دانشگاه تربیت دبیر شهید رجائی
دانشکده علوم پایه
چهارمین سمینار
پیل سوختی ایران
4th Iranian Fuel cell seminar
سوم و چهارم آذر ماه ۱۳۸۹
November 24 & 25 ,2010
www.iranecs.ir/fuelcellseminar

Power Control Strategy of Fuel Cell Hybrid Electric Vehicles

Amin Hajizadeh
Department of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, Iran.
aminhajizadeh@shahroodut.ac.ir

Abstract

This paper deals a novel strategy developed for optimizing the power flow in a Fuel Cell Hybrid Electric Vehicle (FCHEV) structure. This method implemented an on-line power management by a fuzzy controller between dual power sources that consist of a battery bank and a Fuel Cell (FC). This structure included battery and fuel cell and its power train system include an Electric Motor (EM). The proposed method involves an advance supervisory controller in the first layer which included all of possible operation modes. With regards the operation mode, the upper layer make decision to choose the switching chain roles and respect controller in the second layer. Finally in the third layer, there are local controller to regulate the set points of each subsystems to reach the best performance and acceptable operation indexes. Simulation results of a test system illustrate improvement in the operation efficiency of the hybrid power system and the battery state of charge has been maintained at a reasonable level.

Keywords: Fuel Cell Hybrid Electric Vehicle, Fuzzy Controller, Power Management

1. Introduction

The search for improved fuel economy and reduced emissions, without sacrificing performance, safety, reliability, and affordability has made the hybrid vehicles a challenge for the automotive industry. Compared to conventional internal combustion engine vehicles, fuel cell hybrid electric vehicles represent an effective way to substantially reduce fuel consumption. This capability basically is due to: 1) the possibility of downsizing the fuel cell, 2) the ability of the rechargeable storage system to recover energy during braking phases (regenerative braking), and 3) the fact that an additional degree of freedom is available to satisfy the power demands from the driver, since power can be split between thermal and electrical paths. This third point also means that the performance of a HEV system is strongly dependent on the control of this power split.

There are many challenges to design a proper control strategy for hybrid vehicle powertrain. For one thing, the vehicle consists of many large subsystems. Drivetrains of hybrid-electric vehicles exhibit highly nonlinear dynamics due to the nonlinearities of diesel engines, fuel cell, electric machines (generators and traction motors) and batteries, gear and suspension, as well as nonlinear characteristics of power converters. Since these drivetrains are operated as complex systems, modern methods for designing controllers for nonlinear systems must be applied to utilize the full capabilities of hybrid-electric vehicles[1]-[3].

Power management strategies for HEV's can be roughly classified into three categories. The first type employs heuristic control techniques such as rule-based strategy [4] and intelligent strategy [5-6]. These strategies can offer a significant improvement in energy efficiency and are suitable for real-time control strategy that can be used to control a vehicle.

The second approach is based on static optimization methods. Commonly, electric power is translated into an equivalent amount of (steady-state) fuel rate in order to calculate the overall fuel cost [7-9]. The optimization scheme then figures out the proper split between the two energy sources using steady-state efficiency maps. Because of the simple point wise optimization nature, it is possible to extend such optimization schemes to solve the simultaneous fuel economy and emission optimization problem. Static approaches are based mainly on the Equivalent fuel Consumption Minimization Strategy (ECMS), which can be adapted to also consider battery SOC and emissions constraints. One of the drawbacks of the static approach is that some important dynamic effects, such as those related to drivability and battery SOC variations, cannot be explicitly treated.

The basic idea of the third type of HEV control algorithms considers the dynamic nature of the system when performing the optimization. Furthermore, the optimization is with respect to a time horizon, rather than for an instant in time. In general, power split algorithms resulting from dynamic optimization approaches are more accurate under transient conditions, but are computationally more intensive. The dynamic optimization policy is not implementing able in real driving conditions because it requires knowledge of future speed and load profile [10-13].

This paper is arranged as follows. The configuration of the prototype hybrid electric vehicle system is introduced first, followed by the description of the control system architecture implemented in the vehicle. Next, logical state machine for engine control strategy and fuzzy logic control strategy is proposed to develop the power management strategy in the supervisory powertrain controller.

2. Structure of Fuel Cell Hybrid Electric Vehicle

The modeling of a Fuel Cell Hybrid Electric Vehicle (FCHEV) is an important issue that needs to be carefully addressed. Many articles deal with static models that are built up from maps and static relationships between parameters in the model. These models allow for fast simulation, but they cannot show the oscillations and other dynamic phenomena when switching occurs between different modes of operation. However, a good model should consider both accuracy and simulation time. The electric components of a hybrid power system used in this paper comprise a battery bank, DC/DC and DC/AC converters, while the electrochemical component is a Fuel Cell system (FC). The mathematical models describing the dynamic behavior of each of these components are given [14].

