units. In the next chapter, fuel cells are applied in the vehicles to generate electricity. Different combination of these devices and electric motor or internal combustion engine are described and developed for efficiency improvements.

Chapter 4,

Fuel cell vehicle

4.1 Introduction

Recent advancements in fuel cell technology have made them suitable candidates for portable applications and specifically in vehicles. Electric vehicles take the most advantage of fuel cells in different configurations. They bring the advantage of longer driving range compare to battery-powered vehicles and increase the performance of the system by providing fuel-economy configurations. Electric vehicles use fuel cells either as the only source of energy or they are connected to a backup source of power such as battery or ultracapacitors to configure non-hybrid or hybrid electric vehicles respectively. Configuration and characteristics of these vehicles are investigated in this chapter.

4.2 Non-hybrid Fuel Cell Vehicle

Electric vehicles that use fuel cells in their power train are often called fuel cell vehicles. As mentioned earlier, if fuel cells are the only source of power in the vehicle the configuration is a non-hybrid fuel cell vehicle. This vehicle has a fuel cell to provide electric power, a DC/DC convertor to boost up the low output voltage of the fuel cell and an inverter to feed the required waveforms to the electric motor. Figure 4.2.1 shows schematic of a non-hybrid fuel cell vehicle. The fuel cell can provide a range of power in minimum $P_{fc-\min}$ and maximum P_{fc-Max}. This range of power can also be controlled by the power electronic converters in the vehicle to obtain a faster response to the command. In different driving cycles the fuel cell is also controlled to lower the fuel consumption. Like other power sources, fuel cells have an optimum operating point that generates maximum efficient power and increases the fuel-economy. The best design is the one that powers up the system while maintaining the optimal operating point of the fuel cell. The power demand has a huge impact on operation of the fuel cells. To meet the demand in non-hybrid fuel cell vehicles, the nominal power of the fuel cell is chosen at the maximum possible power of the vehicle. Therefore, depend upon the driving conditions, the fuel cell may not necessarily operate in optimal conditions, specifically when it is operating in urban driving cycle while lower loads are required from a huge fuel cell.

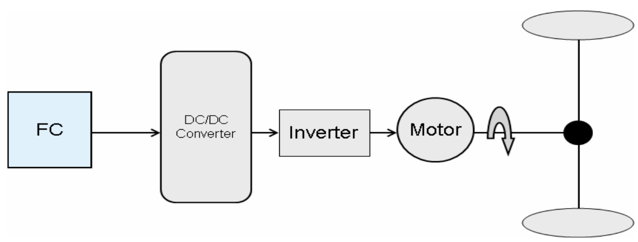


Figure 4.2.1, Non-hybrid Fuel cell vehicle.

4.2.1 Control Strategy

The power management algorithm for this type of vehicle is shown in Figure 4.2.1.1. In this algorithm P_{comm} stands for the command power (also known as the maximum required power P_{max} as (3.2.2)), P_{fc-Max} is the rated (maximum) power of the fuel cell, $P_{fc-\min}$ is the minimum power of the fuel cell. This algorithm explains a comparison-based technique to determine the command power according to the fuel cell capabilities. If the power is out of the range, it is limited to the fuel cell power capabilities, and if it is in range the command power is the power required from the fuel cell.

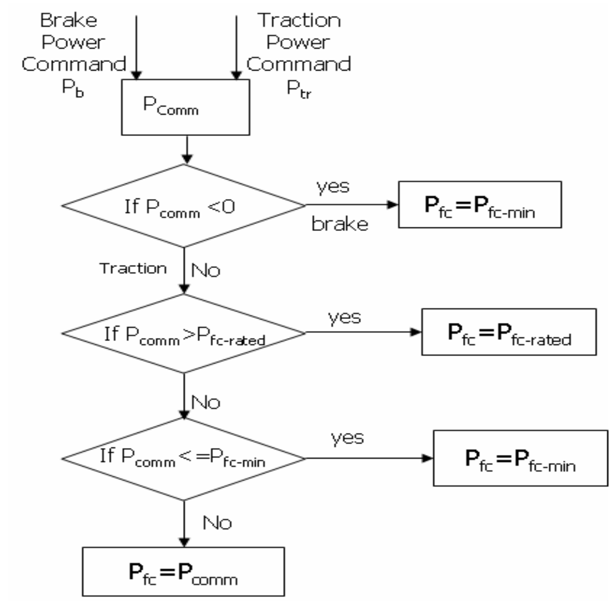


Figure 4.2.1.1, power flow algorithm for the non-hybrid fuel cell vehicle

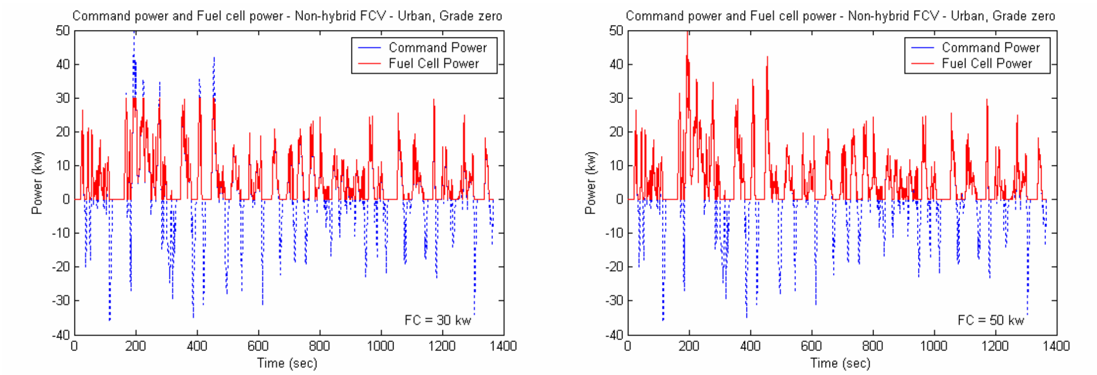
To simulate the control algorithm for different driving cycles, an Sport Utility Vehicle (SUV) with parameters listed in Table 4.2.1.1. is chosen and equipped with fuel cell and electric traction system as shown in Figure 4.2.1.

Table 4.2.1.1: Simulated vehicle parameters (Amrhein & Krein. 2005)

Parameter	Value	Unit
Vehicle Mass, M	1800	Kg
Gravity, g	9.81	$\frac{m}{s^2}$
Rolling Resistance Coefficient, μ	0.008	
Air Mass Density, ρ_a	1.202	$\frac{Kg}{m^3}$
Aerodynamic Drag Coefficient, C_D	0.26	
Front Area, A_f	2.8	m^2

Figure 4.2.1.2 shows the simulation results for the non-hybrid fuel cell vehicle in standard FTP-75 urban driving cycle (grade zero). The command power and the power provided by the fuel cell are overlaid in each graph (Figure 4.2.1.2) to facilitate the fuel cell and command power required in each case. As it is shown in Figure 4.2.1.2, (a), a 30 kW fuel cell

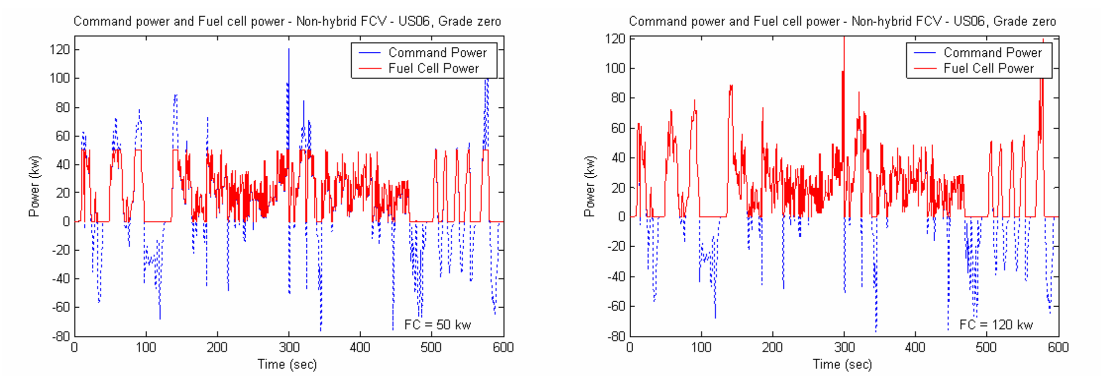
is incapable of providing enough power for the vehicle to meet the demand. However, it mainly operates at a high percentage of its nominal power. A size increment to 50 kW will provide enough power for the vehicle and lowers the loading percentage on the fuel cell. This technique shows a low efficiency in power generation of fuel cell and is generally not a recommended topology. The power generation and command signals are shown in Figure 4.2.1.2, (b).



(a) (b)

Figure 4.2.1.2, Command power and fuel cell power for non-hybrid fuel cell vehicle in urban driving cycle for two sizes of 30 (a) and 50 kW (b) fuel cell.

Highway driving cycle US06 demands even higher powers from the fuel cell, such that the recently increased size of fuel cell falls short in providing enough power for the vehicle. Figure 4.2.1.3 (a) shows this fact, where fuel cell power do not match the power command. Increasing the size of the fuel cell to 120 kW will provide enough power in the vehicle however this drastically lowers the loading percentage of the fuel cell if used in urban driving cycle. Efficiency analysis of low loading percentage is provided in chapter 5.



(a) (b)

Figure 4.2.1.3, Command power and fuel cell power for non-hybrid fuel cell vehicle in US06 highway driving cycle for two sizes of 50 and 120 kW fuel cell

In general, application of a fuel cell in non-hybrid fuel cell vehicles puts the device in non-optimum operating conditions and results in poor fuel economy. Lowering the loading percentage is the main cause of lowering the system's efficiency. It is not fuel-economic to increase the size of fuel cell to meet some peak power demands. Therefore, other energy sources are required to meet the transient loads and lower the demand on the fuel cell.

4.3 Hybrid Fuel Cell Vehicle

Fuel cell vehicles are equipped with a fast response source of power to compensate for transient conditions, therefore, they are called hybrid fuel cell vehicles. Figure 4.3.1 shows a typical schematic of a hybrid fuel cell vehicle. Schematic of a hybrid fuel cell vehicle (shown in Figure 4.3.1) consists of a fuel cell, a backup or storage source of power, and power electronic blocks as that of non-hybrid. The backup source of power can be an ultracapacitor or battery for high energy density and fast response. The structure and modeling of the battery and ultracapacitors are illustrated in the next section.

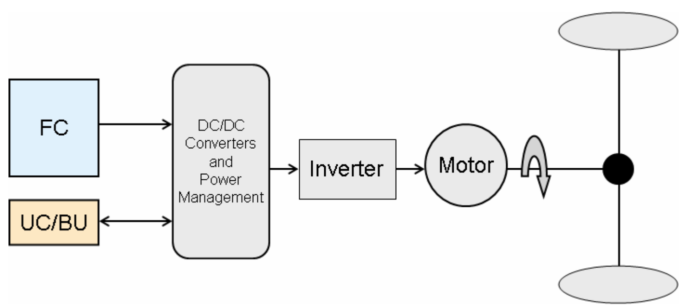


Figure 4.3.1, Traditional hybrid fuel cell vehicle topology

4.3.1 Storage Devices

Two common types of storage devices that are applicable in electric vehicles are ultracapacitors and battery units. These devices can store high amount of energy and release it in short time. Each of these devices has their own dynamical behavior. Ultracapacitors have high performance while battery units provide large storage capability. Specific characteristics of these devices are described in the following.

4.3.1.1 Ultracapacitor

Ultracapacitor or supercapacitor is a storage device known for its high energy density that makes it suitable in electric vehicles. They can store the energy harvested from regenerative braking and assist in providing power to the vehicle during transient conditions such as acceleration and hill climbing. Using ultracapacitors in regenerative braking enhances the fuel efficiency and saves energy specifically in urban driving cycle where the vehicle makes frequent start-stops. Ultracapacitor is the only storage device that can save great amounts of energy and release it quickly for acceleration. Ultracapacitor has the ability to store electrostatic energy up to 20 times more than usual capacitors. However, high performances are obtained at specific powers. It can be charged and discharged numerous times without any change in its performance. Figure 4.3.1.1.1 shows an ultracapacitor module, its schematic and an individual ultracapacitor cell (Dixon & Ortlizar. 2002), (NREL Web page).

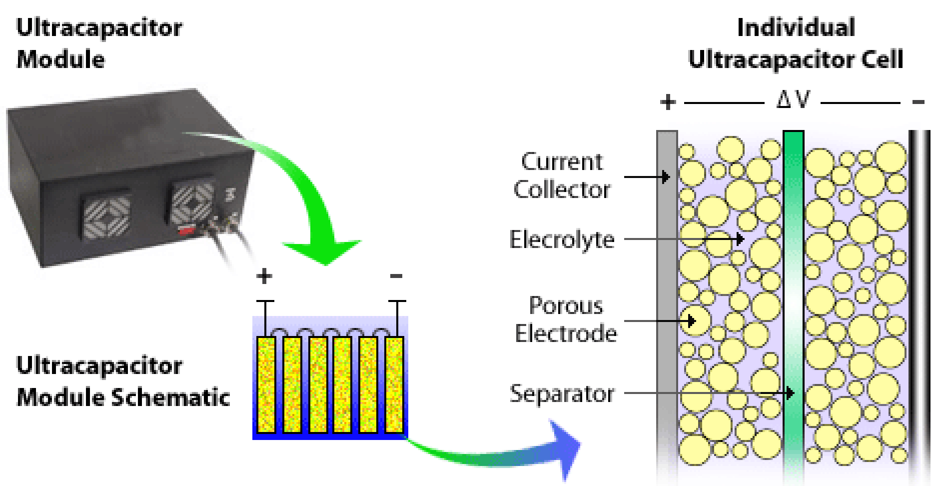


Figure 4.3.1.1.1, ultracapacitor module, its schematic and an individual ultracapacitor cell (NREL Web page)

Terminal voltage of ultracapacitors at various current rates is a good measure of performance of an ultracapacitor. The equivalent circuit of an ultracapacitor is shown in Figure 4.3.1.1.2 with three parameters to model electric potential V_C, series resistance R_s, and dielectric leakage resistance R_L and C the capacitance of an ultracapacitor.

