Optimal Fuzzy Logic Controller for Energy Management in Fuel Cell Hybrid Electric Vehicle

S. Elahian, A. Abrishamifar, and A. Ale-Ahmad, *Member, IEEE*

***Abstract*—Hybrid electric vehicles utilize an energy storage source in order to decrease the size of main power source and increase system efficiency. Energy management in these vehicles plays an important role because of its influence on fuel consumption and system operation. In this paper a fuzzy logic controller is proposed for energy management in fuel cell hybrid vehicle that uses battery as an energy storage device. Since fuzzy logic controller output is not always optimum, its membership function parameters are optimized by genetic algorithm. As optimization of fuzzy controller varies for different driving cycles and also, genetic algorithm optimization for each cycle is too time consuming to implement on-line, it is proposed to use adaptive membership functions in the controller. Adaptation is based on the probability of driving cycle recognition. Membership functions are transferred and optimized according to the evaluated probability. Fuel cell hybrid vehicle is simulated by ADVISOR in the MATLAB/Simulink environment. Results show that fuel economy improves and battery state-of-charge is maintained in a desirable confine for proposed control strategy.**

***Index Terms*—Fuel cell hybrid electric vehicle, energy management, fuzzy logic, genetic algorithm.**

I. Introduction

TODAY using from fossil fuels is confined because of their restriction and environmental pollutions. Invention of electric vehicles was initial step to realize these goals. By passing time, hybrid electric vehicles (HEVs) introduced as a suitable schema to be utilized in industry, which uses two power sources to provide load power demands.

Through different kinds of power sources introduced to use in hybrid vehicles, fuel cell (FC) drawn more attention because of its high efficiency and low harmful emissions. But fuel cell dynamic response is low and can not response to fast power demands. Besides, fuel cell does not have ability to receive and store the energy produced by braking [1].

In fuel cell hybrid electric vehicles (FCHEV) an auxiliary power source is used to improve fuel cell performance and stores braking energy to increase system efficiency [2]-[4]. Battery, ultra-capacitor or their combination usually uses as an auxiliary power source. Each of these elements has different characteristic. Battery has high energy density and low power density in contrary, ultra-capacitor has low energy and high power density. Therefore, battery response to load variations more slowly than ultracapacitor (UC) but it produces power for longer time.

Using each of these energy storage devices affect on system characteristics such as fuel consumption, dynamic response, cost and weight. Effects of various energy storage devices on vehicle performance are discussed in some papers [5], [6]. Among them reference [5], done this work more accurately with more details. According to the paper and have a trade off among different specifications, battery is chosen as an energy storage device for FCHEV. Fig. 1. shows configuration of FCHEV in ADVISOR that includes a fuel cell, battery and motor. This structure is like series hybrid vehicles with replacement of fuel cell by generator.

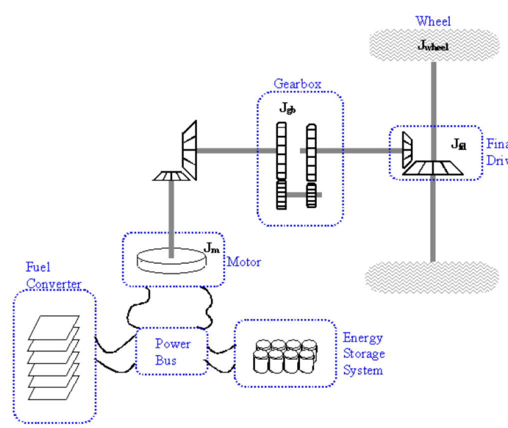

Fig. 1. FCHEV configuration in ADVISOR

Existence of two power sources in hybrid system, imposes to utilize a controller for energy management. The controller determines power distribution between power sources with respect to the demanded power, current status of power sources and their characteristic curves.

Many studies have been done on power distribution strategies in literature. Thermostat [7], equivalent consumption minimization (ECMS) [8]-[10] and fuzzy logic controller [11]-[13] are some of these methods. Each strategy track special

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S. Elahian is with the Electrical Engineering Department, University of Iran Science and Technology; e-mail: s_elahian@elec.iust.ac.ir).

A. Abrishamifar, is with the Electrical Engineering Department, University of Iran Science and Technology (e-mail: abrishamifar@iust.ac.ir).