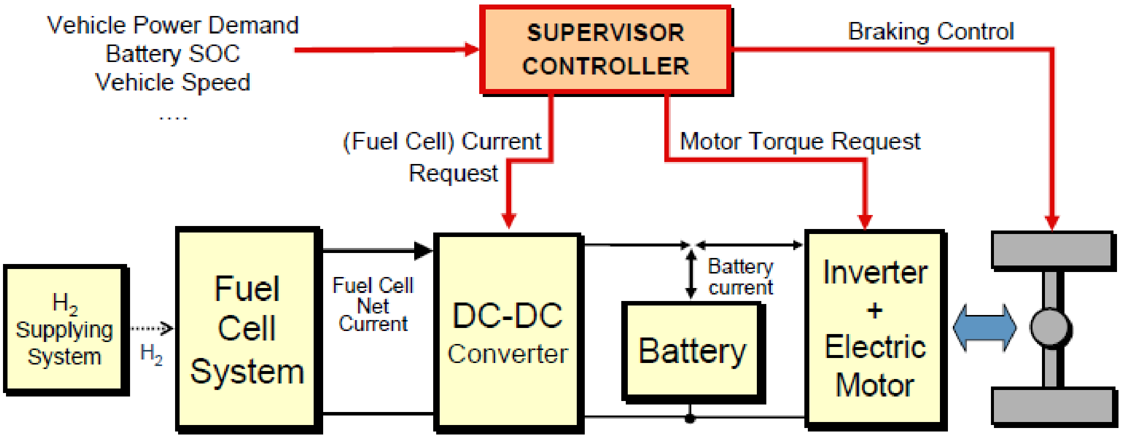


Fig.1 Structure of Fuel Cell Hybrid Electric Vehicle

3. Power Management Problem in Fuel Cell Hybrid Electric Vehicles

The hybrid vehicle is equipped with an electrical traction system, composed of a set of batteries and an electric motor/generator, coupled with fuel cell. Depending on the energy management, two different configurations can be selected: series hybrid vehicles and parallel hybrid vehicles [3].

In the series architecture, the ICE supplies the energy for recharging the battery and its size depends on the mean required power; therefore, the thermal engine works at constant load with reduced pollutant emissions, high reliability and long working life. Fig.1. presents a block diagram of a PHEV with an electrical machine (EM) and fuel cell that EM and ICE power are combined together to propel the vehicle. There are five different ways to operate the system, depending on the flow of energy: 1) provide power to the wheels with only the ICE; 2) only the EM; or 3) both the ICE and the EM simultaneously; 4) charge the battery, using part of the ICE power to drive the EM as a generator; 5) by letting wheels drive the EM as a generator that provides power to the battery that causes to improving fuel efficiency.

During braking or deceleration, the electric motor acts as a generator to charge the battery via the power converter. Also, since both the engine and electric motor are coupled to the same drive shaft, the battery can be charged by the engine via the electric motor when the vehicle is at light load. Recently, the Honda Insight HEV has adopted a similar power flow control.

A common method to control of the complex dynamic systems with many uncertainties is designing some different of local controllers each for a specific operating area or determined objects and then designing of a switching strategy through the subsystems to achieve the global objectives of the system.

The control of hybrid electric vehicle systems involves some complex control processes, such as; generating Throttle (or brake) command according to external environment changes and the driver's expectation, splitting the power between the two power-sources to sustain the efficiency of the engine and/or charging/discharging efficiency of the battery at a relatively high level and driving the mechanical and electrical components to meet the requirement from above level. These processes usually involve logic switching, jump, sample-data control signals, and certainly, the continuous signals; hence hybrid electric vehicle system is a hybrid dynamical system.

Hybrid and switched systems have numerous applications in control of mechanical systems, automotive industry, flight and air traffic control, switching power converters, process control, robotics, etc. Hybrid systems consist of a continuous-time and/or discrete-time process interacting with a logical or decision-making process. The continuous/discrete-time subsystem is represented as a set of differential/difference equations whereas the logical/decision making subsystem (supervisor) is represented as a finite state machine or a more general discrete event system, e.g. a Petri net. In the hybrid system context, the continuous/discrete time subsystem affects the discrete transitions of the supervisor and the supervisor affects the dynamic evolution of the continuous/discrete-time subsystem.

4. Intelligent Power Management Strategy

In particular, management and distribution of power are essential elements in the implementation of fuel cell hybrid electric vehicles, where each power source must be used according to driver demand and the specific features of the driving situation. Since fuel economy and battery usage are primary factors to be considered in the operation of hybrid vehicles, development of power management strategy for this class vehicles has received a great deal of attention [2].

In this paper the proposed controller for power management in fuel cell hybrid electric vehicle (FCHEV), is mainly composed of three parts such as driver's intention predictor (DIP), driver's power computation (DPC) and the fuel cell power controller (FCPC) as shown in Fig.2.