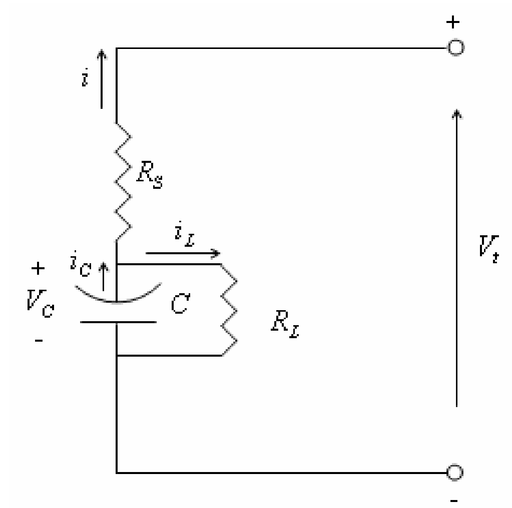


Figure 4.3.1.1.2, Equivalent circuit for Ultracapacitor

The terminal voltage V_t is expressed as

$$V_t = V_C - iR_S \, . \qquad (4.3.1.1.1)$$

Moreover, the electric potential of a capacitor is obtained as

$$\frac{dV_C}{dt} = -\left(\frac{i + i_L}{C}\right), \qquad (4.3.1.1.2)$$

and i_L as,

$$i_L = \frac{V_C}{R_L}. \qquad (4.3.1.1.3)$$

Therefore based on the above equations, the analytical solution for V_C can be found as

$$V_C = \left[V_{C0} \int_0^t \frac{i}{C} e^{t/CR_L} dt \right] e^{t/CR_L} , \qquad (4.3.1.1.4)$$

where i is the discharge current and a function of time. This equation shows a high voltage drop in large discharge currents (Ehsani, Gao, Gay, Emadi. 2005).

4.3.1.2 Battery Units

Electrochemical batteries, or generally named battery units are energy storage devices widely used in hybrid electric vehicles. Batteries convert chemical energy into electrical energy in small cells. Each cell contains two electrodes that are placed into an electrolyte. Hybrid electric fuel cell vehicles use different types of batteries such as conventional lead acid, lithium-ion, propulsion and advanced lead acid batteries known as valve regulated lead acid (VRLA) (Ehsani, Gao, Gay & Emadi. 2005), (NREL Web Page), (Burke. 2007). Figure 4.3.1.2.1 shows a battery module and its schematic in an individual battery cell (NREL Web Page).

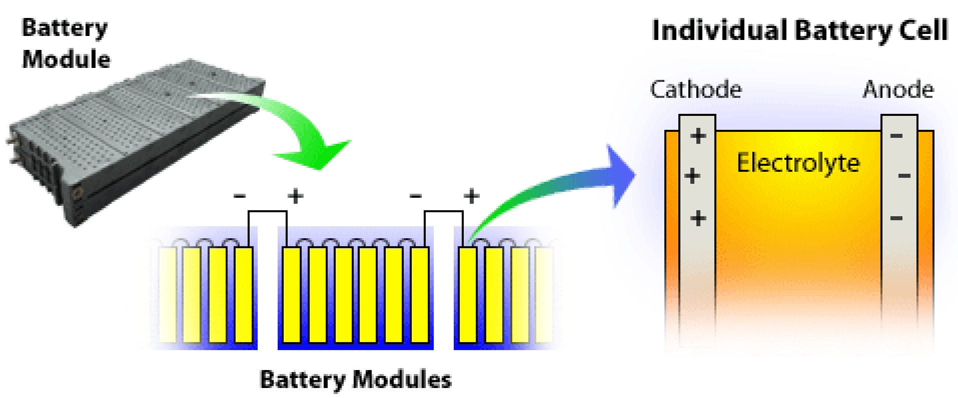


Figure 4.3.1.2.1, battery module, its schematic and an individual battery cell (NREL Web page)

Propulsion batteries are made of high energy density material nickel-Metal Hydride (NiMH) and are used for long cycles (NREL Web Page).

Battery and ultracapacitors are combined to provide a high-performance large-capacity device which requires low maintenance and replacement costs of the battery and extends the life of the battery. This can also reduce the size of the battery and provide more energy for the vehicle during high peak powers. This combination may be costly since it requires additional DC/DC power electronics in the system (NREL Web Page).

4.3.2 Control Strategy

The control algorithm for a hybrid fuel cell vehicle is designed to make use of an ultracapacitor or battery in peak or transient conditions. In "hybrid" mode of operation both fuel cell and UC/BU provide the power demand.

During acceleration three possible conditions are:

Case a), when command power is in the range of fuel cell

Case b), when command power is less than $P_{fc-\min}$

Case c), where command power is larger than P_{fc-Max}

Energy level of the battery also needs to be considered in the algorithm to charge or discharge of the battery. When the stored energy is high enough, the battery is in service and can provide energy to the system, but when the storage is below the minimum level then the battery needs to be recharged. The control algorithm for hybrid fuel cell vehicles is shown in Figure 4.3.2.1 (Gao & Ehsani. 2001), where P_{comm} is the command power, P_{fc-Max} is the rated power of the fuel cell, $P_{fc-\min}$ is the minimum power of the fuel cell, $P_{Decharge}$ is the power provided by storage device during traction, P_{Charge} is the recharging power of the storage device, E is the energy level of the storage device, $E_{\min}$ is the minimum acceptable level of energy in the storage device and P_{fc} is the power provided by the fuel cell.

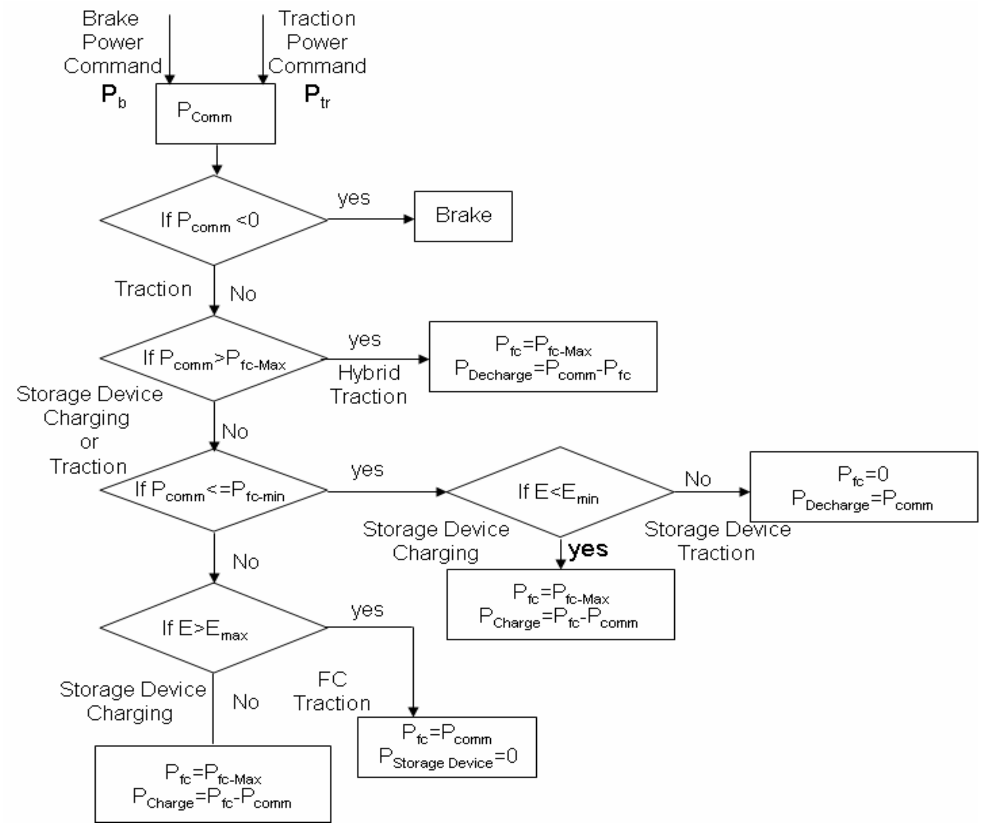
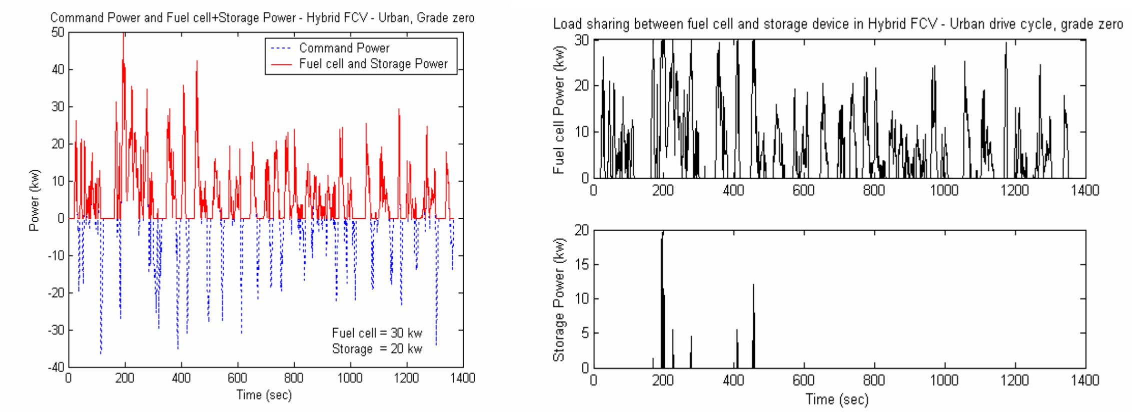


Figure 4.3.2.1, Control algorithm for hybrid fuel cell vehicle (Gao & Ehsani. 2001)

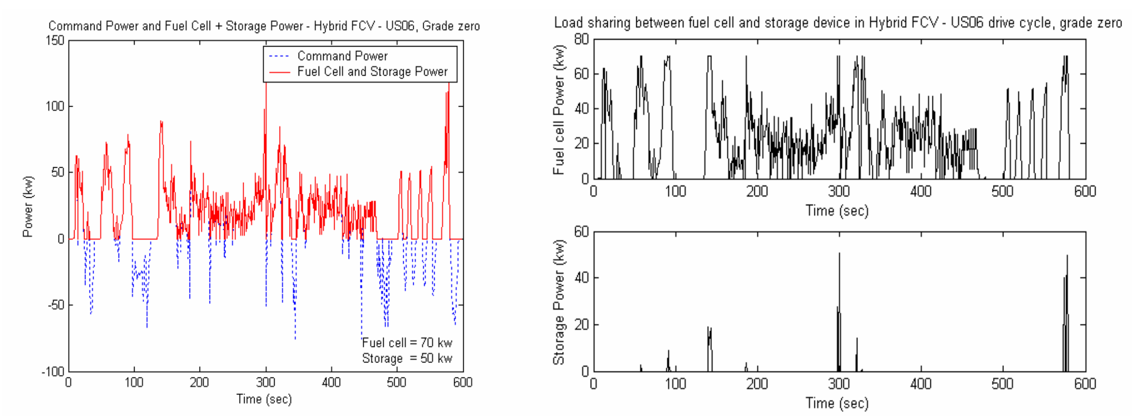
Power management performance of standard urban driving cycle FTP75 for the vehicle introduced in section 4.2.1 Table 4.2.1.1. is shown in Figure 4.3.2.2.a. As mentioned earlier, total power of 50 kW is required for urban driving cycle. Figure 4.3.2.2.b shows the power sharing between the fuel cell and battery unit. The size of fuel cell is 30 kW and battery storage device 20 kW. When the power command exceeds the maximum power of fuel cell, battery unit contributes to the power. Hybridizing the vehicle decreases the size of the fuel cell required in the system and results in lower total cost of vehicle. In addition, transient response is enhances by application of a fast storage device.



(a) (b)

Figure 4.3.2.2, (a), Command power and total power of fuel cell and storage. (b) Load sharing between two sources.

In highway driving cycle US06 a 70 kW fuel cell can provide the base power of the system. This shows a 50 kW reduction in size of the fuel cell. Figure 4.3.2.3.a shows the simulation results of the hybrid fuel cell vehicle for highway driving cycle. Figure 4.3.2.3.b shows the load sharing between fuel cell and storage device. Figure 4.3.2.3.a shows the system base power and transient response improvements by having an additional storage system parallel to the fuel cell.



(a) (b)

Figure 4.3.2.3, (a), Command power and total power of fuel cell and storage. (b) Load sharing between two sources.

Different configuration of fuel cells and battery units may change the overall cost of the system. Next section investigates the cost variation of these systems in hybrid and non-hybrid fuel cell vehicles.

4.4 Cost Analysis

Cost analysis may help us to have a better comparison between different configurations in fuel cell vehicles. In this section, the hybrid fuel cell vehicle is compared to the non-hybrid fuel cell vehicle from economics point of view. Also, a comparison between hybrid fuel cell vehicle which uses battery as storage device and the one in which ultracapacitor is used as the storage device is conducted. One of the main obstacles in development of the fuel cell vehicles is the cost of the vehicle. Despite their many advantages, fuel cell units are still too expensive for vehicle applications. Choosing the right storage devices and downsizing fuel cells can make significant improvements in the vehicular industry.

As it was mentioned earlier, hybrid fuel cell vehicle makes use of a fuel cell power source and an additional storage device which can either be an ultracapacitor or a battery unit. To evaluate the economic improvement of hybrid fuel cell vehicle in comparison with the non-hybrid fuel cell vehicle, the price of each power unit and later, the overall power unit in each case is calculated and compared.

4.4.1 Cost of Different Fuel Cell System Configurations

Rapidly developing fabrication of fuel cells have made them easy to purchase and affordable in vehicle applications. There are several scattered predictions on the future of fuel cells; however, majority of scientists and companies agree on lower prices in mass production of next generation of fuel cells. The current trend of a fuel cell is about $3000 to $4500/kW (Bauman & Kazerani. 2008). However, predictions for the mass-production vary from $225/kW to $400/kW by the end of the decade. (Wu & Gao. 2006) has predicted a cost of $325/kW for the fuel cell which is also used in this research.

