Proceedings of the ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis
ESDA2014
June 25-27, 2014, Copenhagen, Denmark

ESDA2014-20599

PERFORMANCE COMPARISON FOR HYBRID FUEL CELL/BATTERY VEHICLE UTILIZING DIFFERENT POWER MANAGEMENT CONTROL STRATEGIES

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ABSTRACT

Power management systems are one of the most important components in modern hybrid vehicles. They are needed to optimize the operation of the hybrid system components. In this paper, a model for a fuel cell/battery vehicle is developed using PSAT and then tested with four power management control strategies utilizing the driving cycle of Amman city, the capital of Jordan. The main components of the hybrid vehicle are a PEM fuel cell, battery, and a brushless dc motor. PEM fuel cells are popular due to their good start up, high power density, and low operating temperature. The role of the battery in a hybrid system is to boost the system power during start-up and transient events in addition to storing the energy recovered from the braking process. The developed hybrid vehicle model is designed and configured so that it matches the power, acceleration, and maximum speed of a midsized vehicle powered by an internal combustion engine. The proposed control strategies are the thermostat strategy, fuel cell optimized strategy, load following strategy and fuzzy logic strategy. All four control strategies are implemented in simulation utilizing PSAT. The simulation results indicate that the best performance in terms of fuel economy is achieved by the load following control strategy.

INTRODUCTION

It is widely acknowledged how effective it is to use fuel cell-based automotive hybrid systems in order to reduce environmental pollution and fuel consumption. Research work has been ongoing to improve the reliability and reduce the cost of fuel cells (FCs) and to find better ways to operate them in automotive hybrid systems. In order to find best way to run and operate an FC-based hybrid vehicle, different configurations with different components (*eg*. FCs with batteries and/or ultracapacitors (UCs)) have been investigated. Various power management strategies and control techniques have been developed and proposed during the past two decades to improve their performance.

It is well known that the use of a stand-alone FC system for vehicle propulsion is not optimal given the typical power profile of a vehicle. Combining a FC system with another energy storage system can significantly improve the durability of the FC system and enhance the fuel economy of the vehicle. This efficient integration can fulfill the transient power demand fluctuations as well as reduce the FC capacity required to supply the average power demand without facing peak loads. The hybrid FC/battery system can also recover braking energy. Most control techniques are based on State-of-Charge (SOC) for battery/UC and/or hydrogen consumption. Due to their complexity, it is difficult to accurately model a hybrid vehicle system [1]. Thus, in practice the more commonly used control techniques are based on PID and fuzzy controllers that don't require a mathematical model [2, 3, 4].

Jiang and Fahimi [5] presented a novel control design for FC/battery hybrid system that enabled both active current sharing and power source management control. The proposed control system was able to regulate the output power from each source under different scenarios and configurations. They demonstrated experimentally the static and dynamic performance of the control system.

In [1], an adaptive supervisory controller took into account the fuel consumption minimization, the battery charge-sustaining, and the fuel cell durability. The authors report that the controller has been implemented on hybrid city buses.

A study on control strategies for active power sharing in a hybrid fuel cell/battery power source has been conducted to improve the system efficiency and battery life with acceptable load following capability [6]. Fuzzy logic has been developed and implemented to manage the hybrid power system. Simulation was performed to develop and verify control algorithms and experiments were carried out to validate the simulation results. The results show that fuzzy logic can be used to optimize the operational efficiency of the fuel cell system and to keep the battery SOC at reasonable level.

Wang and Li [7] proposed a design algorithm to size the energy storage units in order to achieve the lightest possible mass at 95% efficiency. They also developed a control strategy to achieve the maximum fuel economy of the FC. The state of charge of energy storage units was controlled in a dynamic environment and maintained during the driving cycle. Simulation and experimental results based on simplified urban driving cycles were presented to validate the proposed maximum fuel economy design.

In [8], the power flow management within a hybrid fuel cell-powered vehicle during real-time operation was studied. A real-time control was developed to optimize the global hydrogen consumption while maintaining drivability. Experimental and simulation results were presented, demonstrating clear improvement in fuel efficiency along with robustness and ease of implementation.