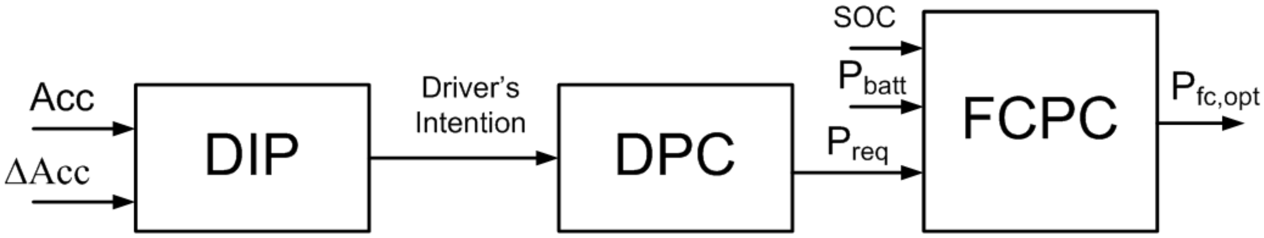


Fig2. Proposed layout for power management in FCHEV

4.1. Driver's Intention Predictor (DIP)

The DIP is introduced in this fuzzy logic controller to enhance the drivability of this vehicle. The output of DIP can be considered as the demanded torque reference satisfying the driver's acceleration/deceleration reflected in acceleration pedal stroke and its rate. Since the driver's intention is reflected on the acceleration pedal stroke, Acc and its rate, ΔAcc, using these values as inputs of the DIP, the demanded torque reference proper to the driver's accelerating/decelerating intention can be produced. The input and output membership functions for the DIP are shown in Fig.3, where Acc is normalized from 0 to 1 and ΔAcc is from -1 to 1. The driver's intention is normalized from -1 to 1.

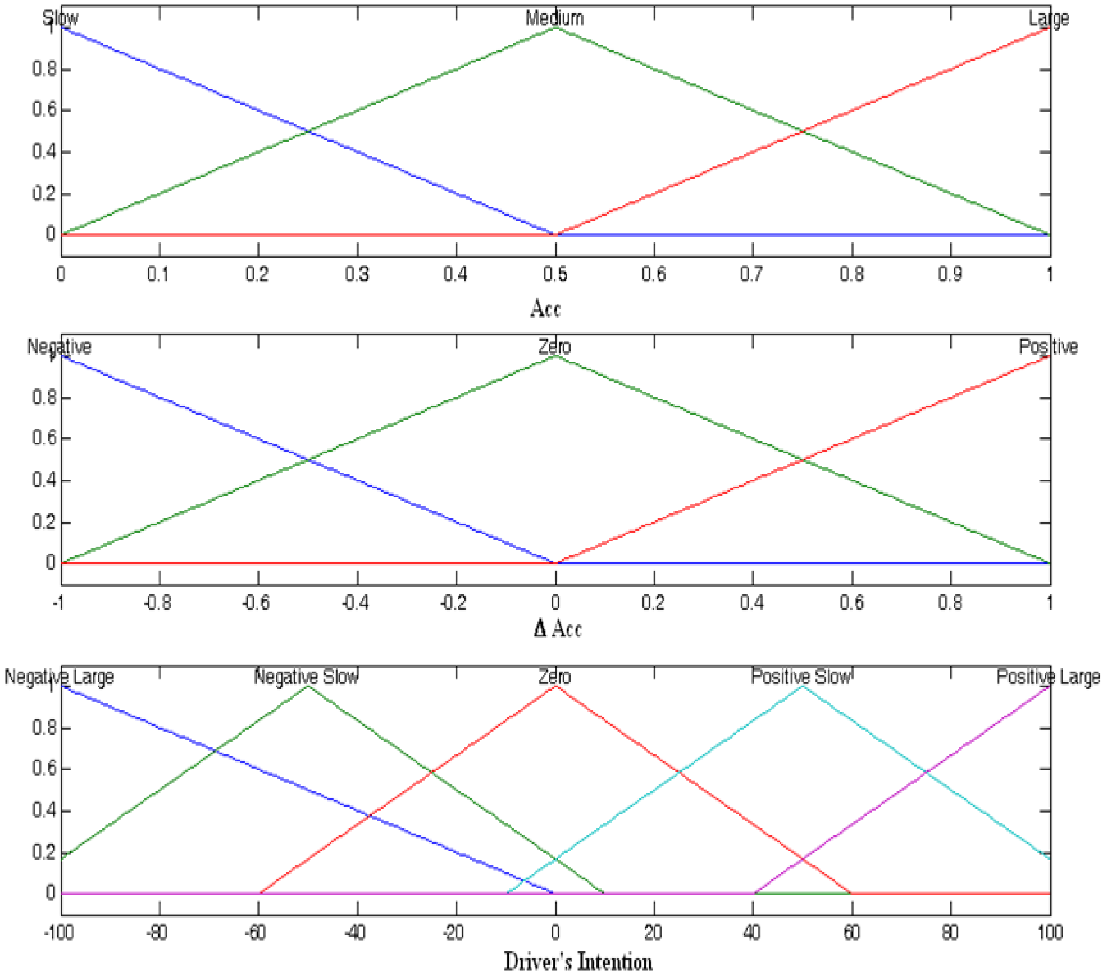


Fig.3. Input and Output membership functions of DIP

4.2. Driver's Power Computation (DPC)

The second block in power management strategy converts driver's intention to road load. For this purpose the maximum available power is computed by adding the maximum available electric motor power. The maximum available electric motor power depends on the instantaneous speed of electric motor and is computed by using the efficiency map of each component. Then, driver's intention multiplies by the maximum available power. The positive part of power is road load and negative part is braking power which implies to braking controller.