4.4.2 Cost of Battery

As it was mentioned earlier, most propulsion batteries are made of nickel-metal hydride (NiMH) batteries which have twice more capability of holding energy than lead acid batteries (NREL Web Page). However, lithium-ion batteries have been rapidly developed recently that are now more considered to be used in the vehicles rather than nickel-metal or lead acid types (Bauman & Kazerani. 2008), (Burke. 2007). The battery chosen for cost analysis in this section is the new high power lithium ion ANR26650MI cell (A123systems). The per kW cost for this battery is about $82.90/kW, reported in 2008 (Bauman & Kazerani. 2008).

4.4.3 Cost of Ultracapacitor

Much research has been conducted to develop ultracapacitor technology since 1990. Ultracapacitors are durable storage devices in comparison with batteries by providing of about 500,000 cycles of deep discharging. Currently several companies such as Maxwell, Ness, EPCOS, Nippon Chem-Con and Power Systems produce ultracapacitor devices (single cells and modules) with capacitance of 1000-5000 F (Burke. 2007). The ultracapacitor in this study is assumed to be BMOD0058 15-V pack ultracapacitor of Maxwell and estimated to have the cost of $59.65/kW (Bauman & Kazerani. 2008).

Table 4.4.3.1: Per kW cost assumptions for power sources in vehicle

Power Source	Cost Per kW
PEM Fuel Cell	$325
Battery (lithium ion ANR26650MI cell)	$82.90
Ultracapacitor (Maxwell BMOD0058 15-V pack)	$59.65

Table 4.4.3.2 shows the results of the cost each of power source also used in this research for simulations.

Considering the price of the components listed in Table 4.4.3.2 the cost (just the battery, ultracapacitor and fuel cell) of a non-hybrid fuel cell vehicle introduced in section 4.2.2 is about $16,250 if designed for urban driving cycle and $39,000 if highway driving cycle is also considered. By hybridizing the vehicle by either ultracapacitor or battery there is a significant reduction in the cost of the power sources. In the urban design the overall cost of power sources choosing battery is about $11,408 which shows a $4,842 reduction in comparison with the non-hybrid vehicle. If ultracapacitors are deployed in urban design another $465 reduction in the cost is obtained and total saving is about $5307. In US06 driving cycle overall cost of a hybrid vehicle is about $26,895 by battery and is $25,732 in case of ultracapacitor, a $12,105 reduction from the non-hybrid to the battery hybrid and another $1,163 reduction from the battery hybrid to the ultracapacitor hybrid is obtained.

Table 4.4.3.2, Cost analysis for the simulated hybrid and non-hybrid fuel cell vehicles

Configuration	**Vehicle Type & Drive Cycle**	**Fuel Cell (KW)**	**Storage (KW)**	**Storage Device**	**COST**		
					Fuel Cell	**Storage Device**	**Total**
Non-Hybrid FCV	City Vehicle-Urban Cycle	50	-	-	$16,250	-	$16,250
Hybrid FCV		30	20	Battery	$9,750	$1,658	$11,408
Hybrid FCV		30	20	Ultracapacitor	$9,750	$1,193	$10,943
Non-Hybrid FCV	Normal Vehicle-US06 Cycle	120	-	-	$39,000	-	$39,000
Hybrid FCV		70	50	Battery	$22,750	$4,145	$26,895
Hybrid FCV		70	50	Ultracapacitor	$22,750	$2,982	$25,732

Despite cost, other important goals to achieve for fuel cell vehicles are maximizing the efficiency, reliability and performance of the system. Next chapter will focus on the issues.

Chapter 5,

Application of Multiple Fuel Cells in Hybrid Electric Vehicles

5.1 Introduction

Recent advances in fuel cell structures have introduced them to many applications such as hybrid electric vehicles and heat/power cogenerations. They bring the advantage of clean energy and decrease the dependency on imported oil by providing fuel efficient devices in many applications such as electric vehicles.

Efficiency of the electric vehicles depends on the size and efficiency of the fuel cell, power electronics and electric motor applied in them. Significant research has been conducted to improve the performance of electric vehicles by introducing more efficient fuel cell and battery configurations, power converters (Drolia, Jose & Mohan. 2003), (Di Napoli, Crescimbini, Giulii, Capponi & Solero. 2002), (Hasan & Husain. 2005) and dynamic modeling of the vehicle (Amrhein & Krein. 2005) in addition to studies on their system interface, loss and control of different topologies studied in (Gao. 2005), (Mehrjerdi & Ghouili. 2006), (Abedini & Nasiri. 2006), (Copparapu, Zinger & Bose. 2006), (Anstrom, Zile, Smith, Hofmann & Batra. 2005), (Van Mierlo, Cheng, Timmermans & Van den Bosschet. 2006), (Ozatay, Zile, Anstrom & Brennan. 2004) & (Vahidi, Stefanopoulou & Peng. 2006). Traditional designs of hybrid electric cars utilize a single fuel cell and battery backup. Figure 5.1.1 shows the schematic illustration of the fuel cell powered vehicle containing a fuel cell, battery unit, power electronics, electric motor and transmission systems as major components.

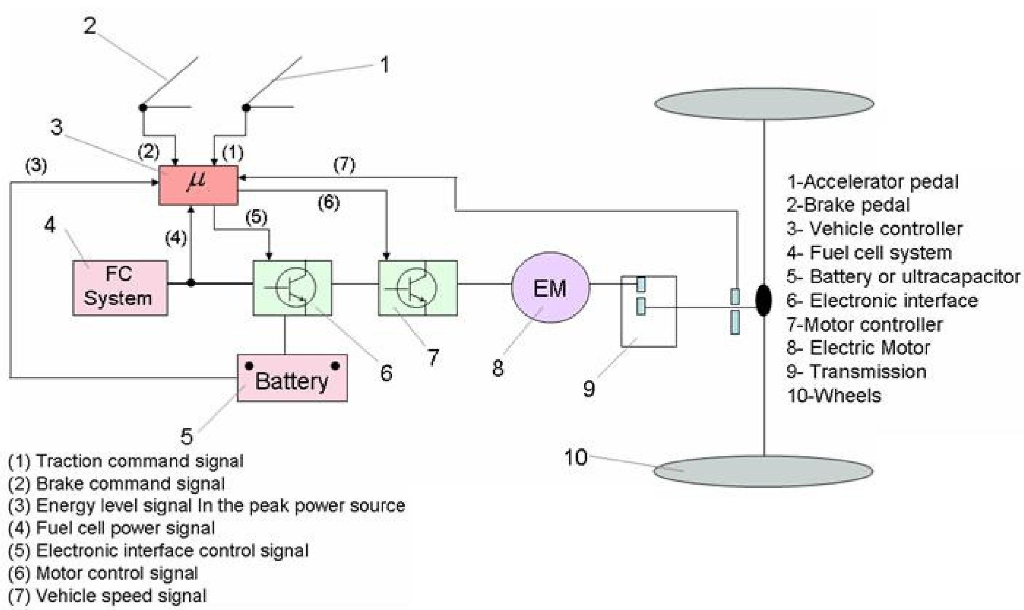


Figure 5.1.1, the schematic configuration of the fuel cell powered vehicle (Gao & Ehsani. 2001)

The system provides the total power required for the vehicle at each time instant. The response time of fuel cells is considered negligible. The fact is that the response times of fuel cells vary by the size and operating conditions, i.e. smaller size fuel cells have short start-up time and they operate efficiently at higher percentage of their nominal power. Therefore, downsizing of a high power fuel cell offers an efficient and fast unit.

In this chapter efficiency curves of fuel cells are investigated and a new configuration of fuel cells in electric vehicles is introduced to improve the efficiency and reliability of the system.

5.2 Efficiency Evaluation

As mentioned so far there are different configurations of electric vehicles which benefit the transportation industry and surrounding environment. Studies have shown that application of fuel cells in vehicle can reduce the energy consumption by 60% and eliminate

55% of the CO_2 emitted from the vehicle compare to internal combustion engines. Efficiency of these vehicles can be measured by different means.

5.2.1 Well-to-Wheels

Well-to-wheels efficiency analysis is one of the criteria to measure and compare the efficiency of vehicles together (Moghbelli, Halvaei Niasar & Langari. 2006). The well-to-wheel efficiency analysis is the product of well-to-tank efficiency and tank-to-wheel efficiency values. The fuel cycle up to storage at retail and emissions is called the well-to-tank efficiency while efficiency and emission analysis resulted from vehicle operation is referred to tank-to-wheel efficiency. Studies show that Direct Hydrogen Fuel Cell Vehicle has the highest efficiency in well-to-wheel and hybrid electric and battery electric vehicles provide good efficiency performance. Battery operated electric vehicles have shown poor efficiency in long distances driving cycles (Moghbelli, Halvaei Niasar & Langari. 2006). Hybrid electric vehicle's efficiency highly depends on topology and system configuration. Studies have shown that parallel hybrid electric vehicles have higher well-to-wheel efficiency (Plotkin.Argonne National Laboratory. 2002). It should be noted that hybridizing makes significant improvement in achieving higher efficiency and fuel economy. Fuel cell vehicles have the advantage of no pollution; they operate quietly and generate less noise than hybrid electric vehicles.

5.2.2 Efficiency Curves

Efficiency curves express the efficiency of fuel cells with respect to their loading percentage. These curves have two distinctive regions to model the dynamics of the cell in light and heavy loading conditions. According to DOE targets, efficiency of fuel cells can reach to a fixed maximum while they show the same value for full load conditions (Zolot, Pesaran. 2004). For instance, Fuel cells can all reach to a maximum efficiency of 60% and full load efficiency of 50%. In addition, a 40% peak efficiency fuel cell implies that the peak efficiency value is obtained at 40% of the nominal power.

Equation (5.2.2.1) introduces the efficiency of a fuel cell up to the peak value of η_{peak} as

$$E(\tau) = \eta_{peak}.(1 - e^{-P/\tau}), \qquad (5.2.2.1)$$

where η_{peak} is the peak achievable efficiency value occurs at for instance 60% of the full load capacity of the fuel cell, P is a percentage of nominal power and τ is a constant determined by fuel cell internal characteristics such as compressors and pumps.

The second part of the efficiency curve is a linear interpolation from the point of peak value (e.g. 60%) of efficiency to the full load efficiency value (e.g. 50%) (Zolot, Pesaran. 2004). Figure 5.2.2.1 shows efficiency curves of three types of fuel cells with maximum efficiencies occur at 10%, 25% and 40% of their nominal power respectively. The main difference between these curves is due to the powers required by ancillary loads of the system such as pumps and valves. Therefore, based on the system loads, their losses and power consumption, different efficiency curves are obtained (Zolot, Pesaran. 2004). In this research the 40% full power fuel cell is assumed in vehicle simulations.

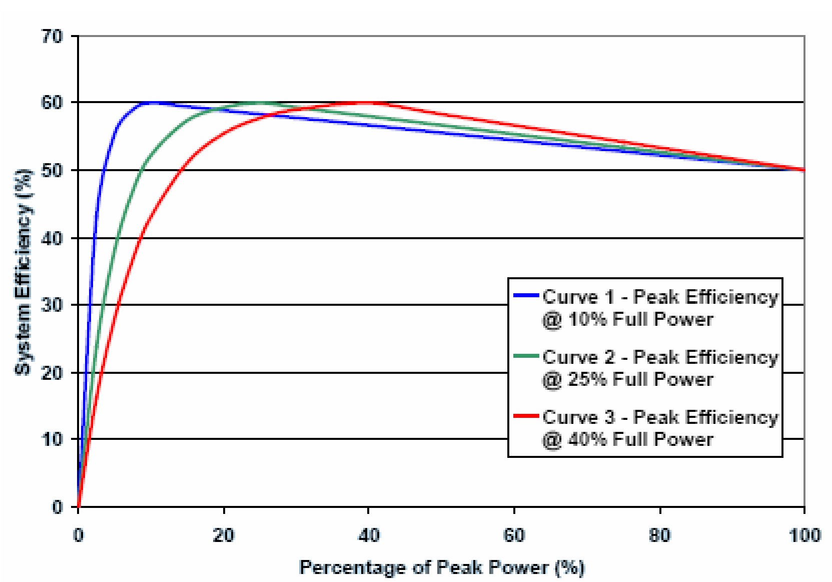


Figure 5.2.2.1, Fuel cell system efficiency characteristics curve for %10, %25 and %40 peak efficiency fuel cell (Zolot, Pesaran. 2004)

Driving cycles demand various power from the traction system and often put their operation in an inefficient mode of operation. For instance, in highway driving cycle high powers are required for long period of time which increases the load percentage of the fuel cell and results in efficient loading condition. However, the same size fuel cell when operates in urban driving cycle, FTP-75 lower power demand decreases the loading percentage and causes inefficient driving conditions.

Low efficiency of a large size fuel cell and its slow dynamic in transient conditions suggest for an alternate design topology to enhance the performance of the system and improve the transient response at the same time.

This chapter illustrates the application of multiple fuel cells in hybrid electric vehicles. Energy management algorithm for a combination of two downsized fuel cells and battery storage is simulated and compared with conventional design of single fuel cell and battery backup units.

5.3 Multi Fuel Cell-Battery Configuration for Electric Vehicle

Efficiency curves of fuel cells in downsized devices show a significant improvement in fuel economy by providing higher loading percentage on fuel cells. Therefore, breaking down the size of a large fuel cell increases the loading and efficiency of vehicle. In either cases of single or multiple fuel cell configurations, power sources should provide enough power for the vehicle to accelerate and maintain the required speed in different driving cycles satisfactorily. Multiple fuel cells are connected in parallel and are controlled to provide power for the engine while operating in high efficiency conditions. They make use of a battery backup to release power in transient conditions. Downsizing of a large size fuel cell also increases the efficiency of the operation over a wider range of load variation. A system with several fuel cells and backup storage requires a different control strategy to keep the fuel cells at the optimum operation and the overall system economic. Figure 5.3.1 demonstrates a double fuel cell configuration of an electric vehicle.