Martínez et al. [9] presented a practical control structure and energy management strategy for a test bed hybrid electric vehicle. The control structure was used to evaluate and compare the different energy management strategies to be implemented in the vehicle. The proposed strategy used a fuzzy logic controller and considered the slow dynamics in the fuel cell system, the vehicle speed, and the state of charge in the super capacitors.

Finally, a prediction-based power management strategy was proposed for fuel cell/battery plug-in hybrid vehicles with the goal of improving overall system operating efficiency [10]. The main feature of the proposed strategy is that, if the total amount of energy required to complete a particular drive cycle can be reliably predicted, then the energy stored in the onboard electrical storage system can be depleted in an optimal manner that permits the fuel cell to operate in its most efficient regime. The proposed strategy showed significant improvement in average fuel cell system efficiency while reducing hydrogen consumption. The prediction-based power management strategy was able to maintain a stable power request to the fuel cell thereby improving fuel cell durability, and that the battery is depleted to the desired state-of-charge at the end of the drive cycle.

In this study the performance of a hybrid FC/battery midsized vehicle is investigated with four different power management control strategies.

HYBRID FC/BATTERY VEHICLE MODEL

A hybrid FC/battery model for a midsized vehicle was developed using the Powertrain System Analysis Toolkit (PSAT) software package. Figure 1 shows the configuration of the developed vehicle model with three main components: the fuel cell system, battery system, and electrical motor.

The Proton Exchange Membrane (PEM) fuel cell system was selected with a capacity of 60kW. The PEM fuel cell systems are common in FC vehicles because of their good start up, higher power density, and lower temperature operation [11]. As for the battery, 120 Ni-MH battery cells with 6.5Ah and 1.2V per cell are connected in series. The presence of the battery system in the proposed hybrid configuration is very important in order to recover the braking energy and to provide power to the driving motor especially during start-up and transient events. A brushless dc motor with 36kw continuous power, 80kw peak power, and 90% efficiency is selected to be the only propelling engine in the hybrid configuration. The power capacity of the dc motor was selected so that the configured hybrid vehicle model matches a midsized ICE vehicle in terms of power, acceleration, and maximum speed. Table 1 lists the main parameters of the hybrid FC/battery vehicle model.

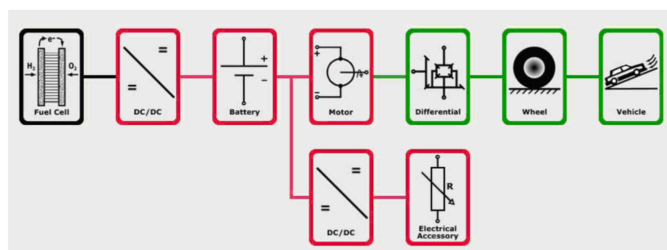

FIGURE 1 – PSAT MODEL CONFIGURATION FOR HYBRID FC/BATTERY VEHICLE

TABLE 1 –MAIN PARAMETERS OF THE HYBRID FC/BATTERY VEHICLE MODEL

Parameter	Value
Fuel cell capacity	60 kW
Ni-MH Battery	60 cells with 1.2V and 6.5Ah per cell
Electrical motor	80 kW peak 36 kW continuous
tire Size	175/70R14
maximum speed	120 km/h
acceleration time for 0-100 km/h	14.7 sec
seating persons	5
overall Length	451.0 cm
overall Width	171.0 cm
overall Height	144.0 cm
drag coefficient	0.42

POWER MANAGEMENT STRATEGIES

Four power management strategies are investigated in this study. All strategies are designed and implemented using the PSAT software. The proposed control strategies are i) thermostat strategy, ii) fuel cell optimized strategy, iii) load following strategy, and v) fuzzy logic strategy and they were tested utilizing the driving cycle of Amman city, the capital of Jordan, shown in Figure 2.