A. Ale-ahmad is with the Electrical Engineering Department, University of Iran Science and Technology, (e-mail: alahmad_ah@yahoo.com).

goal such as decrease fuel consumption, increase power sources lifetime and maintenance of vehicle performance.

In thermostat control strategy, battery lifetime decreases because of many charges and discharges and vehicle lost its good performance. Optimization strategy is very sensitive to exact determination of algorithm factors to have optimum fuel consumption. Therefore, these strategies are not proper for energy management in FCHEV.

It is demonstrated in literature that fuzzy logic controller is appropriate for power distribution in HEVs [11], [14]-[16]. In this paper, fuzzy logic controller is chosen since it is not relying on priori knowledge of power profile and exact mathematical model of system. Besides, this strategy has ability to optimize fuel consumption and its implementation is simple. Fuzzy logic controller response is not optimum in all conditions. Membership functions in fuzzy logic controller should be defined so as vehicle fuel consumption decreases.

Simulation is done for two standard driving cycles including UDDS and HWFET that are defined in ADVISOR to evaluate vehicle performance in urban and highway, respectively (Fig. 2.).

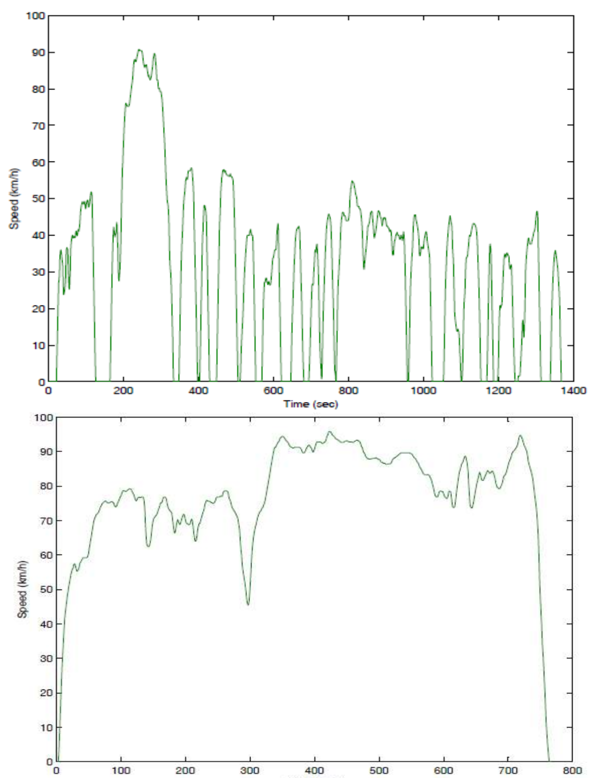


Fig. 2. driving cycles from up to down(a) UDDS and (b) HWFET

FCHEV is simulated by ADVISOR. This software is produced by National Renewable Energy Laboratory (NREL) and implemented in the MATLAB/Simulik environment [17], [18]. In this software various kinds of hybrid vehicles are modeled based on practical models in form of look-up tables. In section II and III power sources of FCHEV and energy management using optimized fuzzy controller by genetic algorithm (GA) are described, respectively. Simulation results are showed in section IV and finally V devoted to conclusion.

II. FCHEV POWER SOURCES

A. Fuel Cell

Different types of FCs are investigated and it is demonstrated that proton exchange membrane fuel cell (PEMFC) is more suitable for automotive applications due to its electrolyte structure, high power density and low operating temperature [2], [3], [19].

Fuel cell efficiency is high in narrow band of its operating range. In low power, high ratio of auxiliary subsystems power to the power produced by FC and high drop of voltage in high power, cause significant loss in FC efficiency. Power controller should be designed so as fuel cell works in its optimal efficiency region (Fig. 3.) to increase system efficiency. A 50kw FC is used in simulations. According to Fig. 3., a confine between 10 to 40kw is good range.

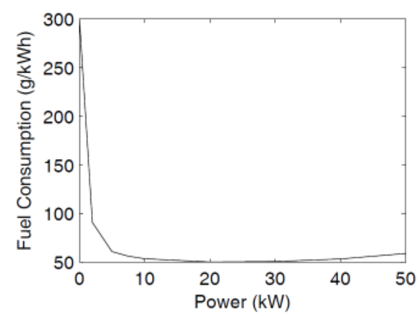


Fig. 3. Fuel consumption of PEMFC versus its power.