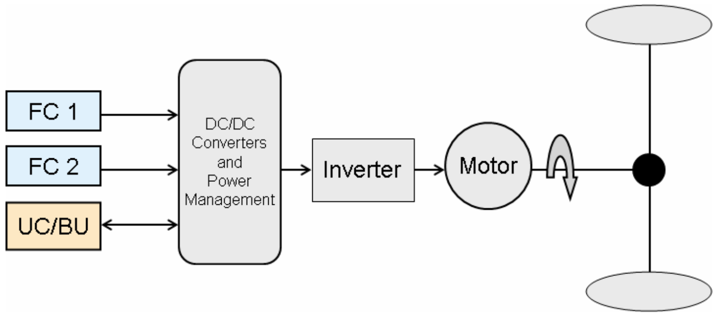


Figure 5.3.1, Multiple downsized fuel cell vehicle topology

5.4 Vehicle Power Management Strategy

5.4.1 Power and Loading Percentage

The required power in the vehicle is presented by P_{comm} which either could carry acceleration or braking command obtained from 3.2.2. The power required for the vehicle includes the grading, rolling resistance and acceleration which is determined by driver. Power management system balances the power generation of fuel cells with the power demand. The loss of the power conversion is neglected in this research.

Loading percentage of a fuel cell vehicle in urban driving cycle is shown in Figure 5.4.1.1. This figure demonstrates the probability of occurrence of a specific percent of the nominal power. The same graph for high way driving cycle is shown in Figure 5.4.1.2. Comparing these figures shows a shift in the mean value and probability of the mode power in highway with respect to urban driving cycle. When efficiency curves and percentage loading bars are plotted on the same graph, the mean power value determines the efficiency of the fuel cell system.

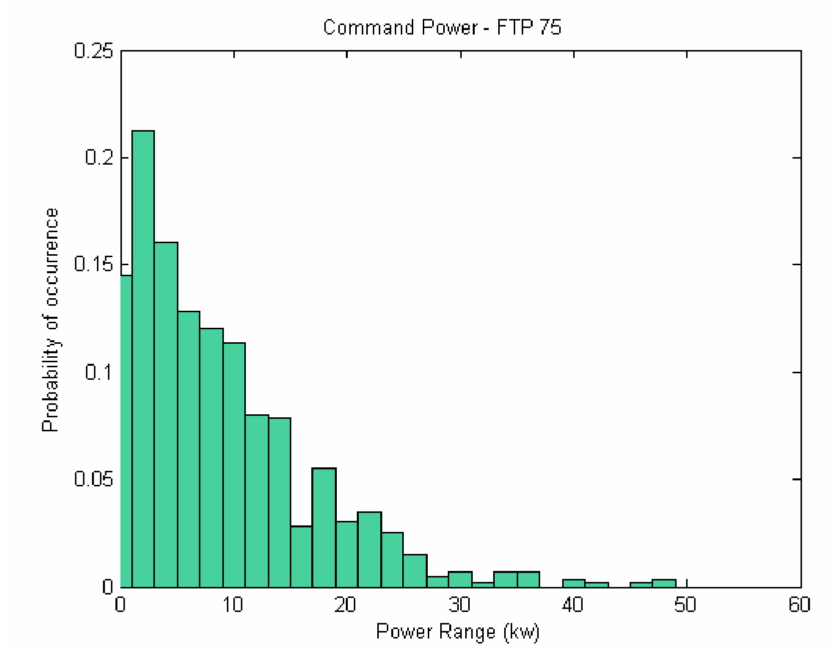


Figure 5.4.1.1, Statistical power demand of the vehicle of table 4.2.1.1 in urban driving cycle

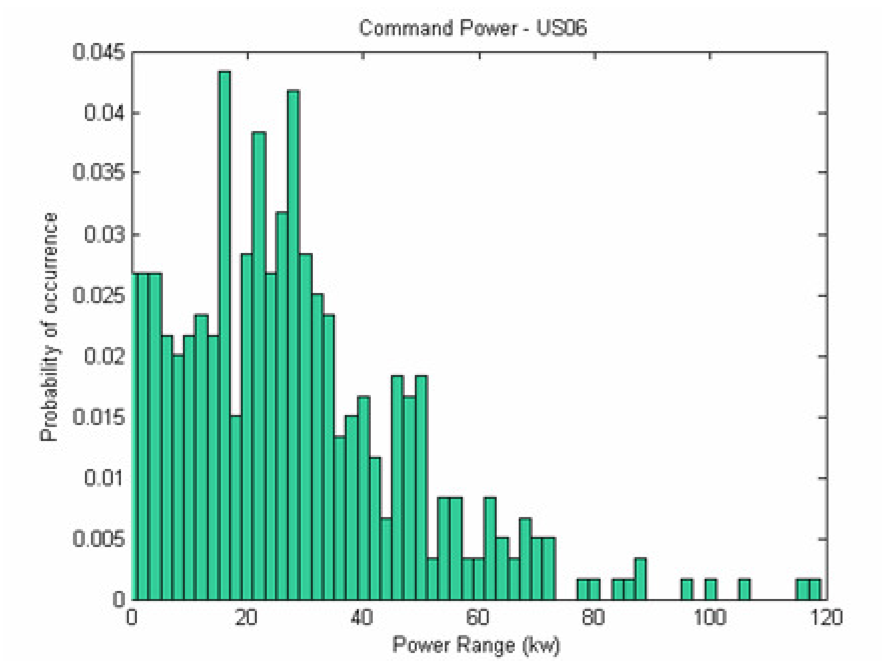


Figure 5.4.1.2, Statistical power demand of the vehicle of table 4.2.1.1 in highway driving cycle

5.4.2 Control Algorithm

In this section, control strategy of a multiple fuel cell vehicle with reduced size devices is illustrated and enhancement in efficiency of the device is investigated. The control strategy is implemented for a double fuel cell electric vehicle and can easily be expanded to other systems.

In order to enable the regenerative energy harvesting, the level of energy in the storage device should be measured continuously (Gao & Ehsani. 2001). This feature is enabled in the control algorithm design. The overall control algorithm (flowchart) is shown in Figure 5.4.2.1.

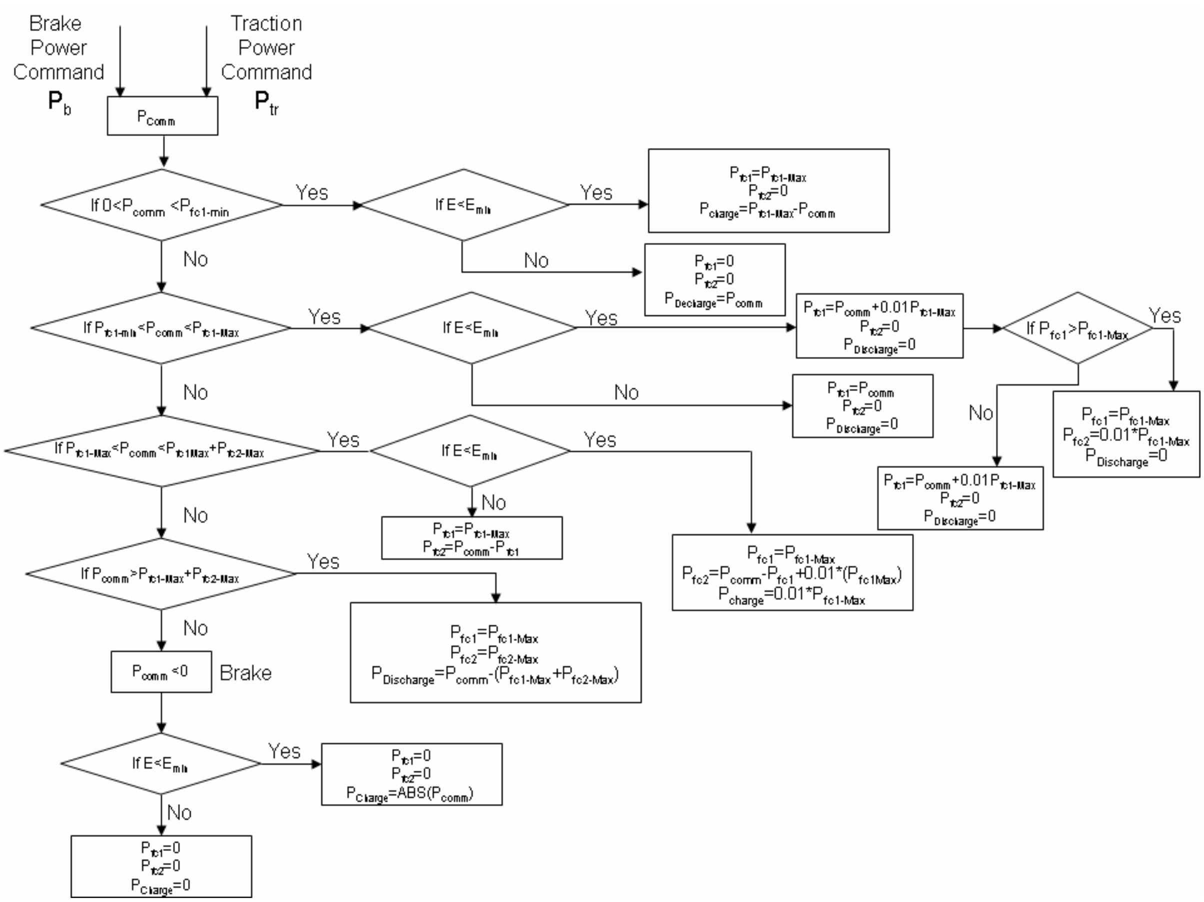


Figure 5.4.2.1, Power control algorithm developed for the hybrid fuel cell vehicle with two fuel cell power sources

This algorithm examines the power command of P_{comm} against limitations of one or two fuel cells combined with storage device and determines the right category that the command belongs to. Then an appropriate command is sent to the fuel cell considering the level of the battery storage device. If there is enough storage energy in the battery, then it is being used in transients, otherwise a charging power request is being sent to the first available and not fully loaded fuel cell. The priority is given to the first fuel cell and the second fuel cell is turned on when the power command exceeds the power limit of the first fuel cell. Battery is used in transients. This way only one of the power sources consumes energy, and more importantly the fuel consumption is efficient due to higher loading percentage in downsized fuel cell. The size of power sources and battery backup ensures enough energy available for the vehicle in urban and highway driving cycles individually. Algorithm explains each of these steps individually where $P_{fc1-Max}$ is the rated power of the first fuel cell, $P_{fc2-Max}$ is the rated power of the second fuel cell, $P_{fc1-\min}$ is the minimum power of fuel cell #1, $P_{fc2-\min}$ is the minimum power of fuel cell #2, $P_{Discharge}$ is the power required for the acceleration of the vehicle in transients, P_{Charge} is the storing rate of power in the storage device when not fully charged or its energy level falls below the minimum value. E is the energy available in the storage device with minimum at $E_{\min}$. The instantaneous fuel cell powers are P_{fc1} and P_{fc2} for fuel cell #1 and fuel cell #2 respectively.

Power demand can fall into four distinctive regions of operation as

- Less than $P_{fc1-\min}$
- More than $P_{fc1-\min}$ and less than $P_{fc1-Max}$
- More than $P_{fc1-Max}$ and less than $P_{fc1-Max} + P_{fc2-Max}$
- More than $P_{fc1-Max} + P_{fc2-Max}$

5.5 Power Management

The power control algorithm developed in previous section is simulated for hybrid electric fuel cell vehicle of Table 4.2.1.1 in driving cycles with grading zero and three. The outcome of the algorithm is the power required from each fuel cell and the battery to feed the power demand in each driving cycle.

Total power from fuel cell is shared between two downsized fuel cells of 30 and 85 kW and a battery unit of 50 kW.

Matlab/Simulink was used for simulations in two standard driving cycles of FTP-75 and US06. Fuel cells are sized to perform economic operation in urban driving cycle and to provide enough power in full load conditions, Therefore, the performance of system is investigated in the standard FTP75 (urban driving cycle) and standard US06 (high speed test). Driving cycle profiles are shown in Figure 3.3.1. In urban driving cycle (FTP-75) frequent stop-starts decrease the average speed compare to the highway driving cycle which increases the optimum operation of the first fuel cell and battery backup. Figure 5.5.1 illustrates the total and shared power among fuel cells and battery backup in urban driving cycle on a grade zero road.

As Figure 5.5.1 shows, the load of fuel cell #1 varies as the power command varies. The second fuel cell is almost OFF during the driving period which saves energy and fuel. The average power provided by fuel cell # 2 is only 0.108 kW which is negligible in comparison with its size. Therefore, fuel cell # 1 provides the majority of the power for the vehicle in this case.

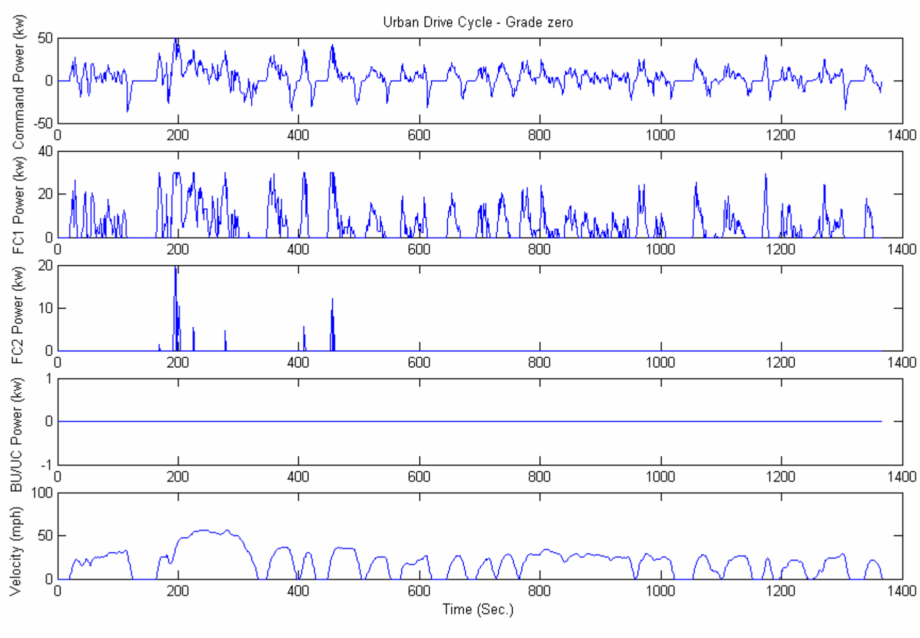


Figure 5.5.1, Simulation results for standard FTP-75 urban driving cycle on a grade zero road.