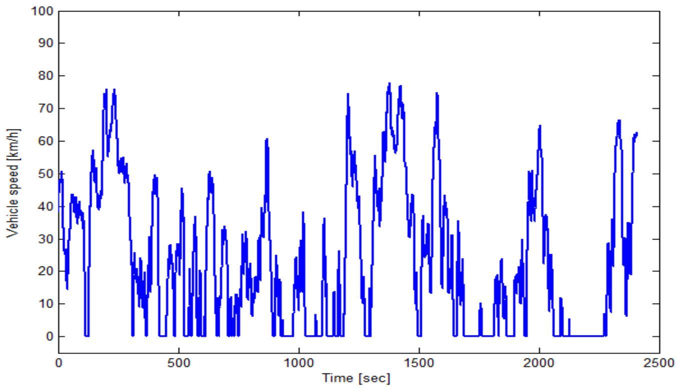

FIGURE 2 – DRIVING CYCLE FOR AMMAN CITY

Thermostat Strategy

In this strategy, the battery provides the power to the motor most of the time. The operation of the fuel cell depends on the battery's state of charge (SOC) and depends on the power demand as well. In other words, the fuel cell turns on when the battery's SOC is below a given lower threshold, while it turns off when the battery's SOC is above a given upper threshold. Hence, the hybrid vehicle is powered by the battery when the fuel cell is off. The power responses for the motor, FC, and battery are shown in Figure 3 when thermostat controller is implemented in the hybrid vehicle. It can be seen from Figure 3 that the battery provides most of the power to the motor, but when its SOC is below certain threshold or the battery power is not sufficient, the FC is turned on to boost source power and to meet the power demands for both the motor and charging the battery.

Fuel Cell Optimized Strategy

In this strategy, the motor is powered while the FC operates at its most efficient region. The fuel cell system in the hybrid FC/battery model has a maximum efficiency when its power is between 25kW and 40kW. Power responses are shown in Figure 4. It can be seen from Figure 4 that when the power is less than 25KW and the battery's SOC is above the minimum threshold, all the power demand is provided by the battery. Also, when the battery's SOC is too low or when the battery cannot meet the power demand, the FC is turned on.

Load Following Strategy

Using the load following strategy, the FC follows the load. In other words, the FC provides the needed power all the time to the motor as shown in Figure 5. The role of the battery is to supplement power (*i.e.*, compensate for any shortage in power) when the demand exceeds the capacity of the fuel cell. Another important role for the FC is to regulate the battery's SOC about certain threshold.