4.3. Fuel Cell Power Controller (FCPC)

In FCHEV one of the primary goals is to set the fuel cell operation in its peak efficiency region. This improves the overall efficiency of the powertrain. The FC operation is set according to the road load and the battery state of charge (SOC). This strategy is used to run the FC about it's peak efficiency region. In this strategy, the operating points of the FC are set near the torque region, where efficiency is the maximum for that particular engine speed. Since an electric motor (EM) is available to load-level, the HEV can use its electric machine to force the engine to operate in a region that consumes less fuel, while maintaining the state of charge (SOC) of the battery pack over the majority of the drive cycle. This is achieved by using the electric motor to compensate for the dearth in torque required to meet the road load. Load levelling has to be done, to meet the total driveline torque request, and to prevent unnecessary charges or discharges of the battery pack.

The power management strategy in the hybrid control structure is crucial for balancing between efficiency and performance of hybrid systems. The term “power management” refers to the design of the higher-level control algorithm that determines the proper power level to be generated, and its split between the fuel cell stack and battery while satisfying the power demand from the load and maintaining adequate energy in the energy storage device. Frequent power demand variations and unpredictable load profile are unavoidable uncertainties. Also, nonlinear and often time varying subsystems add to the complexity of the structure of hybrid system. Hence an on-line control strategy for instantaneous power management based on fuzzy logic has been proposed.

A fuzzy logic controller is designed to distribute the power among the battery and the fuel cell system, to satisfy the load power requirement with respect to dynamic restrictions of these systems such as fuel cell temperature, power demand, battery power, fuel cell power and battery state of charge. Also, fuel cell power must changes smoothly so that the fuel cell operating point deviation is minimized and fuel cell temperature does not increase and remains in desired limit. In this case, both battery and fuel cell system contribute to provide load power with one degree of freedom:

$$P_{load}(t) = P_{batt}(t) + P_{fc}(t) \qquad (13)$$

Fig.4 shows the Fuzzy Logic Controller for Power Management Strategy. A Fuzzy Logic Controller (FLC) is used to decide on operating point of the fuel cell stack. It is necessary to determine the fuel cell stack optimal power to assist the battery in charge or discharge modes. It follows the idea of load leveling, where the battery is used to provide assist or generate, while operating the fuel cell at an optimum. A fuzzy logic controller relates the controller output to the inputs using a list of if-then statements called rules. The if-part of the rules refers to adjectives that describe regions (fuzzy sets) of the input variables. A particular input value belongs to these regions to a certain degree, so it is represented by the degree of membership. To obtain the output of the controller, the degrees of membership of the if-parts of all rules are evaluated, and the then-parts of all rules are averaged and weighted by these degrees of membership. The core of the rule set of the fuzzy controller is illustrated as follows.

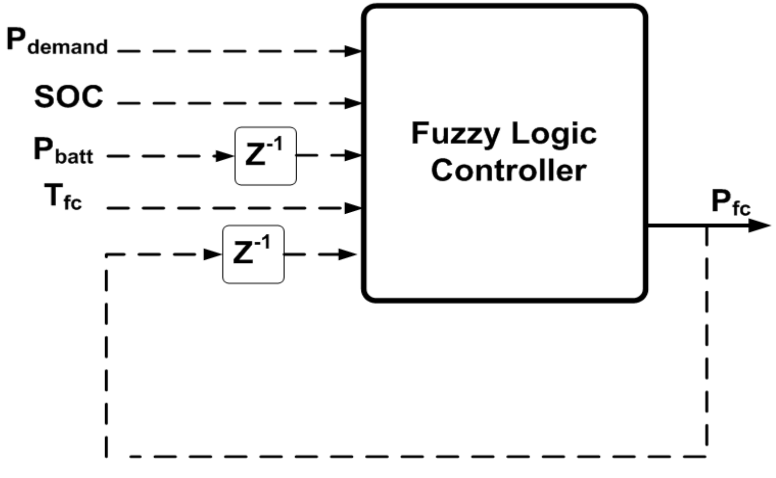


Fig.6 Fuzzy Logic Controller for Power Management Strategy

(1) Battery Charge Mode

Rule 1: if P_{demand} is *Low* and *SOC* is *Low* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Negative High* and $P_{fc}(k-1)$ is *Low* then $P_{fc}(k)$ is *Medium*.

Rule 2: if P_{demand} is *Medium* and *SOC* is *Low* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Negative Medium* and $P_{fc}(k-1)$ is *Medium* then $P_{fc}(k)$ *High*.

Rule 3: if P_{demand} is *Medium* and *SOC* is *Low* and T_{fc} is *High* and $P_{batt}(k-1)$ is *Negative Low* and $P_{fc}(k-1)$ is *Medium* then $P_{fc}(k)$ is *High*.

(2) Hybrid Mode

Rule 4: if P_{demand} is *Medium* and *SOC* is *High* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Low* and $P_{fc}(k-1)$ is *Low* then $P_{fc}(k)$ is *Medium*.