Figure 5.5.2 shows the simulation results of urban driving cycle in road grade three. In this case fuel cell # 1 provides more power to meet the required command power by the vehicle. The power provided by fuel cell # 2 is still negligible (average 0.472 kW) and battery stays off. Therefore, it can be said that the loading conditions of the fuel cells are still in the economic and energy saving region.

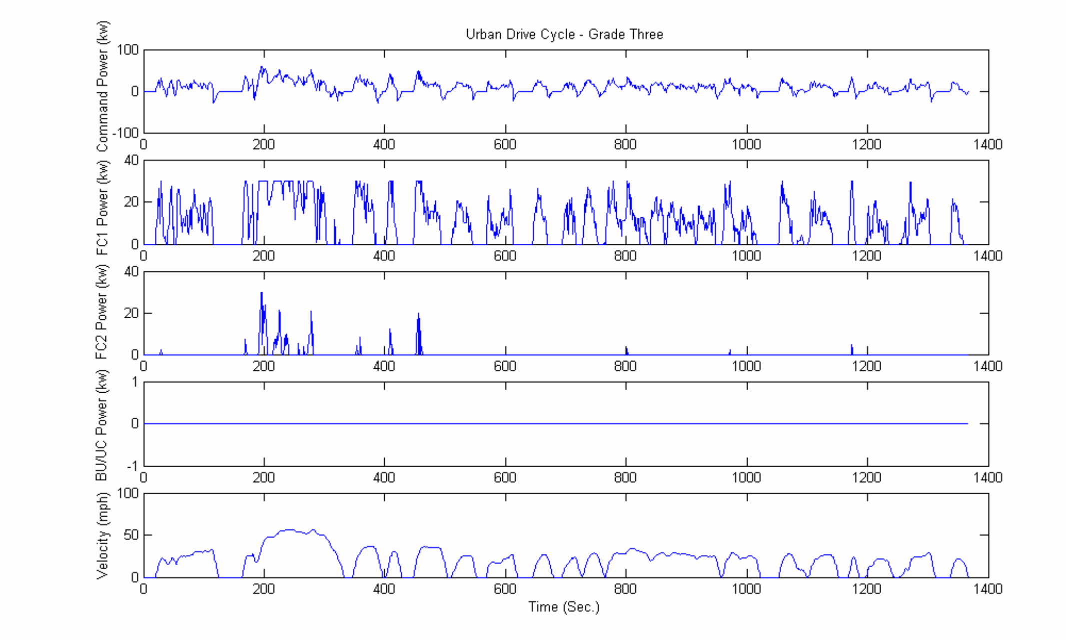


Figure 5.5.2, Simulation results for standard FTP-75 urban driving cycle on a grade three road.

In highway driving cycle (US06), the second fuel cell is ON and provides energy to the system. In this driving cycle higher power is demanded and all power generating sources generate their share of the load while the control system still keeps the first fuel cell economically loaded. Simulation results for US06 driving cycle on a grade zero road is shown in Figure 5.5.3. The required power is provided by the power sources.

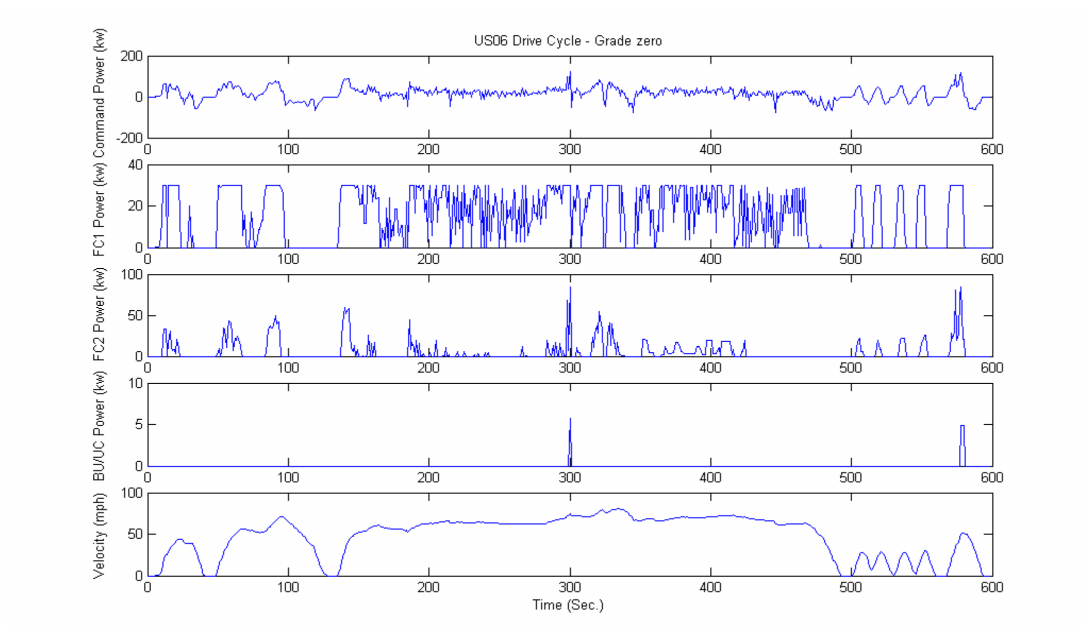


Figure 5.5.3, Simulation results for standard US06 Highway driving cycle on a grade zero road.

In higher grade roads, power management shares are shown in Figure 5.5.4. In this case, fuel cell #1 is operating in the high efficiency conditions and fuel cell #2 provides more power comparing to the previous case. This situation also helps fuel cell #2 to operate in the efficient region of operation. Storage device provides the transient power and is standing by in most cases. This design provides longer life time for the device and requires less maintenance cost while helping two other power sources in transients and high power demands.

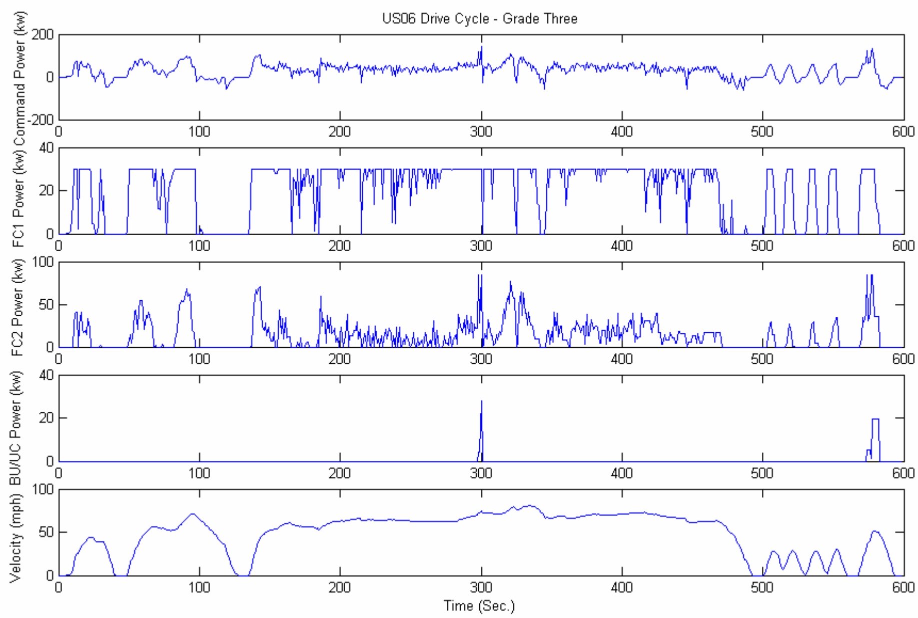


Figure 5.5.4, Simulation results for standard US06 Highway driving cycle on a grade zero three.

As these figures show, urban driving cycle can become more energy efficient by downsizing the fuel cells while providing enough power in highway driving cycle.

5.6 Efficiency Analysis of Multiple Fuel cell Configuration

As mentioned earlier, the main purpose of multiple fuel cell applications in electric vehicles is to reduce the fuel consumption while increasing the efficiency of the system. Suitable sizing and loading of two fuel cell sources, battery backup and economic loading of each fuel cell in several driving cycles are investigated in this section.

5.6.1 Efficiency Enhancement Evaluations

Efficiency curves introduced in section 5.2.2 are used to investigate the efficiency of a fuel cell in different load percentage. In this regard, demographic loading chart of single fuel cell and multiple cells are plotted and compared for several downsized fuel cells to demonstrate the efficiency enhancement obtained by the new topology. The main purpose is to enhance the fuel economy of the vehicle in urban driving cycle; however, efficiency of fuel cells in highway driving cycle US06 is also investigated for possible improvements.

5.6.2 Road Grade Factor

Power command is greatly influenced by grade factor of the road. Increasing the grade of the road shifts the average power toward higher loads and changes the power demographic to higher loading percentage. Higher grade roads can be found in both urban and highway driving cycles. Therefore, we investigate power efficiency in two low and high grades.

As shown earlier, Figure 3.3.1 shows the speed variation in urban driving cycle. Figure 5.6.2.1 shows the power demand variation in grade zero and three. As the figure shows, in higher grades higher powers are demanded for the vehicle. A SUV vehicle was considered for efficiency enhancement investigations with parameters listed in Table 4.2.1.1 shown earlier.

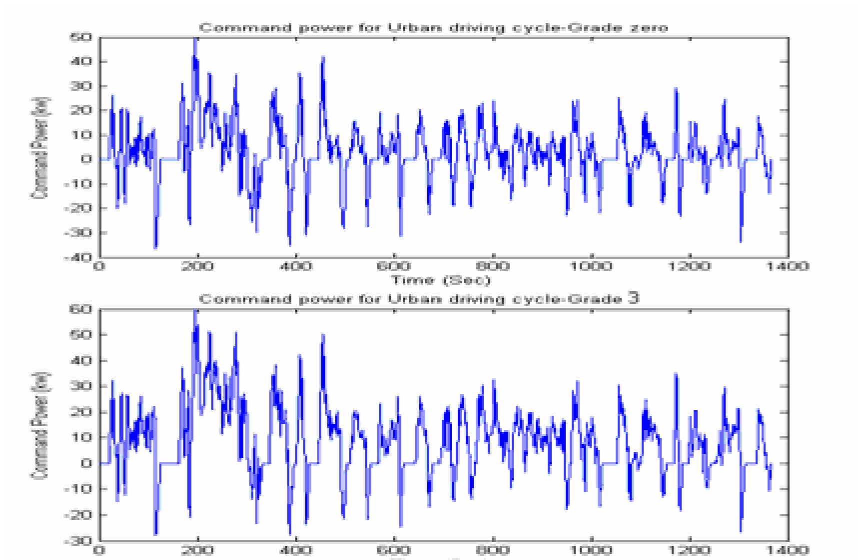


Figure 5.6.2.1, The power demand variation in grade zero and three in FTP-75 driving cycle

5.7 Efficiency

Efficiency improvements of the new design (double fuel cell) are illustrated in this section. A large size of 115 kW fuel cell is replaced with two downsized devices of 30 and 85 kW to increase the fuel economy of the vehicle. Note that the total power of these fuel cells is still 115kW the same as a single fuel cell configuration. The main difference is the load sharing in different driving cycles between fuel cells and to keep their loading at the economic loading percentage. Battery backup is also a 50 kW storage unit. The power management algorithm is designed to start the first fuel cell in light loads and the second fuel cell in heavy power demands which might happen in higher grade driving conditions or highways for the vehicle of Table 4.2.1.1.

5.7.1 Case 1 (Urban Driving Cycle & Grade Zero)

Figures 5.7.1.1, and 5.7.1.2 demonstrate the efficiency improvement from single to double fuel cell power sources with downsized rated power in grade zero of urban driving cycle. The average power is considered as a measure of efficiency improvements. Figure 5.7.1.1 shows, the probability of occurrence as a function of power percentage for a single fuel cell of power 115 kW in urban driving cycle. As the figure shows, the average power density of this system is located at efficiency of 28.1%. An increase of 27.3% is obtained by splitting this power source into a set of double fuel cells and total efficiency of 55.40% is achieved. Figure 5.6.3.1.2 shows the efficiency of the proposed technique to improve the fuel economy of a fuel cell vehicle introduced in Table 4.2.1.1.