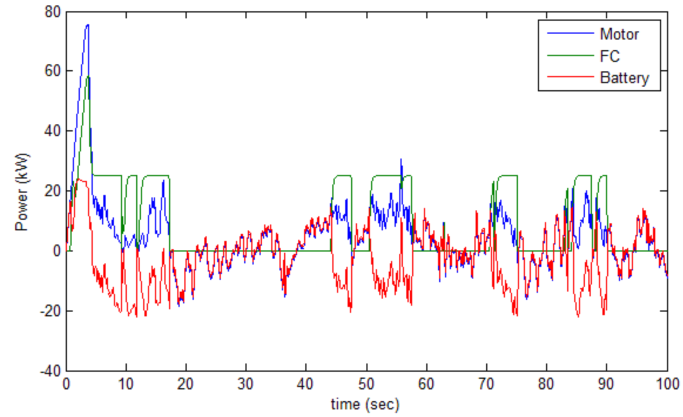

FIGURE 3 – POWER RESPONSE WITH THERMOSTAT STRATEGY

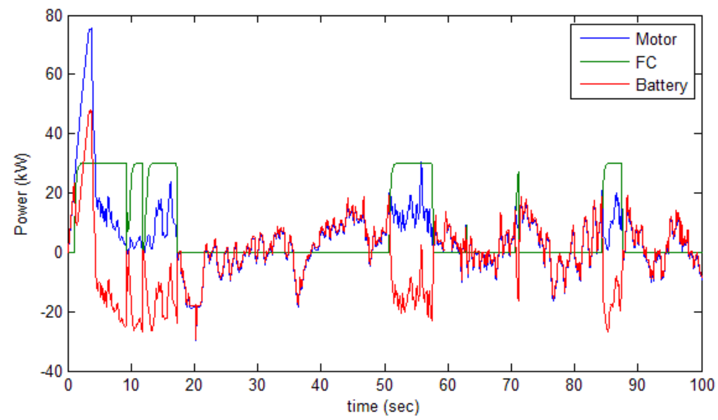

FIGURE 4 – POWER RESPONSE WITH FC OPTIMIZED STRATEGY

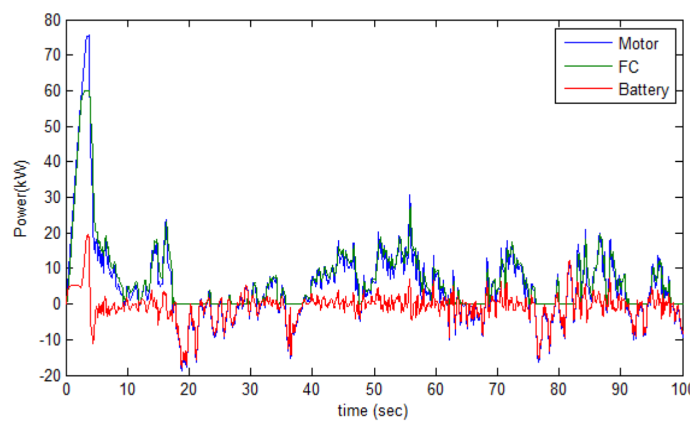

FIGURE 5 – POWER RESPONSE WITH LOAD FOLLOWING STRATEGY

Fuzzy Logic Strategy

In this strategy, a set of rules are chosen to operate the battery and FC harmoniously to effectively drive the vehicle load. The rules implemented in the Fuzzy logic controller are as follows: i) If battery's SOC is low, FC power is high regardless of power demand, ii) If power demand is high regardless of the battery's SOC, the FC power is high as well, iii) If the battery's SOC is high, then the FC power is either low or medium depending on the power demand, iv) when the power demand is negative, the FC power is zero and battery is charged from the recovered braking energy. Thus, the fuzzy logic controller determines the FC power and the battery output (*ie.* the power demand minus the FC power). Figure 6 shows the power responses for the motor, FC, and battery with the fuzzy logic strategy.

In Figure 7, the structure of the proposed fuzzy logic control strategy is shown. The fuzzy control structure has two inputs and one output. The inputs are the battery's SOC and the vehicle power required to drive the load (*i.e.*, power demand). The only output is the FC power. Three membership functions are selected, one triangular function, called medium, and two trapezoid functions, called high and low. Figure 8 shows the membership functions for the inputs and output after tuning the fuzzy logic controller. Defuzzification is implemented by the centroid method.

PERFORMANCE OF THE POWER MANAGEMENT STRATEGIES

The performance of the proposed hybrid FC/battery vehicle is tested by the four power management control strategies documented in the previous section. The overall results are reported in Table 2. In terms of fuel economy, best performance was achieved by the load following strategy. All control strategies successfully regulate the battery's SOC about 70%. Maximum powertrain efficiency is obtained with the load following strategy. The FC optimized control strategy has the best performance in terms of braking energy recovery, which illustrates that this is not the dominant factor when it comes to determining fuel economy, for this application. Overall, the best performance is achieved by the load following strategy.