B. Energy Storage Device

As discussed before, battery is used as energy storage device in HEV. Various kinds of batteries utilizes in these vehicles. Nickel Metal Hydride (NiMH) batteries are more appropriate for this application because of low cost, memory effect and high security [20]-[22].

Battery resistance varies with its charge variation according to Fig. 4. It is revealed that battery resistance is minimum in 0.2 to 0.8 of battery state of charge (SOC) then in this interval, energy losses is more less than other places. Besides, it should be noticed that in this range, battery SOC has to be low enough to store braking energy in deceleration and should be high enough to provide power for vehicle acceleration.

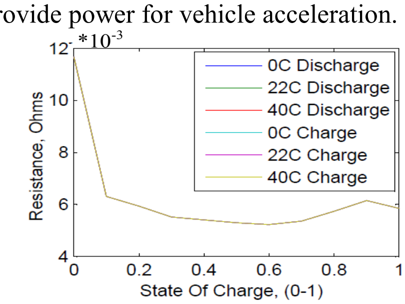


Fig. 4. Battery resistance versus SOC variations.

All specifications of power sources including type and voltage are illustrated in table I.

Table I
Power sources specifications

FC	

Type	FC_ANL50H2
Fuel type	Hydrogen
Output power	50 kW
Peak efficiency	0.6
Battery	
Type	ESS_NIMH90_OVONIC
Nominal voltage	335 v
Nominal capacity	90 Ah
Nominal Voltage	12 v
Number of module	25

III. ENERGY MANAGEMENT

Energy management in hybrid vehicles defines the power that must be produced by fuel cell and battery. In this study the aim of proposed controller is reducing fuel consumption, increasing battery lifetime and reserving vehicle performance.

A. *Fuzzy Logic Controller*

In fuzzy logic controller, outputs related to inputs by IF-THEN rules which acquired by expert knowledge. Fuzzy logic controller has two inputs and one output. Inputs are power demand from driver and battery state of charge (SOC) and output is power must be produced by fuel cell. Table II shows fuzzy controller rule base and its output that described fuel cell power by linguistic variables. Accordingly, battery output power (P_{bat}) can be calculated by using fuel cell power (P_{FC}) and demanded power (P_{dem}) according to (1).

$$P_{bat}(t) = P_{dem}(t) - P_{FC}(t) \qquad (1)$$

Rule base is determined so that fuel cell operates on its optimal efficiency region and battery SOC varies on its specified confine to increase its lifetime. Therefore, when power demand is high and battery has low SOC, fuel cell provides load power on its optimal region and if power demand is less than power in that region it not only supplies power for load but also charges the battery.

In this study Fuzzy logic controller is designed by Mamdani model and centroid method is used for defuzzification. Normalized inputs and output membership functions (MFs) are illustrated in Fig. 5.

Table II
Fuzzy logic controller rule base

Pdem / SOC	L	Med	H
L	H	H	VH
Med	L	L	VH
H	VL	VL	H

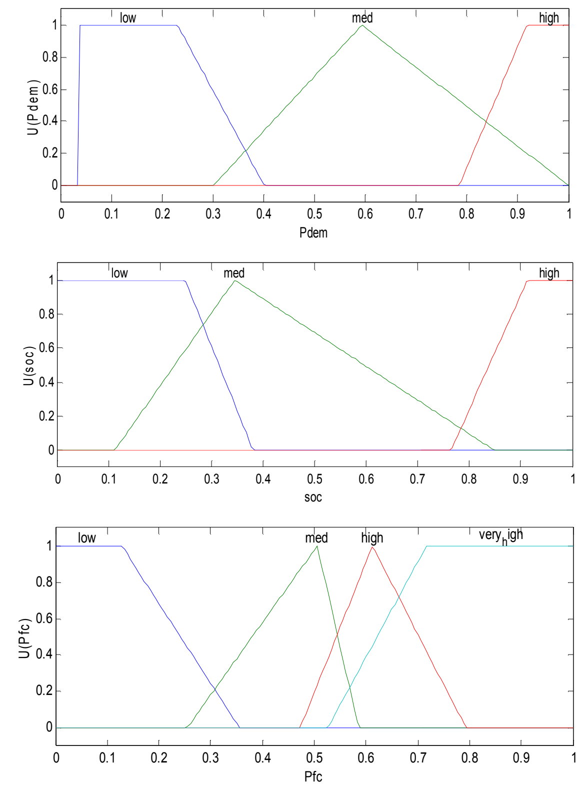


Fig. 5. Normalized fuzzy logic controller MFs for demand power, battery SOC and fuel cell power.