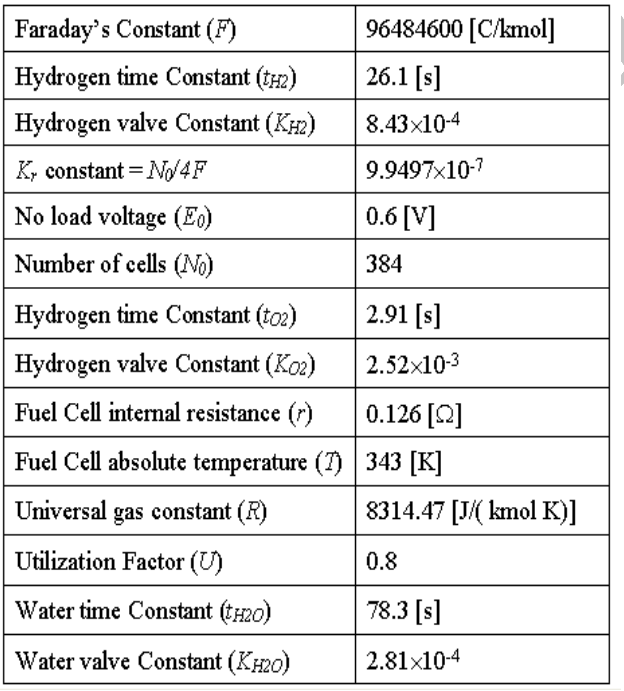
Rule 5: if P_{demand} is *Medium* and *SOC* is *High* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Medium* and $P_{fc}(k-1)$ is *Medium* then $P_{fc}(k)$ is *Medium*.
Rule 6: if P_{demand} is *Medium* and *SOC* is *High* and T_{fc} is *High* and $P_{batt}(k-1)$ is *Medium* and $P_{fc}(k-1)$ is Medium then $P_{fc}(k)$ is *Low*.
Rule 7: if P_{demand} is *High* and *SOC* is *High* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Low* and $P_{fc}(k-1)$ is *Medium* then $P_{fc}(k)$ is *High*.
Rule 8: if P_{demand} is *High* and *SOC* is *High* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Medium* and $P_{fc}(k-1)$ is *Low* then $P_{fc}(k)$ is *Medium*.
Rule 9: if P_{demand} is *High* and *SOC* is *High* and T_{fc} is *High* and $P_{batt}(k-1)$ is *Medium* and $P_{fc}(k-1)$ is *High* then $P_{fc}(k)$ is *Medium*.
Rule 10: if P_{demand} is *High* and *SOC* is *High* and T_{fc} is *High* and $P_{batt}(k-1)$ is *High* and $P_{fc}(k-1)$ is *Medium* then $P_{fc}(k)$ is *Low*.
Rule 11: if P_{demand} is *High* and *SOC* is *Low* and T_{fc} is *Low* and $P_{batt}(k-1)$ is *Low* and $P_{fc}(k-1)$ is *Medium* then $P_{fc}(k)$ is *High*.

5. Simulation Study

The topology used in this study for the combined fuel cell and battery system, power conditioning units, and load is shown in Fig. 8. The proposed FC system operates in parallel with a battery bank connected to the dc bus via a dc/dc converter. The battery bank serves as a short duration power source to meet load demand that cannot be met by the FC system, particularly during transient or peak demand periods. In this study, the battery bank is designed to provide the difference between the load and the fuel cell system output power. Simulation results are obtained by developing a detailed MATLAB, Simulink, and SimPowerSystems-based software packages using the mathematical and electrical models of the system described earlier.

The FC system parameters in this study are given in Table 1 [14]. The power conditioning units parameters include DC/DC and DC/AC converters and battery system specifications are given in Table 2 and 3. The Profile of power demand has a significant effect on determining the power management strategy. The power demand profile used is shown in Fig. 5. It is good representation of transient states and it has periodic property. From this load profile, it is evident that the average power demand is less than 45 kW. The load profile during peak load periods varies from 53 to 57 kW, as illustrated in Fig. 5. The output power of the FC system is limited to 45 kW and the battery bank system is capable of sustaining the extra load of 20 kW for 100s during peak demand periods.

Table 1 Fuel Cell System Model Parameters



Faraday's Constant (F)	96484600 [C/kmol]
Hydrogen time Constant (t_{H2})	26.1 [s]
Hydrogen valve Constant (K_{H2})	8.43×10^{-4}
K_r constant = $N_0/4F$	9.9497×10^{-7}
No load voltage (E_0)	0.6 [V]
Number of cells (N_0)	384
Hydrogen time Constant (t_{O2})	2.91 [s]
Hydrogen valve Constant (K_{O2})	2.52×10^{-3}
Fuel Cell internal resistance (r)	0.126 [Ω]
Fuel Cell absolute temperature (T)	343 [K]
Universal gas constant (R)	8314.47 [J/(kmol K)]
Utilization Factor (U)	0.8
Water time Constant (t_{H2O})	78.3 [s]
Water valve Constant (K_{H2O})	2.81×10^{-4}

Table 2 Power Conditioning Units Parameters

DC/AC Converter Parameters	
Voltage reference signal *(V_r)*	220 [V]
Line reactance *(X)*	0.05 [Ω]
DC input voltage *(V_{dc})*	220 [V]
DC/DC Converter Parameters	
Rated voltage	400 [V]
Resistance *(R)*	14 [Ω]
Capacitance *(C)*	1.5 [mf]
Inductor *(L)*	415 [μH]

Table 3 Battery Model Parameters

Capacity *(Q_m)*	50 [A.h]
No. of module	25
Rated voltage	308 [V]
Internal resistance *(R_a)*	0.015 ± 25% [Ω]
Terminal resistance *(R_b)*	0.015 ± 25% [Ω]
Incipient capacitance *(C_i)*	3 [F]
polarization capacitance *(C_p)*	3 [F]
Minimum state of charge	70%
Maximum state of charge	80%

The inverter is assumed to have an input of 200-V dc and output of 220-Vrms ac. In the dc/ac inverter, PI controllers are used to control the ac output voltage and active power, which adjusts the modulation index and phase angle, according to the load variations. Thus, the ac output voltage is kept at 220 Vrms and the total load power demand is met from FC system and battery bank by the power flow PI controller. In this study, PCU losses are assumed to be negligible.