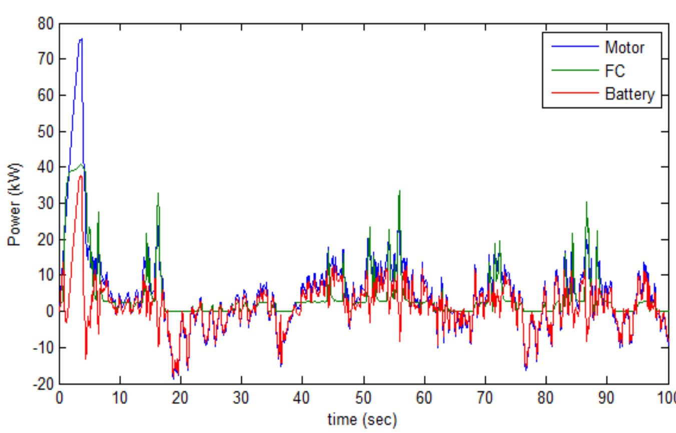

FIGURE 6 – POWER RESPONSE WITH FUZZY LOGIC STRATEGY

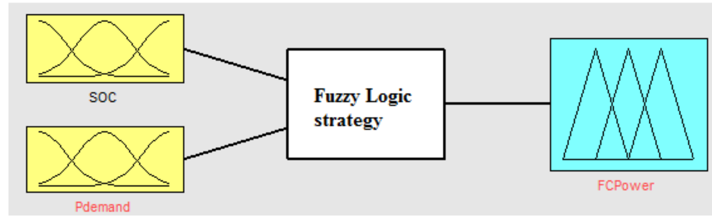

FIGURE 7 – STRUCTURE OF FUZZY LOGIC CONTROL STRATEGY

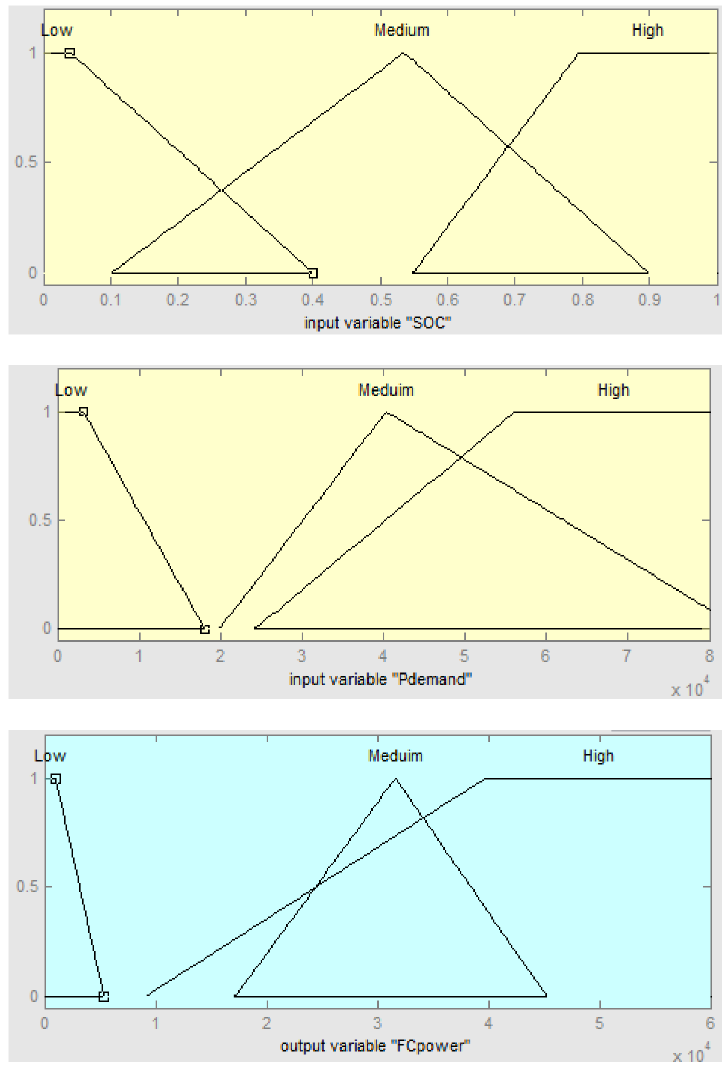

FIGURE 8 – TUNED MEMBERSHIP FUNCTIONS FOR THE a) BATTERY SOC, b) POWER DEMAND AND c) FC POWER

CONCLUSIONS

In this study, the effect of different power management control strategies on the performance of hybrid FC/battery vehicle was investigated. Simulation tests with four control strategies were conducted on a hybrid FC/battery vehicle model implemented with the PSAT software. Best performance in terms of fuel economy was obtained by the load following control strategy. This study represents a preliminary step in any future experimental implementation.

ACKNOWLEDGMENT

This work is supported by the scientific research support fund of the ministry of higher education and scientific research in Jordan under grant No. EWE/2/04/2010.

TABLE 2 – PERFORMANCE OF HYBRID FC/BATTERY VEHICLE WITH DIFFERENT CONTROL STRATEGIES

	Load Following	Thermostat	Fuzzy Logic	Fuel Cell Optimized
Fuel economy gasoline equivalent (L/100km)	4.59	4.97	4.83	5.06
Initial SOC %	70.0	70.0	70.0	70.0
Final SOC %	74.5	71.8	76.9	73.2
Powertrain Bidirectional Path Efficiency (%)	44.8	39.2	42.0	38.4
Percentage Braking Energy Recovered at Battery (%)	61.7	60.7	61.0	69.3

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