B. *Optimization of Fuzzy Logic Controller*

In fuzzy control strategy, determination of rule base and MFs affect on efficiency and fuel consumption of vehicle. Rule base is defined according to power sources limitations to increase system efficiency and MFs optimized so that fuel consumption minimizes.

In several researches fuzzy MFs are optimized using GA [23]-[25]. Genetic algorithm is an optimization technique that does not need to derivative. It iterates a determinate algorithm in order that get specified conditions [25].

All parameters of inputs and outputs MFs are coding in a chromosome (Fig. 6.). These parameters and also fitness function are chosen as minimum fuel consumption attained.

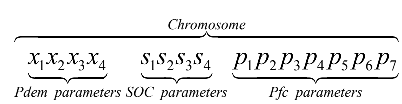


Fig. 6. A chromosome including parameters of all MFs

Coding of demand power (Pdem) MFs parameters are shown in Fig. 7.

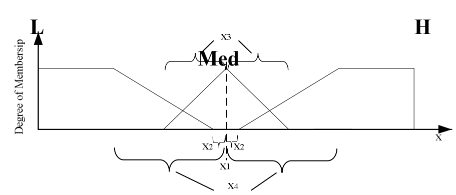


Fig. 7. Coding parameters of MFs

It is illustrated in literature that optimization vary with variation of driving cycle [26], [12]. Therefore, in online power distribution, driving cycle must be denoted so that appropriate MFs handled to have optimized fuel consumption.
In UDDS driving cycle, many variations occur in vehicle speed whereas this variation is very low in HWFET cycle. Then it is proposed to use gradient of average speed variations (2), to recognize that how much is the driving cycle close to UDDS or HWFET, two standard cycles that optimization is done for them.

$$\bar{a} = \left(\sum_{k=1}^{n} x(k+1) - x(k)\right)/n \tag{2}$$

where x(k) is vehicle speed at time k and n is period of each driving cycle. Equation (2) can be simplified as:

$$\bar{a} = (x(n+1) - x(1))/n \tag{3}$$

MF transfer defined using $\bar{a}$, by (4).

$$MF_i = MF_{HWFET} + (1 - \bar{a}_i / \bar{a}_{HWFET}) \times (MF_{HWFET} - MF_{UDDS}) \tag{4}$$

In this equation, ($\bar{a}_i/\bar{a}_{HWFET}$) shows probability of being close to highway cycle. Simulation is done to survey performance of suggested method for UDDS and HWFET driving cycle. To do this, each driving cycle divided to 50 second intervals and in each interval, optimized MFs achieved.

IV. SIMULATION RESULTS AND CONCLUSION

Proposed energy management strategy is implemented in FCHEV with ADVISOR in non-GUI format in order that GA can be used for optimization in shorter time. After that, the best MFs that give minimum fuel consumption defined and fuzzy logic controller apply these MFs. To do this, the controller block of FCHEV simulink model replaced by specified fuzzy logic controller as represented in Fig. 8.