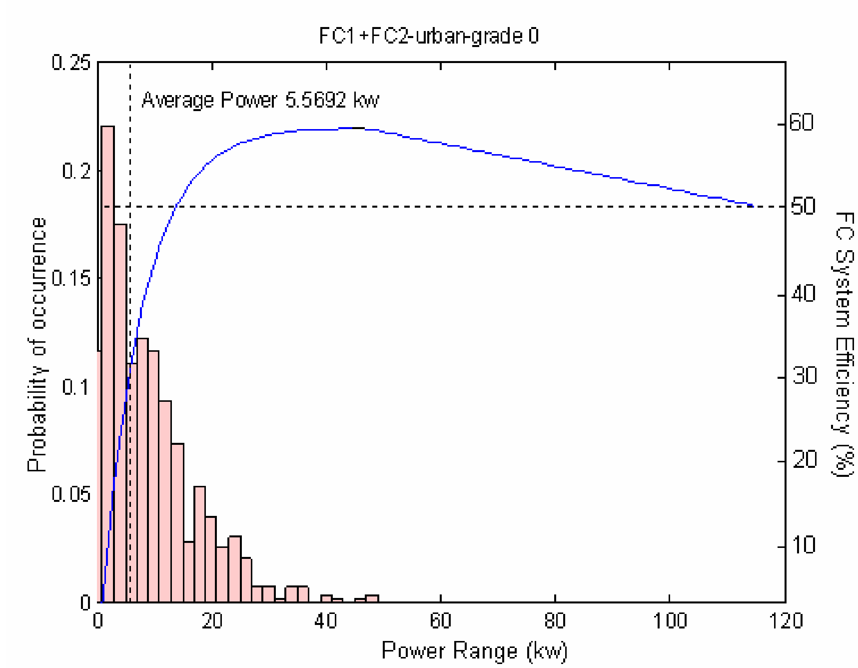


Figure 5.7.1.1, Single Fuel Cell Efficiency configuration (28.1%)

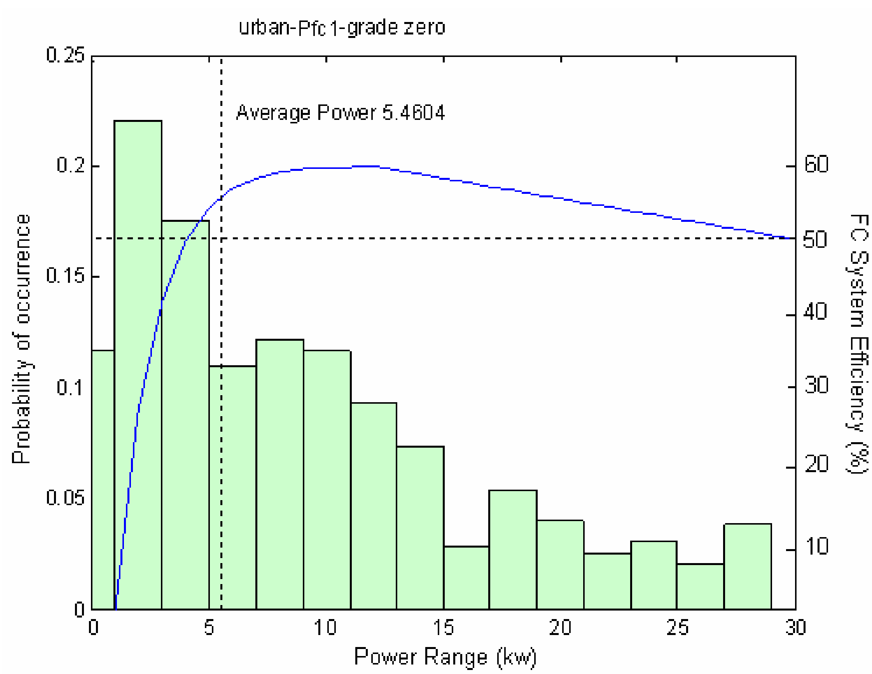


Figure 5.7.1.2, Efficiency improvements of a double fuel cell configuration (55.4%)

5.7.2 Case 2 (Urban Driving Cycle & Grade 3)

In this case, the overall efficiency of a single fuel cell system is about 43.5%. Figure 5.7.2.1 shows the efficiency of a single fuel cell vehicle. In higher grade roads, extra power demand increases the power percentage and its average which results in higher efficiency values. Downsizing provides 16.1% improvement in addition to what was obtained from higher loading percentage in grade 3 and makes the system more efficient about 59.6%. Figure 5.7.2.2 shows the efficiency improvements of a double fuel cell configuration. As the figure shows, higher loading percentage puts the system in efficient mode of operation.

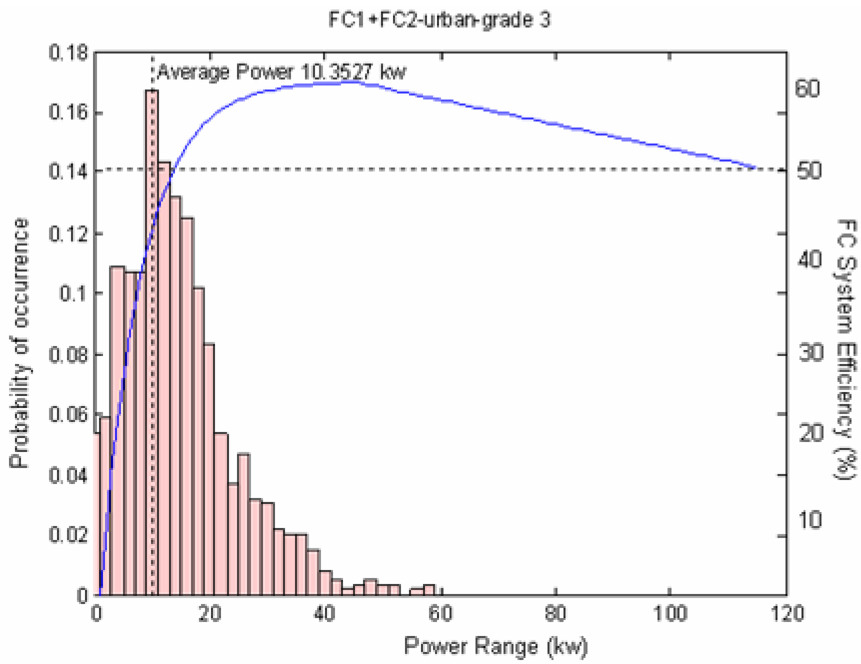


Figure 5.7.2.1, Single Fuel Cell Efficiency (43.5%)

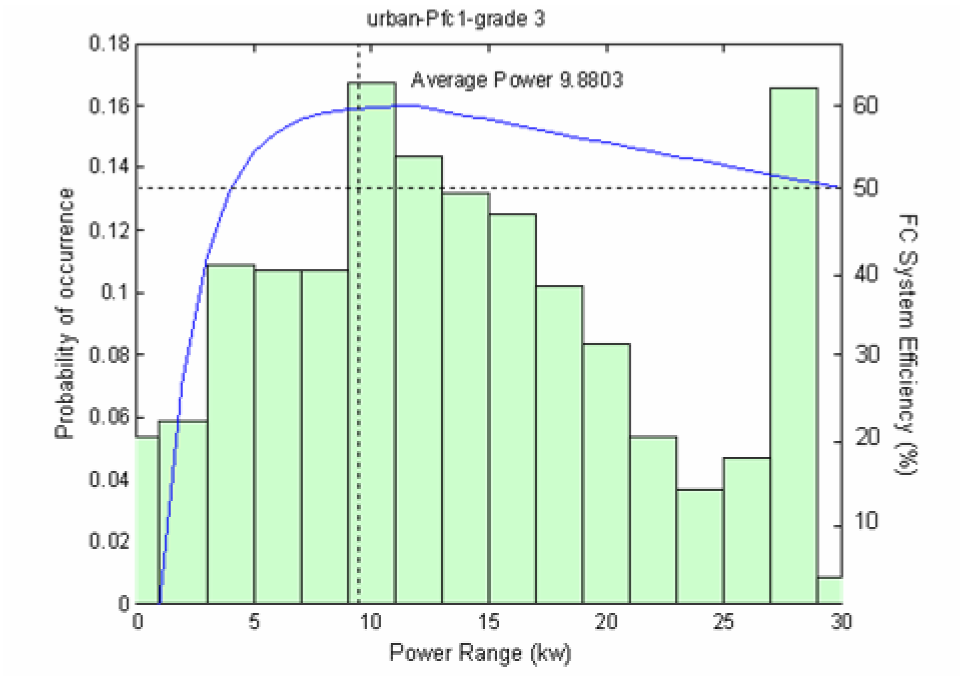


Figure 5.7.2.2, Efficiency improvements of a double fuel cell configuration (59.6%)

5.7.3 Highway Driving Cycle

Fuel economy is very important in both urban and highway driving cycles. The main goal of downsizing of fuel cells was to achieve a high fuel economy and efficient vehicle in urban driving cycle. In this section the effects of downsizing and application of double fuel cell is investigated in highway driving conditions. The standard US06 driving cycle imposes the speed variation as shown earlier in Figure 3.3.1.C. which demands powers as shown in Figure 5.7.3.1 in different grading conditions. As the figure shows, higher grade require higher power from the power generators. Under these conditions, the second fuel cell is turned on to generate power and feed the electric engine and accelerate the vehicle.

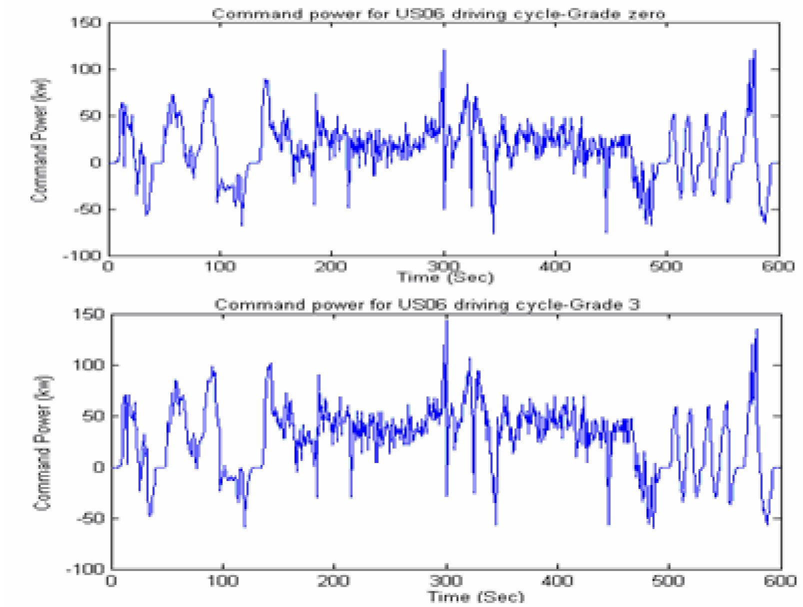


Figure 5.7.3.1, Power command in Highway driving cycle in grades zero and three.

5.7.4 Fuel Economy in US06 Driving Cycle

In highway driving cycles, due to higher power demands, a high power fuel cell operates close to the optimum point. However, since we have replaced a large fuel cell with two downsized devices the efficiency of the system should almost be the same. In grade zero, fuel cell #1 is fully loaded which results in a 58.2% efficiency and as for the second device due to the light loading it provides 36.10% efficiency. Fuel cell #1 is operating better than a single fuel cell with efficiency of %56.105. Efficient operation of both fuel cells #1 and #2 are shown in Figure 5.7.4.1 and 2.

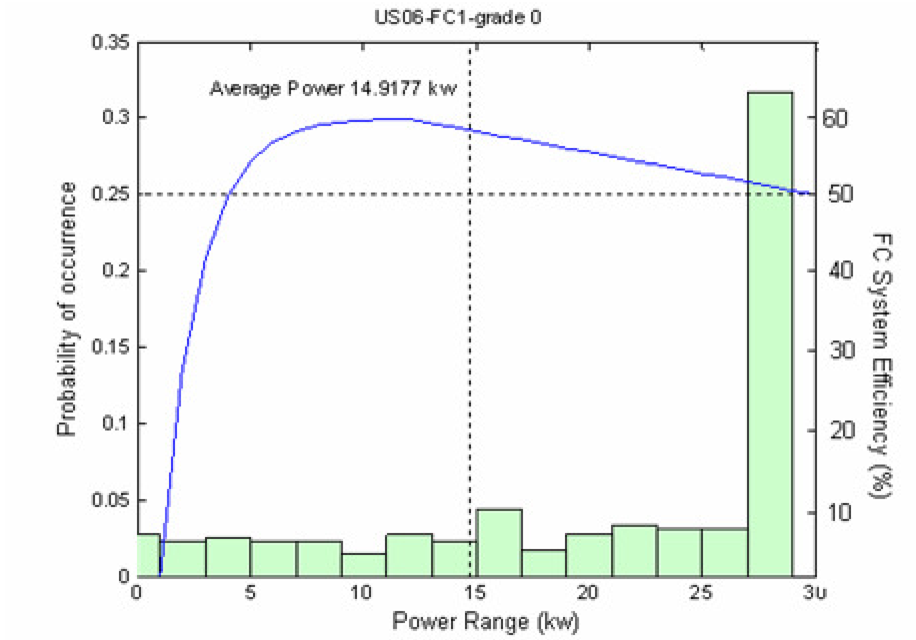


Figure 5.7.4.1, Loading and efficiency of fuel cell #1

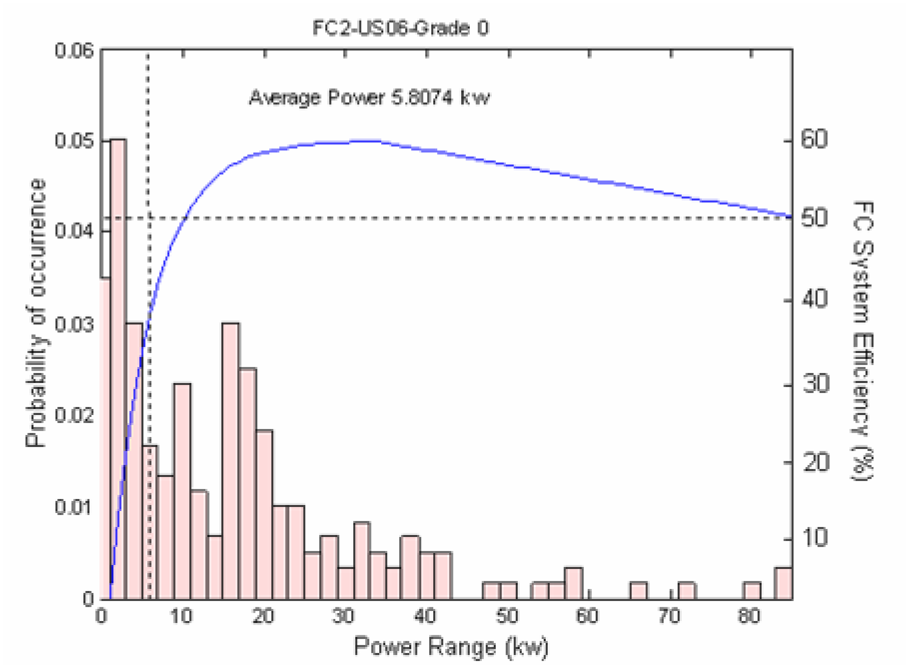


Figure 5.7.4.2, Loading and efficiency of fuel cell #2

In higher grade roads i.e. grade 3, higher power is shifted towards the second fuel cell and results in efficiency improvements of the second fuel cell by 18.4%. First fuel cell has a higher average which results in a decline in its efficiency by 2.7%. The overall system is almost as efficient as a single fuel cell; however, it was not aimed in the purpose of downsizing and double power source. This is demonstrated in Figure 5.7.4.3 for fuel cells 1 and Figure 5.7.4.4 shows the efficiency of the second fuel cell.