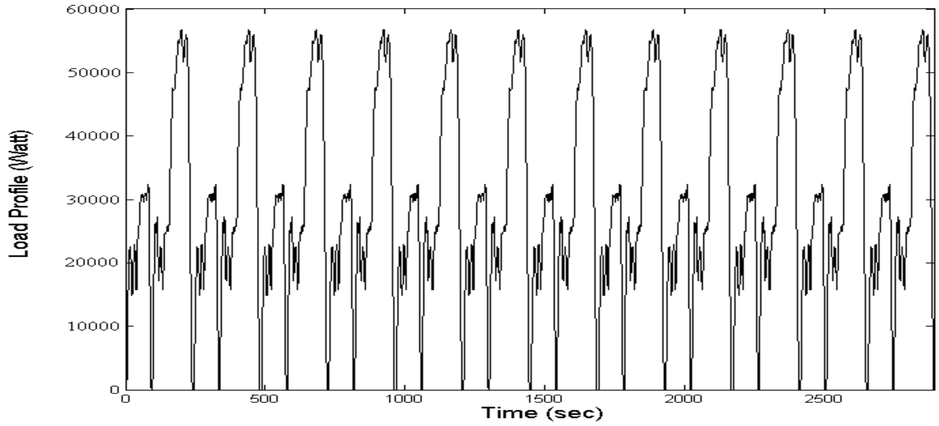


Fig.5. AC electricity demand.

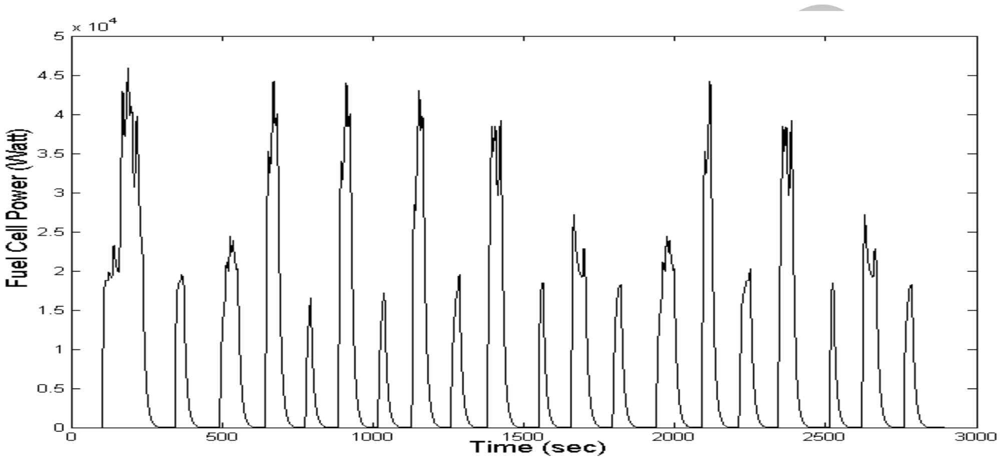


Fig.6. Variation of FC system output power.

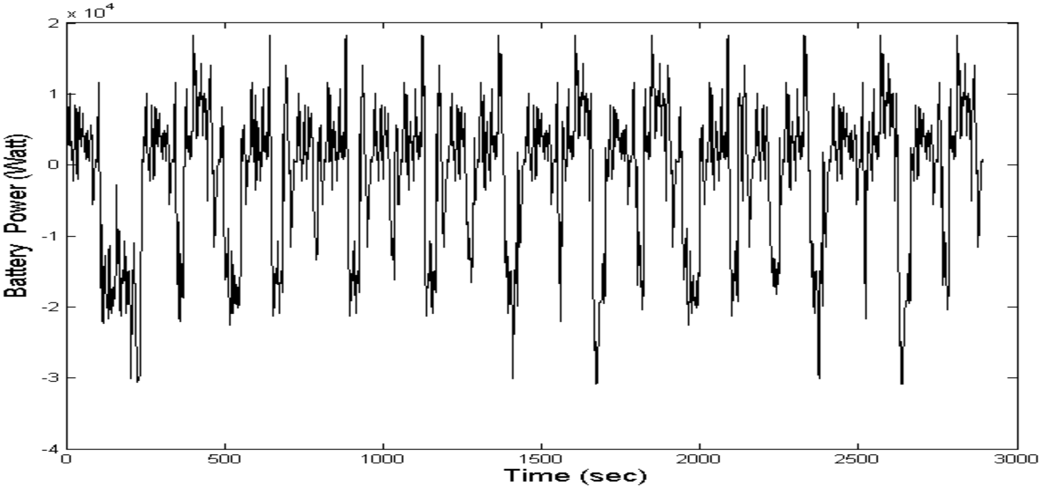


Fig.7. Variation of Battery Bank output power.