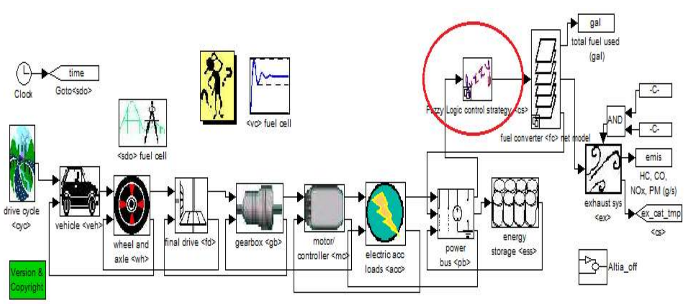
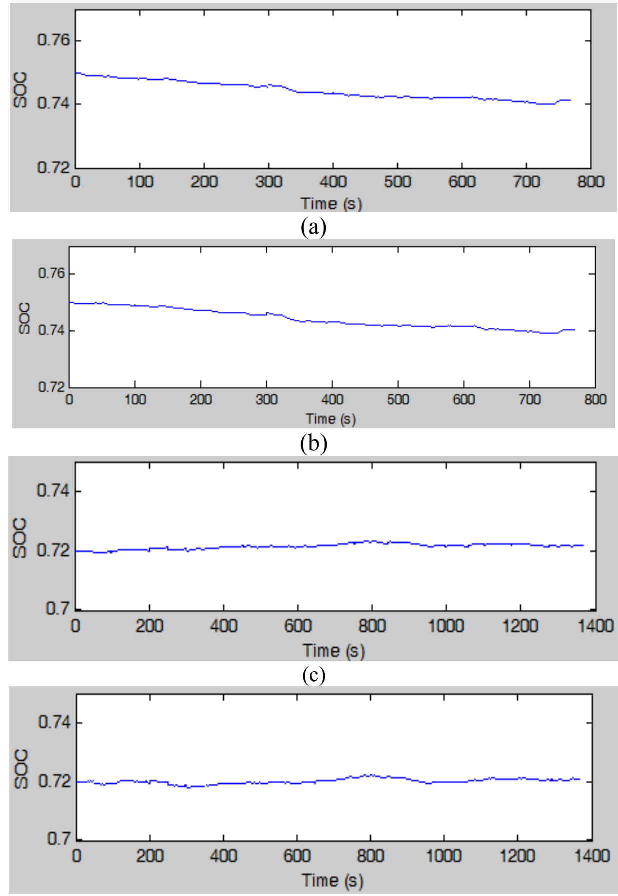


Fig. 8. FCHEV simulink model

To exert optimized MFs in each section of cycle, FCHEV model is run in non-GUI format to apply best values of MFs defined by GA for defined interval.



(a) (b) (c) (d)

Fig. 9. Battery SOC of HWFET cycle for (a) optimized by GA (b) adaptive MFs and UDDS cycle for (c) optimized by GA (d) adaptive MFs.

SOC variations illustrated in Fig. 9. In both strategies battery SOC is maintained in desirable range. In each interval, SOC initial value is set equal to the last value of SOC from previous interval then SOC has continuous variations.
Fuel economy of optimized MFs by GA and adaptive MFs are demonstrated in Table III for UDDS and HWFET cycles. Many acceleration and deceleration exist on UDDS driving cycle that cause the vehicle lose much energy and its efficiency become less than HWFET cycle.

Table III
Mpgge for UDDS and HWFET driving cycles for both GA optimized and adaptive MFs

	Optimized MFs	**Adaptive MFs**
HWFET	97.91	102.1
UDDS	87.54	89.49

In UDDS cycle, partial of cycle is steady like high way cycle and also, in HWFET cycle partial of cycle has many variations in speed like urban cycle. So, by using adaptive MFs fuel economy improves in comparison with GA optimized MFs.

V. CONCLUSION

Today transportation plays an important role in human beings everyday life. Limitation of petroleum fuels and increase in environmental pollutions persuade government to find a solution to overcome these problems. Fuel cell can be a good replacement for fossil fuels. Energy management in vehicles is very important because of its influence on fuel consumption, power source efficiency and battery lifetime.

Among different methods that offered in literature for energy management, fuzzy logic controller characteristics is more compatible with hybrid vehicle. Genetic algorithm is suggested to optimize fuzzy controller response for UDDS and HWFET driving cycle, and adaptive membership function optimization for any other cycles. Simulation results show 2.2% and 4% improvement in fuel consumption for UDDS and HWFET driving cycles with battery SOC maintenance in 1.3% and 0.08% confine, respectively. Therefore, this method can be used as an optimum on_line energy management with simple with low volume of calculations.

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Samaneh Elahian was born in Tehran, Iran, in 1984. She received the Electrical Engineering degree from the Shariaty University of Tehran, Iran in 2007 and currently is working toward M.Sc. degree in electrical engineering from Iran university of Science and Technology (IUST). Her research deals with the study and analysis of fuel cell hybrid electric.

Adib Abrishamifar received the B.Sc., M.Sc. and Ph.D. degrees in Electronics Engineering from Iran University of Science and Technology (IUST) in 1989, 1992 and 2001, respectively. He has been with the Department of Electrical Engineering, IUST, since 1993. His current research activities include analog integrated circuit design and power electronics.