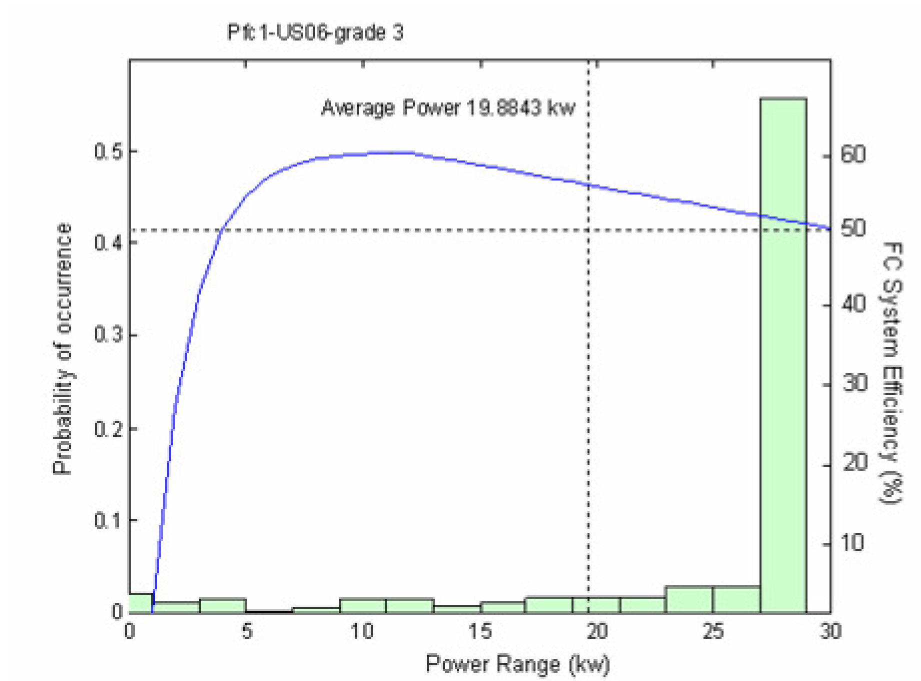


Figure 5.7.4.3, Loading and efficiency of fuel cell #1

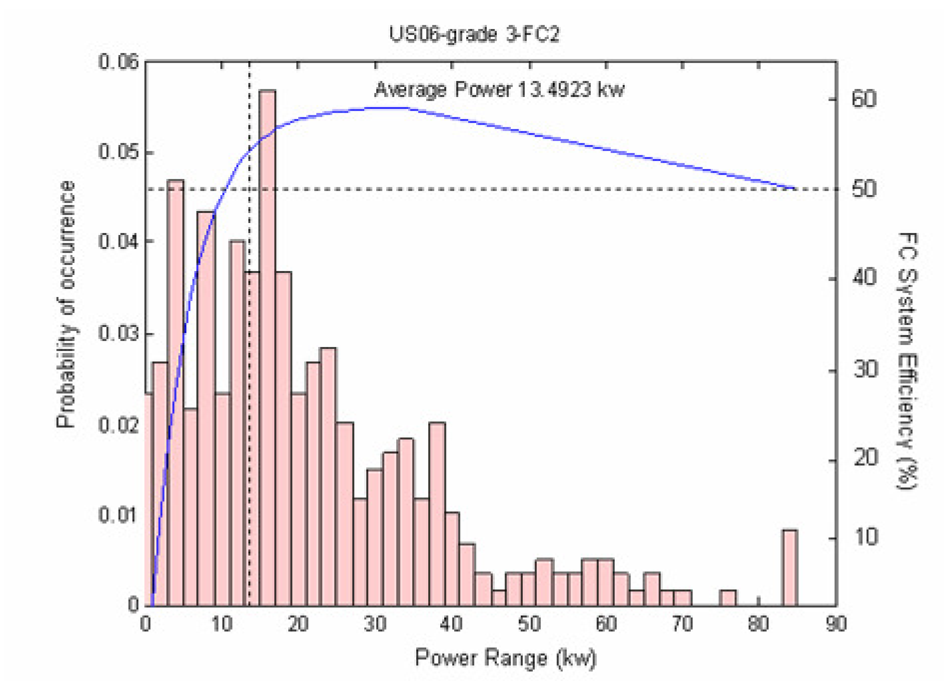


Figure 5.7.4.4, Loading and efficiency of fuel cell #2

Figures 5.7.4.5-6 show the operation and efficiency analysis of a single fuel cell configuration of SUV in highway driving conditions in grade 0 and 3, respectively. As these figures show, when the average power grows it becomes closer to the economic operation point.

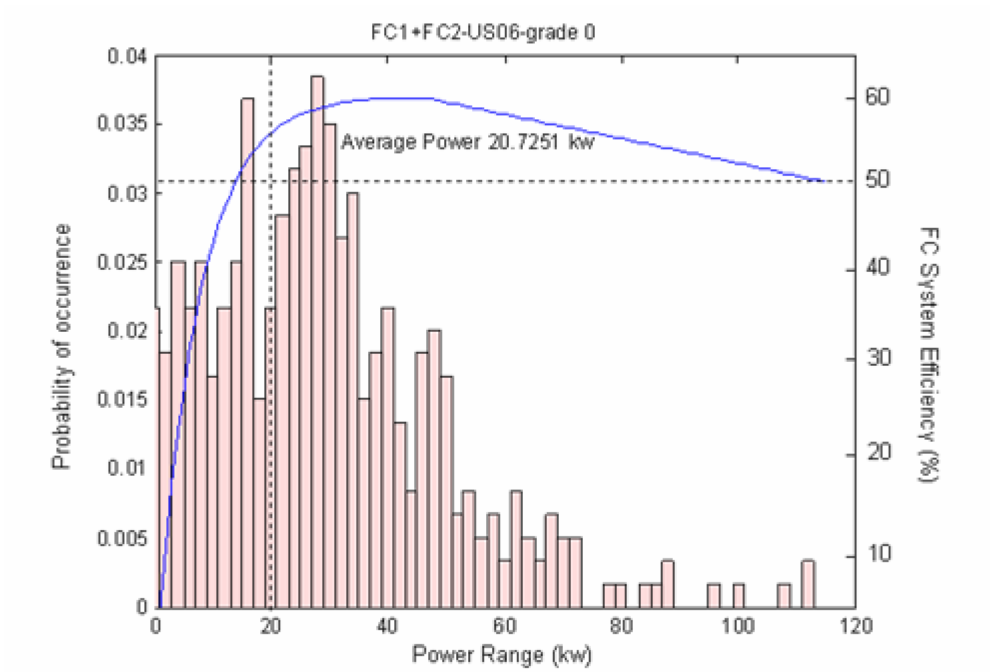


Figure 5.7.4.5, Efficiency analysis of a single fuel cell in grade zero.

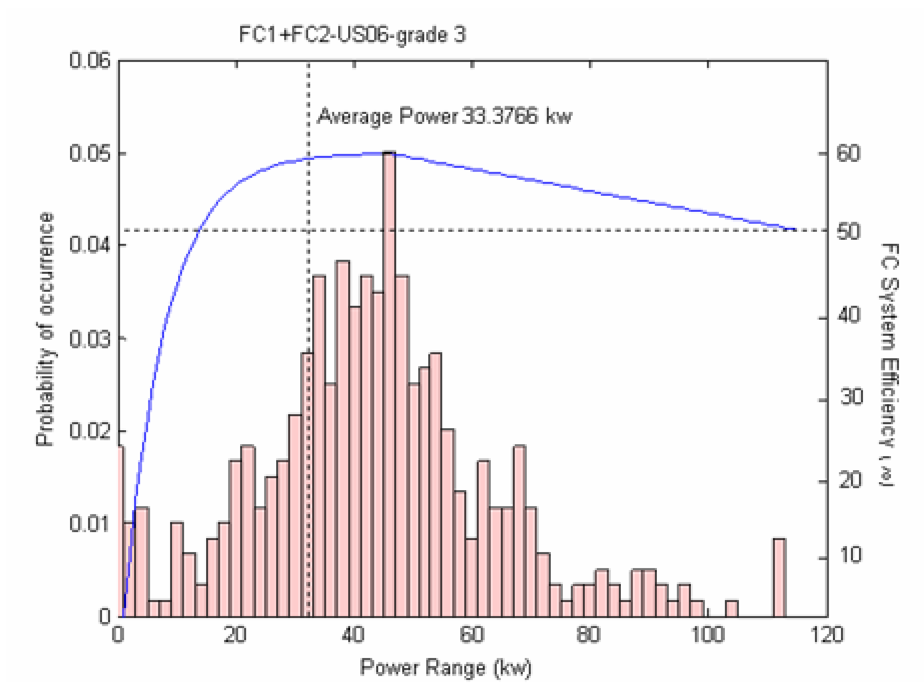


Figure 5.7.4.6, Efficiency analysis of a single fuel cell in grade three.

Economic operation and efficiency enhancement of the double fuel cell configuration in SUV proposed in this section are listed in Table 5.6.4.1.1. This table also demonstrates a comparison of efficiency improvement in urban and highway driving conditions.

Table 5.7.4.1, Economic operation and efficiency enhancement of double fuel cell configuration

Driving Cycle	Grade	Efficiency at Average Power		
		Single FC (115kW)	Downsized FC 1 (30kW)	Downsized FC 2 (85kW)
Urban	0	28.10%	55.40%	-
Urban	3	43.50%	59.60%	-
US06	0	56.10%	58.20%	36.10%
US06	3	59.30%	55.50%	54.50%

Double fuel cell is an economic topology in electric vehicles. It enhances the efficiency of the system by 27.3 % in the best conditions and stays efficient in different grades of driving cycles. The new configuration demonstrates a significant improvement in fuel economy of urban driving cycle; however it provides suitable operating conditions in standard highway driving cycles of grade 0 and 3.

5.8 Reliability of a Double Fuel Cell System

Efficiency enhancement and other benefits of multiple fuel cell configurations have been demonstrated in previous sections. Another benefit of this configuration as a parallel source of energy is the reliability improvements. One of the major obstacles in commercialization of fuel cell vehicles is their low reliability of operation (Marchesoni & Savio. 2005) which results in a huge reduction in overall system reliabilities. (Marchesoni & Savio. 2005) & (Wu & Li. 2006), have conducted research on overall reliability of fuel cell vehicle. Reliability analysis of a single PEM fuel cell system is studied in (Mangoni, Pagano & Velotto. 2007) and (Feitelberg, Stathopoulos & Qi. 2005). (Aydinli, Sisworahardjo & Alam. 2007) has focused on the reliability analysis of a single Direct Methanol Fuel Cell.

In the following sections, reliability enhancement of a double fuel cell power source is compared with the traditional designs. The reliability is introduced and used for various system configurations.

5.8.1 Reliability

"Reliability is the probability that an item will perform its function adequately for the desired period of time when operated according to specified conditions" (Dhillon. 1983). Reliability is defined mathematically as

$$R(t) = \int_{t}^{\infty} f(x)dx \,, \qquad (5.8.1.1)$$

where $f(x)$ is the failure probability density function and t is the time period. $F(t)$, the cumulative probability distribution function which is also called the failure probability, is defined as

$$F(t) = \int_{-\infty}^{t} f(x)dx \,, \qquad (5.8.1.2)$$

In reliability analysis, it is assumed that the system have the chance to operate without failure during a specific period of time. A fuel cell is a two state device which either operates or fails during its operation. Configuration of components in the system can categorize a network into four distinctive cases of series, parallel, k-out-of-m unit network and standby redundant system. These systems are defined for the convenience of readers.

5.8.2 Series Network

If the devices/subsystems of a network are connected in series, it is called a series network. In such network, failure of any of the components leads to failure of the whole system. In the series network, overall reliability of this network consisting of k components is calculated by

$$R_S(t) = \{1 - F_1(t)\}\{1 - F_2(t)\}\{1 - F_3(t)\}...\{1 - F_k(t)\}, \qquad (5.8.2.1)$$

where $R_i(t)$ is the ith unit/component reliability and $F_i(t)$ is the ith component failure probability for $i = 1,2,....k$ and is defined as,

$$\{1 - F_i(t)\} \equiv R_i(t) \qquad (5.8.2.2)$$

5.8.3 Parallel Network

If the devices/subsystems of a network are connected in parallel, the network is called a parallel network. This type of system only fails when all its components/subsystems fail to operate; therefore, this configuration is used to increase reliability of the overall system. The reliability of the overall system is calculated by

$$R_p(t) = 1 - \prod_{i=1}^{k} F_i(t)\,. \tag{5.8.3.1}$$

5.8.4 k-out-of-m Unit Network

This type of network contains m units and operates if k parallel units operate. The reliability is defined as

$$R_{k/m}(t) = \sum_{i=k}^{m} \binom{m}{i} [R(t)]^i [1 - R(t)]^{k-i}\,, \tag{5.8.4.1}$$

where $R(t)$ is the unit reliability, m is the total number of system units and k is the number of units required for the function of the system.

5.8.5 Standby Redundant System

In a standby redundant system, k units are on standby while one unit functions. The system reliability in this case is calculated by

$$R_s(t) = \sum_{i=0}^{k} \left\{ \int_0^t \lambda(t).dt \right\}^i e^{-\int_0^t \lambda(t)dt} (i!)^{-1}, \tag{5.8.5.1}$$

where λ is the hazard rate or instantaneous failure rate and is defined as "the rate of change of the failed components quantity divided by number of survived components at time t" (Dhillon. 1983).