Simulation results are obtained for the time interval between 0 and 3000s. Figs.6-10 show the fuel cell power, battery power, battery current, battery voltage and battery state of charge, respectively, as a function of time. If the power demand is low, only the battery bank supplies power to load. In these conditions the battery's SOC is decreased. While the power demand is increasing, the fuel cell power is raised smoothly and power and power deviations are provided by battery. Battery response for load changes is faster than fuel cell system. The battery bank supplies power to meet the fast load change and fuel cell power changes slowly for fuel cell stack safety and durability. Fig. 8 shows that the variation of the battery bank current between negative (charging) and positive (discharging) according to the required load demand. From Fig. 7 and Fig.8, it is evident that the FC system and battery bank together share this load requirement. During peak load demand, the load power requirement is higher than the power generated by the FC system. Therefore, the FC system supplies the available power and the battery bank supplies the remaining extra power. Although the battery bank voltage is affected by the load conditions as seen in Fig. 9. At this time, the battery bank discharge current is very high and the battery bank terminal voltage drops significantly. If the produced power by the fuel cell is more than the required power of load, the extra power of fuel cell is used to charge the battery and the battery state of charge goes high. The result shows that the SOC can be maintained at a reasonable level as seen in Fig. 10.

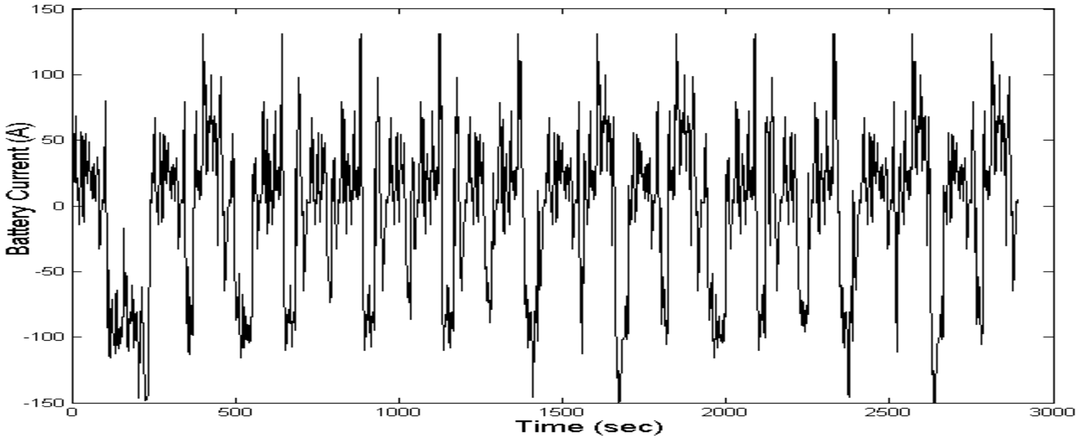


Fig.8. Variation of battery bank charging and discharging current according to load profile.

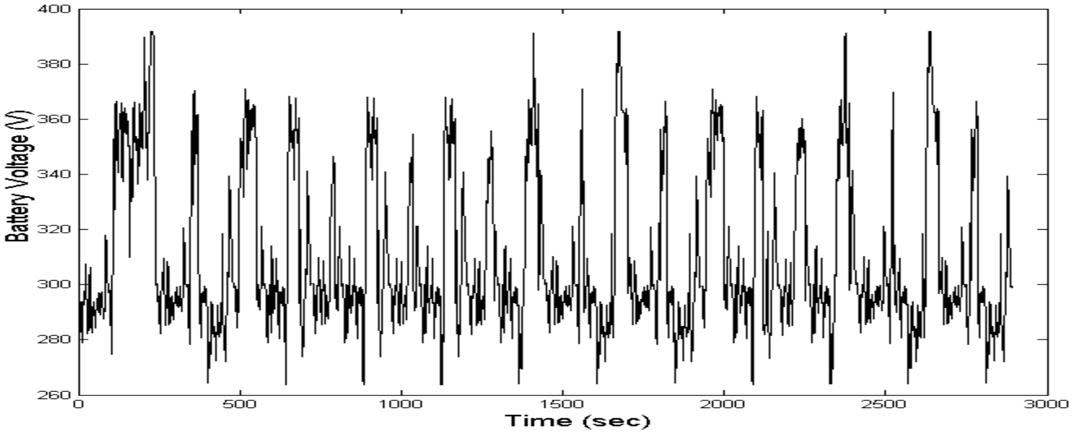


Fig.9. Variation of battery bank output voltage.

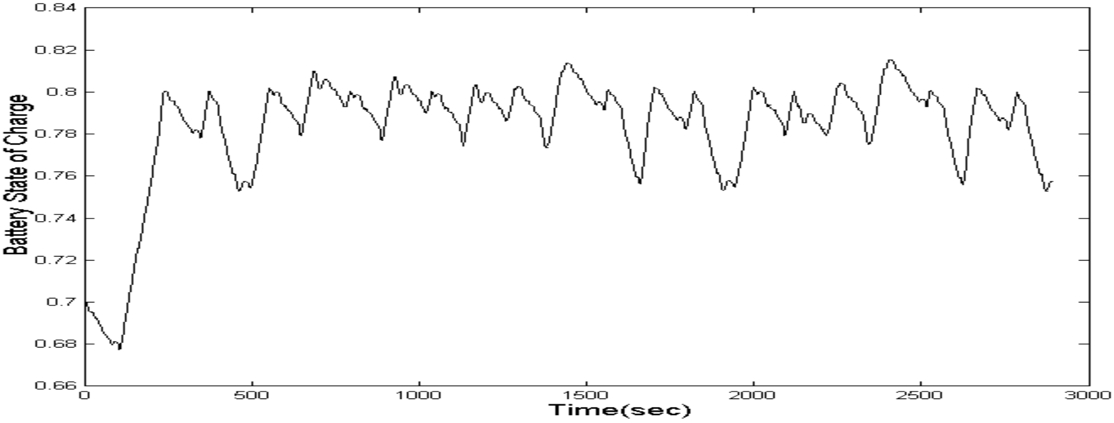


Fig.10. Variation of battery bank state of charge.

5. Conclusion

This paper presents a new approach for power sharing in a hybrid fuel cell/battery electric vehicle to improve the system efficiency and battery life with acceptable load following capability. This method implemented a real time power management by a hybrid controller between dual sources in this kind of hybrid systems. This structure included two energy sources, battery and the stack of fuel cell. The proposed method involves an advance supervisory controller in the first layer which captured all of possible operation modes. With regards to the operation modes, the upper layer makes decision to choose the switching chain roles and corresponding controller in the second layer. Finally in the third layer, there are local controllers to regulate the set points of each subsystems to reach the best performance and acceptable operation indices.

References

[1] G. Majumdar, K.H.Hussein, K.Takanashi, M.Fukada, J. Yamashita, H. Maekawa, M. Fuku, T.Yamane, T. Kikunaga."High-Functionalty Compact Inelligent Power Unit (IPU) for EV/HEV Applications". Proceeding of 2001 International Symposium on Power Semiconductor Devices & Ics, Osaka

[2] S.M.T Bathaee, S.R.Emami Maybodi, A.Hajizadeh Gastaj, "Dynamic Modeling and Intelligent Control of Hybrid Electric Vehicel", The 9th World Multi-Conference on Systemics, Cybernetics and Informatics, July 10-13, 2005 – Orlando, Florida, USA.

[3] S.M.T Bathaee, A.Hajizadeh Gastaj, S.R.Emami Maybodi, "A Fuzzy-based Supervisory Robust Control For Parallel Hybrid Electric Vehicles" 2005 IEEE Vehicle Power and Propulsion Conference, Chicago, USA.

[4] Anthony M. Philips, Miroslava Jankovic, and Kathleen E.Baily." Vehicle System Controller Design for a Hybrid Electric Vehicle" International Conference on Control Applications Anchorage, Alaska, USA (September 2000)

[5] S.D.Farrall and R.P.Jones,"Energy management in an automotive electric/heat engine hybrid powertrain using fuzzy decision making".In Proc. International Symp.on Intelligent Control,1993.

[6] Niels J.Schouten, Mutasim A. Salman, Naeim A.kheir." Fuzzy Logic Control for Parallel hybrid Vehicle". IEEE Transaction on Control System Technology (MAY 2002) .

[7] Gino Paganelli, Makoto Tateno, Avra Brahma, Giorgio Rizzoni, Yann Guezennec," Control Development for a Hybrid Electric sport-utility vehicle: strategy, Implementation and field test results" Proceeding of the American Control Conference Arlington, VA June 25-27,2001

[8]Gino Paganelli, Gabriele Ercole, Avra Brahma, Yann Guezennec, Giorgio Rizzoni "General supervisory control policy for the energy optimization of charge-sustaining hybrid electric vehicles" 2001 Society of Automotive Engineers of Japan, Inc. and Elsevier Science

[9]Valerie H. Johnson, Keith B. Wipke and David J. Rausen, National Renewable Energy Laboratory," HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions" Copyright © 2000 Society of Automotive Engineers, Inc.

[10] Kleimaier, A. and Schroder .D " Optimization strategy for design and control of a hybrid vehicle" 6th International Workshop on Advanced Motion Control 2000

[11] Kleimaier, A. and Schroder .D " An Approach for the online optimized control of a hybrid powertrain" 2002 IEEE

[12] S. Delprat, T.M Guerra, J. Rimaux," Optimal control of a parallel powertrain : From global optimization to real time control strategy, Electric Vehicle Symposium," EVS18, Berlin, (Allemagne), Octobre 2001.

[13]S. Delprat, T.M Guerra, J. Rimaux "Control Strategies for Hybrid Vehicles: Optimal Control" 2002 IEEE.

[14] A.Hajizadeh, M.Aliakbar Golkar" Fuzzy Control of Fuel Cell Distributed Generation Systems", Iranian Journal of Electrical & Electronic Engineering (IJEEE), Vol.13, No 1& 2, Jan. 2007.