5.8.6 Weibull Distribution

Different distributions such as Weibull, Normal, Exponential Uniform, Extreme value, etc. have applications in reliability engineering analysis. Weibull distribution is commonly used for reliability analysis related to PEM fuel cell systems (Feitelberg, Stathopoulos & Qi. 2005). The hazard rate for the Weibull distribution is defined as,

$$\lambda(t) = At^{B}\,. \tag{5.8.6.1}$$

More details are defined as

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t-t_0}{\theta}\right)^{\beta-1}, \tag{5.8.6.2}$$

where β is defined as the shape parameter, θ is the characteristic life or scale parameter and t_0 is the location parameter. The probability density function of Weibull distribution is expressed as,

$$f(t) = \frac{\beta}{\theta}\left(\frac{t-t_0}{\theta}\right)^{\beta-1} e^{-\left(\frac{t}{\theta}\right)^{\beta}}\,. \tag{5.8.6.3}$$

The reliability function is expressed as

$$R(t) = e^{-\left(\frac{t-t_0}{\theta}\right)^{\beta}}\,. \tag{5.8.6.4}$$

Weibull distribution becomes an exponential case when $\beta = 1$ (the failure rate is independent of age). In the next section the system reliability analysis for the proposed configuration of multiple fuel cells in hybrid fuel cell vehicle is presented.

5.9 Reliability Analysis for Multiple Fuel Cell System

In this section, reliability analysis of one fuel cell is formulated and is expanded for a parallel network. The probability of a single fuel cell is considered "1" at the start of operation and decreases as time increases. In (5.8.6.4), β equals 1 (Åström, Fontell &

Virtanen. 2007) which results in a constant failure rate of $\lambda = \frac{1}{\theta}$, and t_0 is zero for a brand new fuel cell unit (Relex Web Page).

Figure 5.9.1 shows the reliability of individual fuel cells and the resultant parallel network of double power sources for different failure rate values. This figure illustrates a case where failure rate of fuel cell #1 is more than failure rate of fuel cell 2; therefore, the reliability of fuel cell #1 decays faster. This figure shows an improvement in the overall reliability of the system which is more than each of fuel cells individually. This demonstrates higher reliability of the multiple fuel cell configuration proposed in this research.

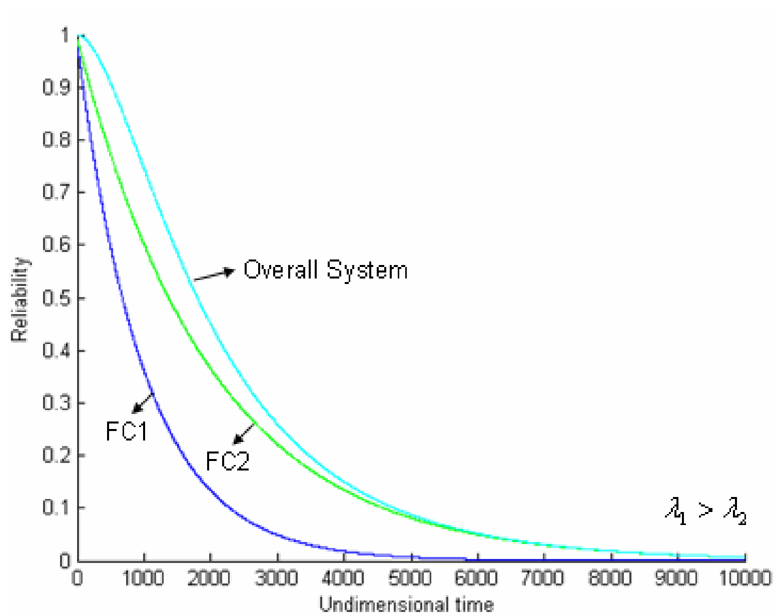


Figure 5.9.1, Each fuel cell and the parallel system reliability curves for $\lambda_1 > \lambda_2$

Figure 5.9.2 shows the reliability evaluation of fuel cells with the same failure rate values. In this case both fuel cell reliability curves decay with the same rate; however, the overall reliability of the parallel system is higher than the cells individually.

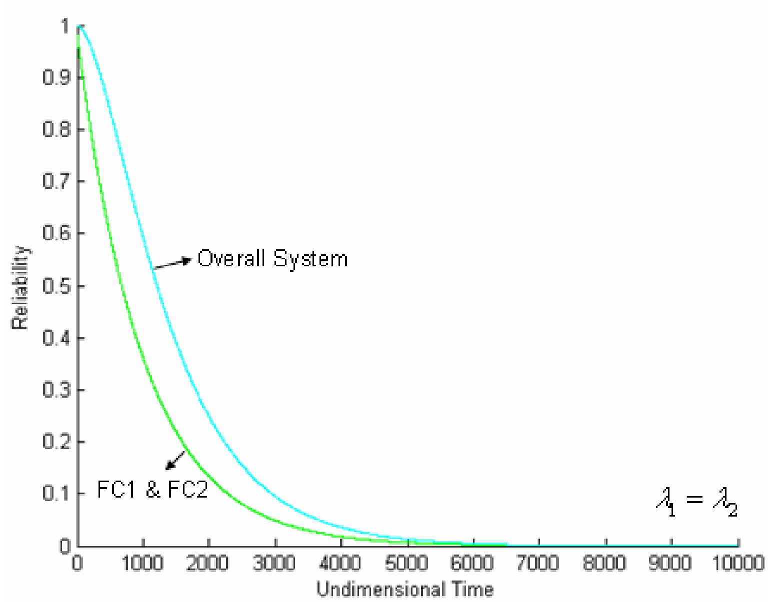


Figure 5.9.2, Each fuel cell and the parallel system reliability curves for $\lambda_1 = \lambda_2$

Simulations indicate that by using the multiple fuel cell configuration not only higher efficiency is gained for the system in urban driving cycles, but also, a more reliable system is achieved by implementing the new topology.

Chapter 6,

Conclusion and Future Work

6.1 Conclusion

Conventional designs of hybrid fuel cell vehicles make use of a single fuel cell power source and a storage device to provide the base load and transients in various driving cycles. This research proposed a new configuration of multiple fuel cell power sources in hybrid fuel cell vehicles. Multiple fuel cells were downsized to provide the same amount of power, which brought the advantage of a highly fuel economic design. Highly efficient driving conditions in urban applications were obtained which also resulted in more reliable system configurations. The proposed power management for this new configuration was presented and the simulation results for a double fuel cell configuration showed the predicted response of power sources. Fuel cells were efficient while they operated in their higher loading percentage. Efficiency curves were introduced and used for efficiency analysis. To gain higher efficiencies in hybrid fuel cell vehicles, fuel cells should be loaded in their efficient region of operation. The main objective of this thesis was to achieve a higher efficiency in urban driving cycle. In conventional configurations, the fuel cell was not efficiently loaded in urban driving cycles, where small powers were required from the single fuel cell power source. In that case, the fuel cell was usually loaded in its low efficient region which made the whole system inefficient. By utilizing the new configuration, fuel cells could be loaded in their efficient region in urban driving cycles and provided a fuel economic vehicle.

Efficiency simulations showed that in standard urban driving cycle (FTP75), efficiency was enhanced for almost 27.3% in urban driving cycle which showed.

6.2 Future work

- Power Control Strategy Changes with Accordance to the Loading Condition

To enhance better efficiencies in the configuration of multiple fuel cell vehicle different control strategies can be implemented in different cases. The power control management can be composed of two algorithms. One can be used in low range of speeds where the power can be fed by the first fuel cell and storage device while keeping the second fuel cell idle to avoid low efficiencies in the second fuel cell. The power management can be switched to a new program in case of high speeds where the second fuel cell is turned on and battery is kept off except for transients. Higher efficiencies are expected from this technique.

- Experimental Results

Experimental results are always the ultimate demonstration of an applied method. Practical implementation of the control algorithm with two smaller size fuel cells and battery backup should attest the results obtained from the simulations.

- Power Management Algorithms for More than Two Fuel Cells.

Double fuel cell configuration as the potential design of an economic system was examined in this research. Optimal numbers of power sources are required to be determined to achieve the highest efficiency and fuel economy. Higher number of fuel cell power sources connected in parallel increase the reliability of the overall system.

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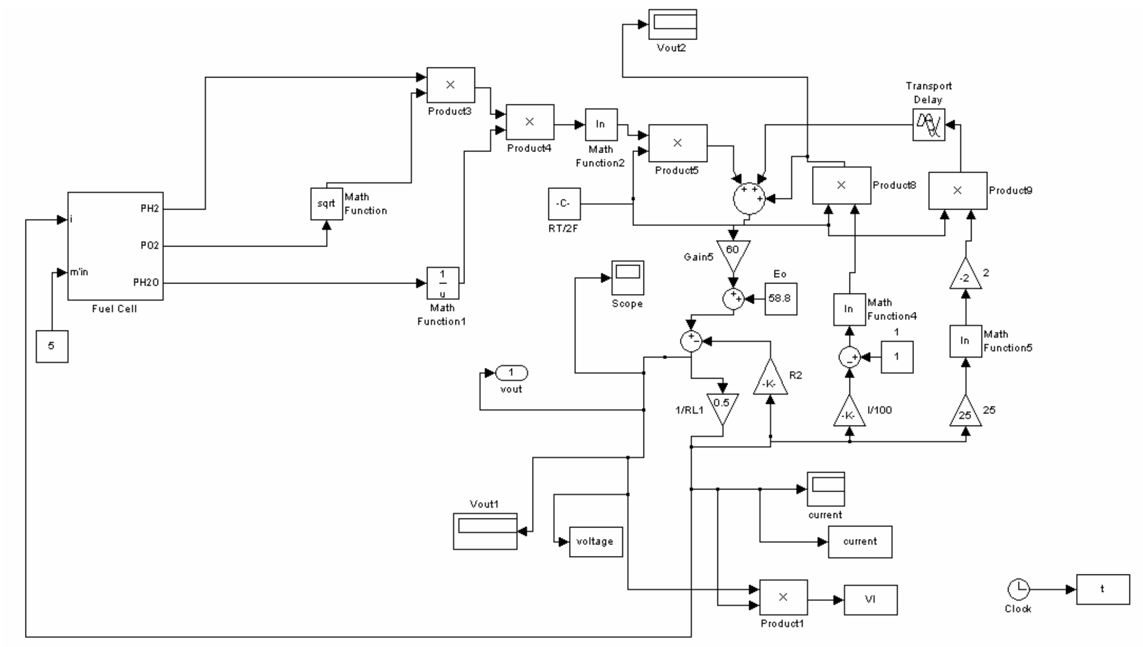
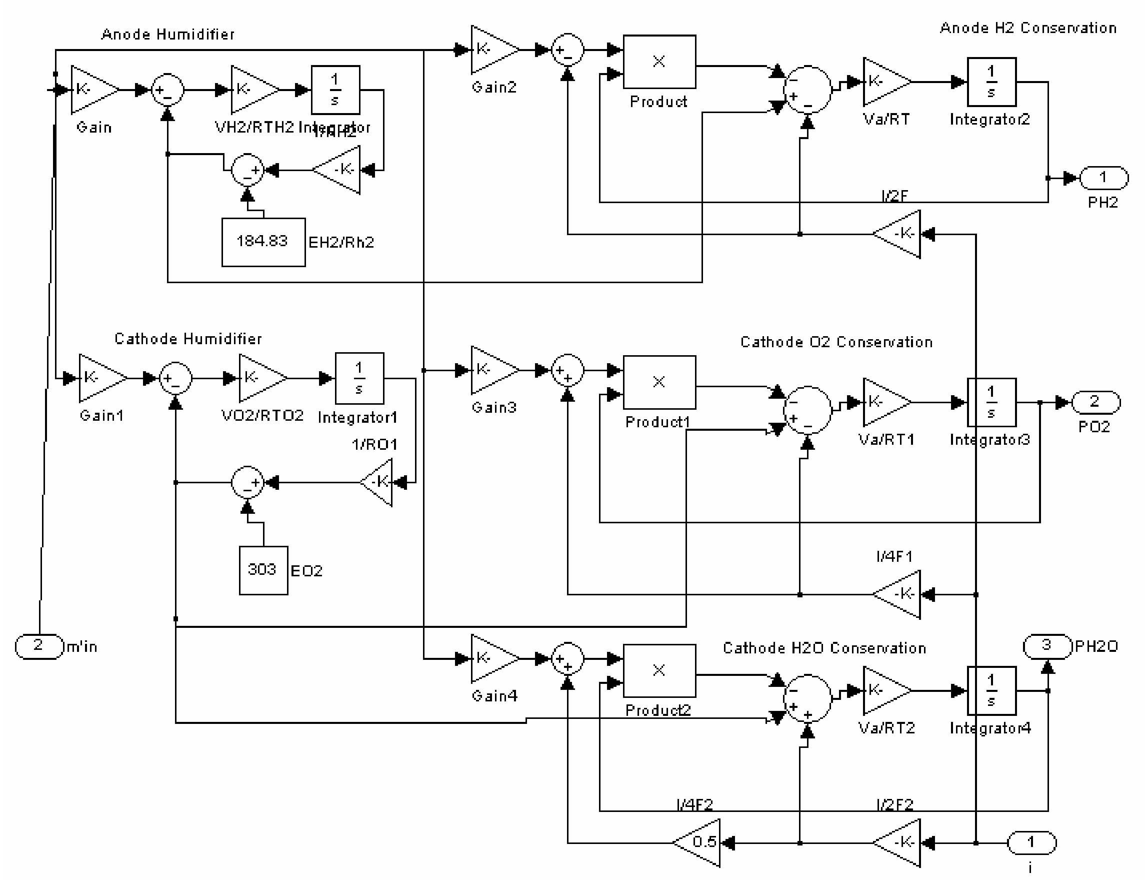
APPENDIX A

Fuel cell model in MATLAB/Simulink:



Fuel cell sub-model in MATLAB/Simulink:



Fuel Cell Model Details:

R= 8.314, universal gas constant, [joule/gm-mol-K]
N= 60, number of cells
F= 96439, Faraday Constant [Coulombs per mol]
V_a= 0.985, anode fuel cell volume [m^3]
V_c= 1.68, cathode fuel cell volume [m^3]
T= 333, operating temperature [K]
A_c= 19.4, Channel flow area [cm^2]
E_0= 0.98, standard state voltage [V]
n= 2, molar flow rate [gm-mol/sec]
V_{H2}= 0.0149, hydrogen volume [m^3]
V_{O2}= 0.0224, oxygen volume [m^3]
r= 0.1734, mole density [gm-mol/m^3]

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